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RAINFALL-RUNOFF MODELLING IN WAINGANGA RIVER BASIN IN MADHYA PRADESH

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PREFACE

The rainfall runoff relationship is one of the most complex hydrologic phenomena to comprehend due to tremendous spatial and temporal variability of watershed characteristics, snow pack, precipitation patterns and the number of variables involved in modelling the physical processes. Conceptual models are a handy tool for the modeling in which the various interrelated hydrologic processes are conceptualized. More sophisticated procedures have also evolved based on the physical concept of the process which tries to model this hydrological phenomenon on the basis of physical laws governing them.

Monthly rainfall runoff models are very useful tools for the water resources engineers for the planning, design and operation of the water resources projects. These models are helpful in computing forecasts and in generation of arbitrarily long runoff series. These models are helpful to ascertain the availability of water during the season so as to plan for the operation of schemes. The Wainganga river basin in Madhya Pradesh has not been tapped to its potential and many projects are envisaged on it for the future. In order to plan for these projects the water availability studies are imperative for which the knowledge of the rainfall – runoff relationship is essential.

A monthly rainfall runoff model of simple structure has been developed which is able to reproduce the flows with a fair degree of accuracy. The study was proposed by the Water Resources Department and has been conducted by the Ganga Plains South Regional Centre, National Institute of Hydrology, Sagar. The report has been prepared by Sh. T. Thomas, Scientist-B, Sh. R. K. Jaiswal, PRA and Sh. Ravi Galkate, Scientist-C of Ganga Plains South Regional Centre, Sagar under the able guidance of Dr. A. K. Bhar, Scientist-F, Coordinator and Head.

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ABSTRACT

The problem of transformation of rainfall to runoff has been a very active area of research throughout the evolution of the subject of hydrology. The relationship of rainfall-runoff is known to be highly non-linear, complex, time varying and spatially distributed. It involves many highly complex components such as interception, depression storage, infiltration, overland flow, interflow, percolation, evaporation and transpiration. Transformation of rainfall to runoff is to be understood in order to forecast the stream flows for water supply, flood control, irrigation, drainage, water quality, power generation and wild life propagation. Every model is an attempt to capture the essence of the complex hydrologic system in a meaningful and manageable way, but it is important that the conceptualization involves considerable degree of simplification. Conceptual rainfall runoff models are designed to approximate within their structures the general internal sub-processes and physical mechanisms, which govern the hydrologic cycle. Conceptual models provide daily, monthly or seasonal estimates of the stream flow for short-term and long-term forecasting by mathematically formulating the entire physical process in the hydrologic cycle. A 6-parameter conceptual model of simple structure has been developed to represent the rainfall runoff relationship. The efficiency of the model varies between 0.67 and 0.83 during calibration and between 0.76 and 0.82 during validation. The percentage difference in volume between the observed and computed annual flows varies between –5.84% and 25.65%. The correlation coefficient between the observed and computed flow series varies between 0.90 and 0.96.

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1.0 INTRODUCTION

In many parts of the world, rapid population growth, urbanization and industrialization have increased the demand for water. These pressures have resulted in altered watersheds and river systems, which have contributed to a greater loss of life and property damages due to recurrent floods and droughts. It is becoming increasingly critical to plan, design and manage the water resources system carefully and intelligently.

Transformation of rainfall to runoff is rather very significant for the estimation of available water resources and to explore new sources of water so that the precious and scant water resource can be managed properly. Water flowing down the streams is considered as the main source of fresh water. Estimation of this water flowing down the natural streams is not easy, that too when it is to be estimated on a continuous basis. In order to know the quantity of water flowing in the streams, indirect approaches are adopted by estimating the runoff by knowing the amount of rainfall in the catchment areas. The runoff process is simulated by inputting the rainfall and some other characteristics of the catchment in a suitable mathematical model, thereby transforming the rainfall into runoff. Rainfall runoff modeling thus forms an important component of many hydrological studies.

The hydrological processes within a catchment are dynamically and heterogeneously distributed. The hydrological appraisal of the watersheds is the basic requirement for the planning, design and management of water resources projects. The analysis of the factors affecting the formation of the basin flow is still one of the key areas of research in hydrology. The hydrologic behavior of a catchment is a very complicated phenomenon, which is controlled by an unknown large number of climatic and physiographic factors that vary both in time and space. The relationship between rainfall and runoff is known to be highly non-linear as in addition to the rainfall, the runoff is dependent on numerous factors such as initial soil moisture, land use, watershed geomorphology, evaporation, infiltration and distribution and the duration of rainfall. The interaction of vegetation and rainstorm dynamics may lead to very non-uniform inputs to the upper boundary of the soil. Further, the soil and bedrock heterogeneity may further complicate the flow paths. A catchment is a complex system where various physical, chemical and biological processes take place and govern the movement of water. In practice it is difficult to model all these processes and some simplifications have to be made either in the representation of the system or in the processes involved or both. The most common simplification made is spatial lumping and replacement of various components of the hydrological cycle by conceptual storage's. It amounts to saying that the catchment system and its inputs and responses can be represented using the dimensions of depth and time. The within catchment variations of inputs and parameters are ignored. As pointed out by Blackie and Eeles, (1985) due to this spatial averaging, the lumped model concept can be considered adequate only for small homogeneous catchments. However, in practice they have been applied to sufficiently big and heterogeneous catchments.

A hydrologic model is a simplified description of the hydrologic cycle. Hydrologic models are required for not only deciding water yields or design parameters, but also for understanding and evaluating the effects of developmental and other activities on the hydrological regime of the river basins. The use of modelling approach can also incorporate scenarios of proposed or likely land use changes in the river basin for use in planning and operation of water resources projects.

Broadly hydrologic models can be classified as deterministic and stochastic models. A deterministic model is one in which the processes are modeled based on some physical laws and no uncertainties in prediction are allowed. It has no component with stochastic behavior, i.e. the variables are free from random variation and have no distribution in probability. The physically based models are based on understanding of the physics of the hydrologic processes, which control the catchment response, and use physically based equations to describe these processes. These models require broad database for calibration and much computational time. Black box models are generally empirical and do not consider the nature of the hydrologic system. The conceptual model approach to rainfall runoff modeling lies intermediate between physically based models and black box models. The term conceptual is used to describe the models, which rely on a simple arrangement of a relatively small number of interlinked conceptual elements, each representing a segment of the land phase of the hydrologic cycle. The various components of the hydrologic cycle are conceptualized to consist of various storages. Each of this unequal sized storage usually has one input and one or more outputs and represents catchment storage like detention, soil moisture etc. The linear reservoirs and channels are used for routing. The modelling basically consists of a set of rules, which govern the moisture flow from one element to another. The model is therefore a logical procedure to regulate the inputs and withdrawals of water from these storages. The conceptual models generally ignore the spatially distributed, time-varying and stochastic properties of the rainfall-runoff process; they attempt to incorporate the realistic representations of the major non-linearities in the rainfall-runoff relationships.

The conceptual rainfall runoff models were initially developed for small homogeneous areas. However, they have been successfully applied to basins having wide variations in topography and vegetation and catchment area of the order of thousands of sq. km. The input data requirements for these models are quite modest and can be easily met with. Blackie & Ecles, (1985) provide excellent discussion on philosophy and applications of these models. Conceptual rainfall-runoff models are generally reported to be reliable in forecasting the important features of the hydrograph, but they require significant amounts of calibration data and some degree of expertise and experience with the model.

2.0 REVIEW OF LITERATURE

Sherman (1932) introduced the concept of unit hydrograph on the basis of superposition principle. Nash (1959) expressed the unit hydrograph in terms of parameters to be estimated from catchment characteristics or by means of statistical procedures. Problems related to the use of conceptual and physically based models have been pointed out by Klemes, (1988) and Beven, (1989). Conceptual models have been discussed at length by Ciriani et al., (1977) and Blackie and Eeles, (1985). Ibbit and O'Donnel, (1971) have given a comprehensive discussion on the various aspects of calibration of the conceptual models. The World Meteorological Organization, (1975) has conducted a study in which performance of ten rainfall-runoff models were compared. One of the major concerns in rainfall runoff modelling is the determination of the number of parameters of the model sufficient enough to simulate the stream flows similar to the observed flow which is discussed by Moore and Mein (1975), Weeks and Hebbert, (1980) and Loague and Hornberger, (1993). Chiew et al., (1993) compared six different modeling approaches for the simulation of stream flows. They conceded that simpler models might provide adequate estimates of monthly and annual yields. Mimikov et al., (1992) and Hughes (1995) have applied some models to different arid and semi-arid regions for prediction of stream flows.

In the Indian context, many studies have been undertaken on the aspect of rainfall runoff model, which suits Indian conditions. Mehrotra et al., (1996) studied the influence of model parameters in which six rainfall runoff models were analyzed with respect to the efficiency of the model and aridity of the catchment. Some simpler model structures operating in a monthly time step were applied on twelve catchments of Central India. Vijaya Kumar et al., (1999) attempted the daily rainfall runoff modelling for Gundalakamma river in Andhra Pradesh using a simple conceptual 5-parameter model based on the concept of probability distributed method as proposed by Moore (1985). Jain et. al., (1993) studied the aspects of model calibration of conceptual models and applied a Shuffled Complex Evolution Method (SCE-UA) algorithm for calibration of CRR model. Shetty et al., (1999) attempted rainfall runoff modeling of Western Ghat region of Karnataka, wherein regionalized parameters of a catchment water balance model for the estimation of water yield of ungauged catchment. Mehrotra et al., (1999) simulated flood hydrograph of Narmada basin up to Jamatra using an event based rainfall runoff model. Jain, (1997) applied the TOPMODEL, a GIS based rainfall runoff model for Hemvathy catchment in Western Ghats. Sudheer et al., (1999) applied the SWRRB model for estimating the hydrological parameters for water balance studies in Tambaraparni basin, Tamil Nadu. Ramji et al., (1997) applied the conceptual water balance model to the Tambaraparni basin in Tamil Nadu for the analysis of surface runoff and base flow. Ramji et. al., (1996) applied the conceptual catchment water balance model to the Sarada river basin of Andhra Pradesh. Shetty et al., analyzed the surface and ground water flow process in Western Ghats of Dakshina Kannada district, Karnataka by the water balance model. Mishra et al., applied a modified SCS-CN hydrologic model for the long term hydrologic simulation studies in Ramganga and Hemvathy catchment.

3.0 THE CATCHMENT

The Wainganga river originates from Mundara village in Seoni district at an elevation of 640 meters. After flowing for a short length it takes a turn towards the east and then south forming a big loop. It flows through Madhya Pradesh for a distance of about 273.58 km. with a drainage area of 15429 sq. km. It forms about 32 km common boundary between Madhya Pradesh and Maharashtra and then flows further down south for another 302.54 km. in Maharashtra to join river Wardha. The combined water of Wainganga and Wardha rivers called the Pranhita forms a common boundary between Maharashtra and Andhra Pradesh for a length of 112 km. before joining the Godavari at an elevation of 107.0 meters.

The main tributaries of Wainganga river within Madhya Pradesh include Bagh river from the left, Pench river, Kanhan from its right while Bijna river, Hirri river, Halon river, Bawanthadi river and Son river are some of its important tributaries. Wardha is its major tributary in Maharashtra. The major sub-basins of the Wainganga river basin are Kanhan sub-basin, Pench sub-basin, Thanwar sub-basin, Bawanthadi sub-basin, Chandan sub-basin, Bagh sub-basin. The catchment area of the Wainganga river on M.P. lies between latitude 21°15'00" to 22°45'00" and longitude 78°00'15" to 80°47'30" which covers Betul, Chindwara, Seoni and Balaghat districts. The Wainganga river forms the common district boundary between Balaghat and Seoni and common state boundary between Madhya Pradesh and Maharashtra state.

The rainfall in the Wainganga basin occurs mostly during the monsoon months of June to September. The average annual rainfall in the basin is 1073.40 mm. The rainfall pattern indicates increasing rainfall when proceeding from west to east. The rainfall varies from 900 mm to 1600mm. The temperature variation in the basin is not very large with the highest temperature of about 40°C at Seoni and lowest of 10°C at Chindwara. Few gauge discharge sites are also being maintained by the Water Resources Department at Bandol, Deoghat and Ugli on Wainganga river. Floods do not frequently affect the basin and only some marginal area along the Wainganga is subjected to submergence during floods.

The geological structure of the basin is just like the Deccan plateau, forms a single crust block, the rigidity of which is not weakened by any overloading of large and deep belt of deposits. The valley is all bounded by faults. The substructure of the basin is composed of generally horizontally reposing rock beds that stand on a firm and immovable foundation and have remained so for ages. Lateral thrusts and mountain building forces have had very little effect on folding or displacing its originally horizontal strata. The geological formations observed are generally metamorphic and crystalline complex, Gondwanas, Lametas, Deccan Trap and recent Laterite, alluvium and soils. In the Deccan Trap basalts, the groundwater occurs in joints, fractures faults and other such zones of weaknesses. An inter-trappean bed when of sufficient thickness plays a very distinct role in the local behavior of groundwater. Vesicular basalts due to their interconnection of vesicles are also of much significance to the groundwater. The quality of the groundwater in the basin is expected to be good for drinking and irrigation purposes.

Nearly 55% of the basin is under mixed deciduous forest, which comprises of teak, sal, bamboo, tendu leaves and mixed type trees. The percentage of the forest area of the districts lying in the Wainganga basin is Balaghat (55.08%), Mandla (47.46%), Betul (44.86%), Seoni (33.84%), and Chhindwara (41.15%). The soils vary from deep black to thin red or yellow soil. Six to seven feet deep black soil below which is murram. On the crystalline and Gondwana formations the sub-soil is usually sandy. On the hillsides and slopes, a thin red soil and thin yellow soil is formed by the decomposition of trap rock. The soils in the basin are generally fertile.

The cultivation is principally rainfed as the basin has very little irrigation facility. During the normal years there is generally one crop. The cropping pattern generally consists of paddy, jowar, maize, soyabean, groundnut and vegetables. The mineral wealth in and around the basin consists of large deposits of high grade iron-ore, lime stone, bauxite, dolomite, manganese ore, copper, clay, coal and other deposited minerals.

The present modeling study has been limited to Wainganga upto Bandol gauge-discharge site where concurrent data on rainfall and stream flow are available. The study area lies between latitude 21°54'00" to 22°15'50" and longitude 79°13'50" to 79°37'45". The catchment area up to Bandol GD site is 935 sq. km. The slope of the basin is from south to north and then to east as the river changes its direction. The average annual rainfall in the catchment is about 1200 mm. The study area lies within Seoni district of Madhya Pradesh, which is well connected by road (NH-7) and rail. The study area falls in the Survey of India toposheet no. 55- N/4, 7, 8, 12 and 55 O/5, 9. The elevation in the catchment varies between 650 m. to 600 m. above mean sea level. The map showing the Wainganga basin up to Bandol is presented as Fig. 1. The rainfall data at Seoni has been used for the study. Even though the discharge is being monitored at Bandol, but there is lot of gaps in it. Looking into the availability of concurrent data sets for rainfall and runoff, the study has been limited for seven years.

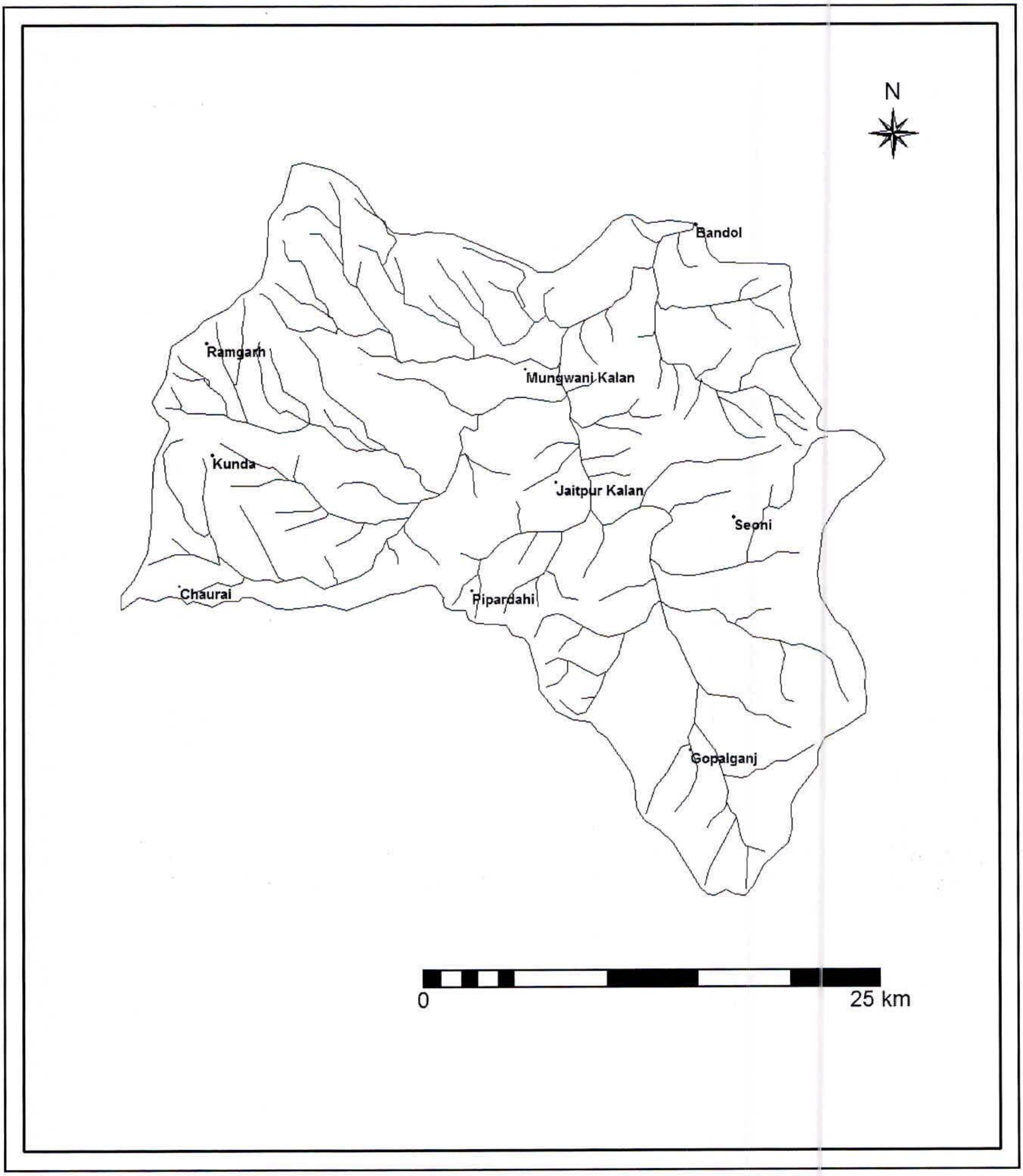


Fig. 1 : Wainganga river basin up to Bandol

4.0 DATA PROCESSING AND ANALYSIS

The use of a conceptual model requires a number of hydro-meteorological data as input parameters. In general, rainfall, runoff and evapotranspiration data are needed for model calibration. The normal evapotranspiration values as derived by India Meteorological Department for the respective districts/ zones are used. As practically all rainfall occurs during the monsoon season in most of the catchments, five monsoon months from June to October are considered in the analysis. The following available data of Wainganga basin upto Bandol gauging site have been used for the analysis.

(i) Monthly rainfall data at Seoni and Seoni observatory.

(ii) Monthly stream flow data of river Wainganga at Bandol.

(iii) Monthly mean of daily evapotranspiration values.

(iv) Topographic map, soil map and land use map of the basin.

All the data processing including the transfer of rainfall and discharge records to the computer files, checking for errors etc. were carried out prior to the model setup and simulation. Few reports pertaining to the study area were also referred to gather the relevant information on the basin properties. Processing and analysis of various types of data collected for carrying out the present study are mentioned below.

a) Topography

The toposheets obtained from the Survey of India in the scale 1:50,000 were used for digitizing the catchment boundary, rivers and contours. The catchment area of the basin up to Bandol gauge-discharge site is 935.0 sq. km. The time of concentration was also computed.

b) Rainfall data

The daily rainfall at Seoni in Seoni district was scrutinized and the missing rainfall values were estimated by distance power method. The monthly rainfall data for the monsoon months have been computed based on the daily rainfall data.

c) Runoff data

The runoff data of Wainganga basin upto Bandol have been scrutinized for errors and was converted into the format as required for the model application. Before using the processed rainfall runoff records in the model, it is necessary to check whether the rainfall and runoff data are consistent or not. Plots were made for comparing the rainfall and the corresponding runoff (after converting it into the same units as rainfall) for all the years. It was observed that the data behaved consistently.

For checking the consistency, runoff coefficients in different time periods also provide useful inferences about the portion of precipitation appeared at the outlet of the catchment during that period. The runoff coefficient is the ratio of runoff and rainfall within the specified period. In order to check the consistency of rainfall-runoff records, the monsoon runoff coefficients are computed for the four years. The monsoon rainfall, monsoon runoff and runoff coefficients are given in Table 1.

It is observed that the runoff coefficients are always less than one.

A graph between the monsoon season rainfall and runoff has been plotted and given in Fig.2 to study its pattern. The rainfall runoff data used in the study are consistent on seasonal and annual basis. So it can be used for the calibration and validation of model. The monthly mean evapotranspiration recorded at Seoni is used for the study and is given in Table 2.

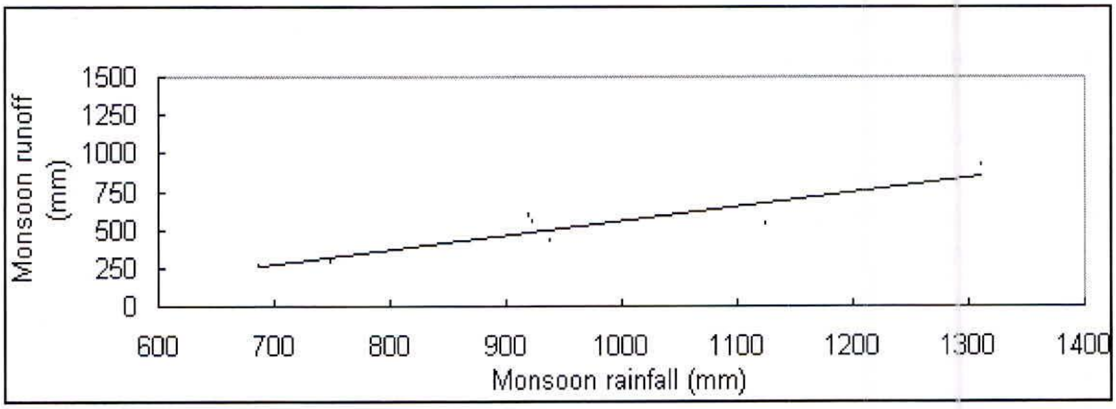


Fig. 2 : Relation between monsoon rainfall and runoff

5.0 MODEL DEVELOPMENT

For water resources management and planning and specifically for water budget studies of lakes and reservoirs, a continuous flow model is needed to simulate the inflow volumes. The output of the continuous flow models is usually on monthly, seasonal or annual time scale. The two factors which generally affect the selection of a time scale is a) the objective of the modelling effort and b) accessibility of the necessary model input information. Generally a monthly time scale is sufficient since the water resources management is generally on a monthly or longer times scales and as such the data requirement is also less on a monthly time scale.

The few available monthly rainfall runoff models can generally be applied to the regions for which they have been developed or are complex and have parameterized the hydrologic processes using numerous interdependent calibration coefficients. So the aim of the study is to develop a conceptual model which is of simple structure and which requires minimum input data and can simulate the flows reasonably well. As the region is completely rainfed, no snowmelt component is to be conceptualized.

A conceptual model generally includes the following elements namely, a) input parameters representing the behavior of the catchment, b) input of precipitation and other meteorological data, c) computation of outflows – both surface and sub-surface, c) calculation of water storages – both surface and sub-surface, d) catchment outflow. Two main processes are considered in these models namely, the climate phase and the land phase. The climate phase generally deals with the precipitation, temperature and evapotranspiration. The land phase deals with all processes and storages, which are encountered during the movement of water on land and below it.

A rainfall runoff model, which estimates the stream, flow as a sum of three components has been developed. The components are fast surface runoff, quick surface runoff and base flow. Storage in the system is divided into two layers: soil moisture storage and ground water storage. The model input consists of meteorological data on rainfall and evapotranspiration. The model consists of six parameters. S_{max} is the parameter, which relates to the moisture holding capacity of the soil storage. T_{hres} is the parameter which defines the threshold value of the rainfall such that rainfall greater than this value appears directly as fast surface runoff. The threshold value of rainfall T_{hres} above which the rainfall appears as fast surface runoff is the sum of soil moisture deficit in the soil moisture storage and a parameter $X_{a,}$ which is the head required for the fast surface runoff to begin. X_1 and X_2 are the discharge coefficients from the two outlets of the soil moisture storage which is responsible for the fast surface runoff and quick surface runoff respectively. X_3 is the parameter that decides about the actual evapotranspiration occurring from the soil storage. X_k is the parameter, which governs the base flow from the groundwater storage. A schematic flowchart of the proposed model is shown in Fig. 3. The governing equations are given below:

$$F_{SR} = X_1 * (P_{PN} - T_{hres}) \qquad \text{……… (1)}$$

$$Q_{SR} = X_2 * P_{PN} * \left\{1.0 - EXP\left(-\frac{S_{mav}}{S_{max}}\right)\right\} \qquad \text{……… (2)}$$

$$I_{NF} = P_{PN} - F_{SR} - Q_{SR} \qquad \text{……… (3)}$$

$$T_{hres} = S_{md} + X_a \qquad \text{……… (4)}$$

$$S_{md} = S_{max} - S_{init} \qquad \text{……… (5)}$$

$$A_{EV} = P_{ET} \;; if\ S_{mav} > P_{ET} \qquad \text{……… (6)}$$

$$A_{EV} = P_{ET} * X_3 * S_{mav} / S_{max} * S_{max} \qquad \text{……… (7)}$$

$$S_F = S_{mav} - A_{EV} \qquad \text{……… (8)}$$

$$D_{PL} = S_F - S_{max} \;; if\ S_F > S_{max} \qquad \text{……… (9)}$$

$$G_{WS} = G_{init} + D_{PL} / 2 \qquad \text{……… (10)}$$

$$B_{FL} = X_k * G_{WS} \qquad \text{……… (11)}$$

$$T_{RF} = F_{SR} + Q_{SR} + B_{FL} \qquad \text{……… (12)}$$

where,

T_{RF} = Total runoff

F_{SR} = Fast surface runoff

Q_{SR} = Quick surface runoff

P_{PN} = Precipitation

I_{NF} = Infiltration

S_{md} = Soil moisture deficit

S_{max} = Maximum water holding capacity of the SM storage a parameter

S_{init} = Initial soil moisture of SM storage

S_{mav} = Available soil moisture at any instant

S_F = Final soil moisture of SM storage

A_{EV} = Actual evapotranspiration

P_{ET} = Potential evapotranspiration

D_{PL} = Deep percolation

G_{WS} = Groundwater storage

G_{init} = Initial moisture in groundwater storage

B_{FL} = Base flow

S_{max}, X_a, X_1, X_2, X_3, X_k are the parameters of the model

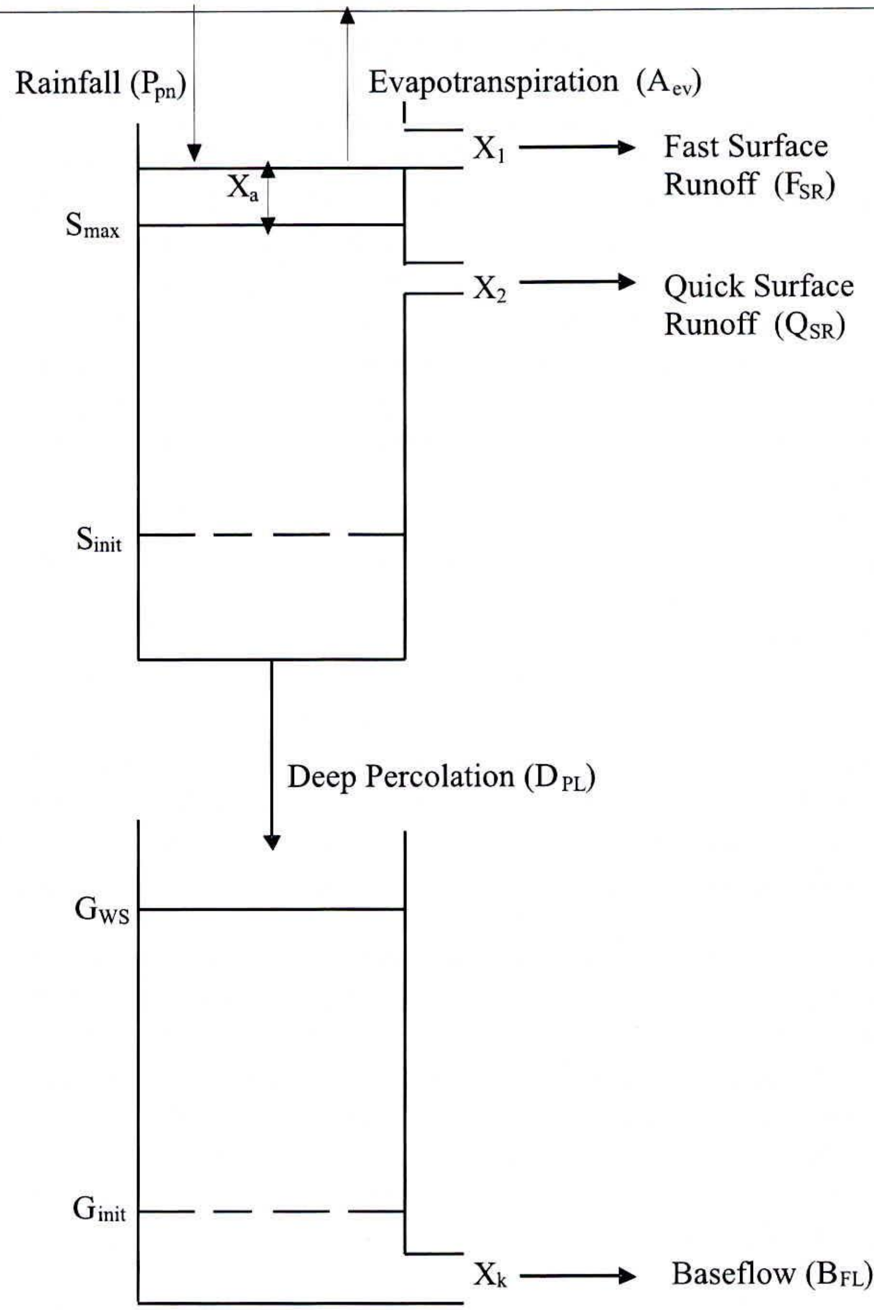


Fig. 3 : Proposed model structure for Wainganga basin

6.0 CALIBRATION AND TESTING OF THE MODEL

An important step in application of a conceptual model to a catchment is model calibration. The objective of a calibration is to determine the model parameters such that an acceptable match is obtained between the observed and the computed discharge hydrographs. Basically two approaches are followed for calibration of a conceptual model - manual using trial and error and automatic using an optimization algorithm. The parameters obtained from automatic calibration may be further fine tuned manually to achieve an improved match from the point of view of interest. According to Sorooshian and Gupta, (1983) the purpose of calibration may be: a) To obtain a unique and conceptually realistic parameter set which closely represents our understanding of the physical system, or b) to obtain a parameter set which gives the best possible fit between the model-simulated and the observed hydrograph. Four aspects of the conceptual rainfall runoff models which cause problems during automatic calibration were listed by Johnston and Pilgrim, (1976) as: a) interdependence between the model parameters, b) indifference of the objective function to the values of the inactive parameters, c) discontinuities of the response surface, and 4) presence of local optima.

Sorooshian and Gupta, (1983) identified three areas which hinder the accurate calibration of the CRR models : a) model structure representation, b) data and their associated measurement errors, and c) imperfect representation of the physical process by the model. The data, which are used in calibration, may not represent the entire range of hydrologic events that the catchment may experience and the consequent lack of activation of parameters leads to differing sensitivities of the response surface & poor convergence properties. This problem is accentuated since the optimum parameters are to be found in a high dimensional parameter space. The threshold parameters, cross-correlation between parameters and auto-correlation also cause difficulties, Beven and Binley, (1992). The degree of complexity of model plays a significant role in model calibration phase.

Sorooshian and Gupta, (1983) point out that use of more and more data is not necessarily the answer. What is required is the *right kind of data* and *adequate data* for model calibration.. The term right kind of data implies the data, which activate all the model parameters. Clearly, both the right kind and right duration of data are needed for a good calibration. Besides ensuring that the data are error free, the periods of extreme events should been suitably incorporated. Only those parameters that are independent should be included in the optimization algorithm. The initial values of the storages should be estimated based on some physical considerations of the basin. The soil storage may be taken as zero at the end of dry season. Also basins with steeper slopes would have smaller surface storages than basins with milder slopes.

The six model parameters include S_{max}, X_a, X_1, X_2, X_3, and X_k. Out of these six parameters, the main 4 parameters which affected the volume of the simulated hydrograph to a larger extent namely S_{max}, X_1, X_2 and X_k have been estimated using the automatic calibration approach. The calibration was performed for a period of five years namely, 1993, 1995, 1996, 1998 and 1999. The constrained Rosenbrook's optimization algorithm has been used for parameter estimation. Even though it is rather very difficult to find the global optimum values of the parameters, many runs with different initial values of parameters can increase the likelihood of finding parameters close to the global optimum. The objective function was to minimize the sum of squares of errors (SSE) between the observed and computed surface runoff, which is given by

$$SSE = F^2 = \sum_{1}^{n} (Q_{obs} - Q_{sim})^2 \qquad \text{......... (13)}$$

Many runs with different initial values of parameters were considered to find the parameter values for the minimum SSE. At each time the graphical comparison of the historical and simulated runoff was also performed. For initial values of soil and groundwater storage's were assigned as zero and increased systematically. The performance of the model is also checked on the basis of Nash-Sutcliffe goodness of fit test or efficiency and difference in volume between the observed and simulated runoff on a seasonal basis.. If the initial variance of the runoff is given by

$$F_0^2 = \sum^{n} \left(Q_{obs} - \overline{Q_{obs}}\right)^2 \qquad \text{......... (14)}$$

The efficiency of the model is given by

$$R^2 = \frac{F_0^2 - F^2}{F_0^2} \qquad \text{......... (15)}$$

The difference in volume between the observed and simulated runoff is given by

$$D_{vol} = \sum_{i=1}^{i=n} (Q_{obs} - Q_{sim}) \qquad \text{......... (16)}$$

Another measure of the quality of calibration is the correlation coefficient r between the monthly simulated and observed runoff data given by

$$r = \frac{\sum_{i=1}^{n} \left\{\left(Q_{obs_i} - \overline{Q_{obs}}\right)\left(Q_{sim_i} - \overline{Q_{sim}}\right)\right\}}{\sqrt{\sum_{i=1}^{n} \left(Q_{obs_i} - \overline{Q_{obs}}\right)^2 \left(\sum_{i=1}^{n} Q_{sim_i} - \overline{Q_{sim}}\right)^2}} \qquad \text{......... (17)}$$

A number of optimization runs were made with different initial values of the parameters. The response surface in the vicinity of optimum parameter values was then examined in detail by manually varying the parameter in small steps. The parameter values, which gave the least objective function, were assumed to be the true parameter values. The model was tested on the remaining data for the years 2001 and 2002 keeping the parameters values same as obtained from the calibration.

7.0 ANALYSIS AND DISCUSSION OF RESULTS

The rainfall-runoff response of the catchment has been studied using the two-component model, i.e. quick flow and slow flow response of the catchment. Due to limited data availability the parameters have been estimated on the basis of six years data. Out of the six parameters only four were estimated using the automatic optimization routine so as to limit the problems of multiple optima and interdependence between the parameters. The optimized parameters include S_{max}, X_1, X_2, and X_k. The parameters X_a and X_3 were optimized manually by trial and error. The optimum parameter values obtained during the calibration are given in Table 3.

The agreement between the observed and simulated runoff volumes on a monthly basis is given in Table 4.

The comparison of the observed and simulated runoff for the calibration period is shown in Fig. 4. It is observed that the model is able to simulate the flows with a fair degree of accuracy. The discharges are simulated properly and the contribution from the soil moisture storage and the groundwater are accounted for. The base flow contribution is more towards the end of the monsoon

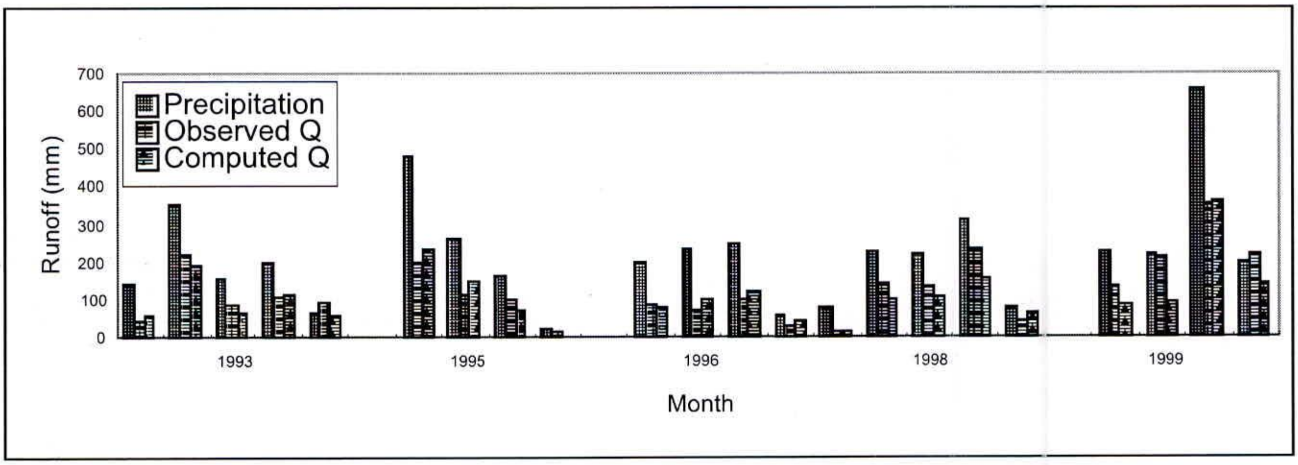


Fig. 4 : Comparison of the observed and simulated monthly runoff during calibration

season when the soil moisture storage as well as the groundwater storage is full which is generally the phenomenon observed in the basin. But for the year 1999, it is observed that there is significant difference between the observed and simulated discharges. This is due to the fact that the runoff for the month of August has been recorded as 214.60 mm which more or less equal to the observed precipitation. The rainfall and runoff for the particular month needs further investigation in this regard. The comparison of the observed and simulated seasonal runoff along with the model efficiency, difference in volume between observed and computed seasonal runoff and correlation coefficient is given in Table 5. It is observed that the model is able to simulate the seasonal flows with reasonable accuracy except during 1999. A comparison of the same is presented as Fig. 5.

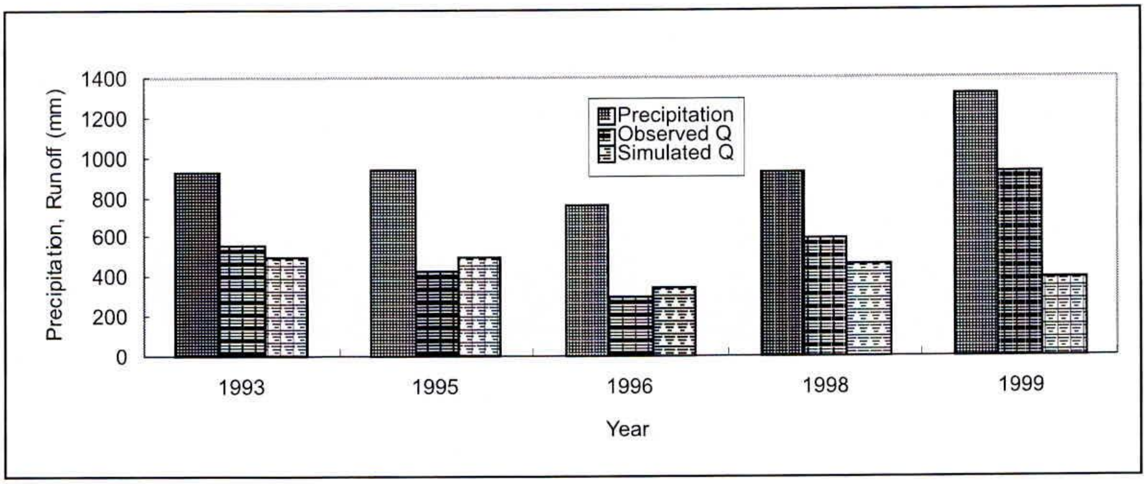


Fig. 5 : Comparison of the observed and simulated seasonal runoff during calibration

The model efficiency during calibration varies between 0.67 and 0.83 whereas the correlation coefficient varies between 0.92 to 0.96. The percentage seasonal difference in volume varies between –14.59 % and 25.65 %. Efforts can be made to improve the performance of the model by incorporating few more components of the land phase of the hydrologic cycle into it. This may make the model more complex and also the number of parameters may increase. But as the aim of this study was to develop a model with simple structure the study has been limited to this model only which able to simulate the seasonal flows quite well which can be used to exploit the available water resources in the river system.

The model was tested on the independent data of 2001 and 2002 and the comparison of the observed and simulated monthly and seasonal flows is given in Table 6. The comparison of the observed and simulated monthly flows during validation is presented in Fig. 6.

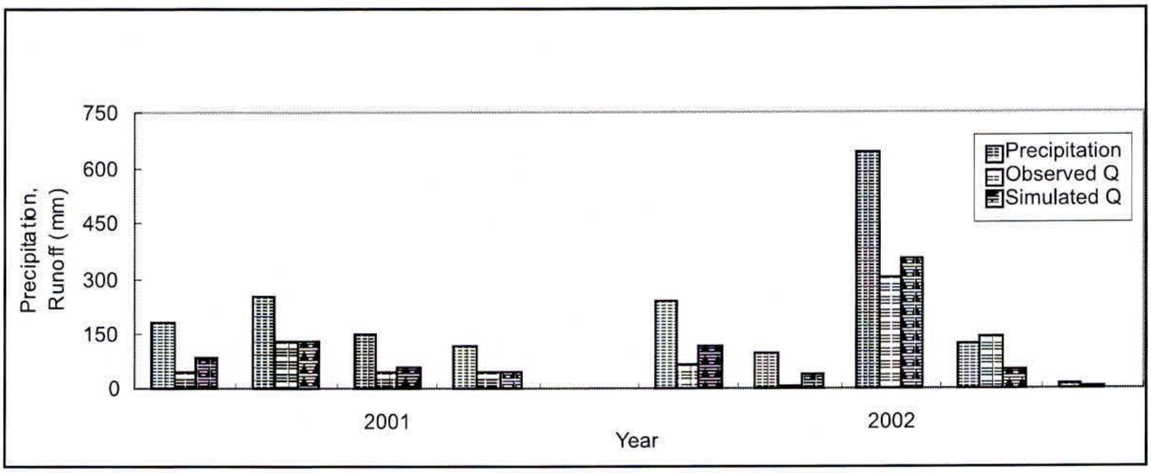
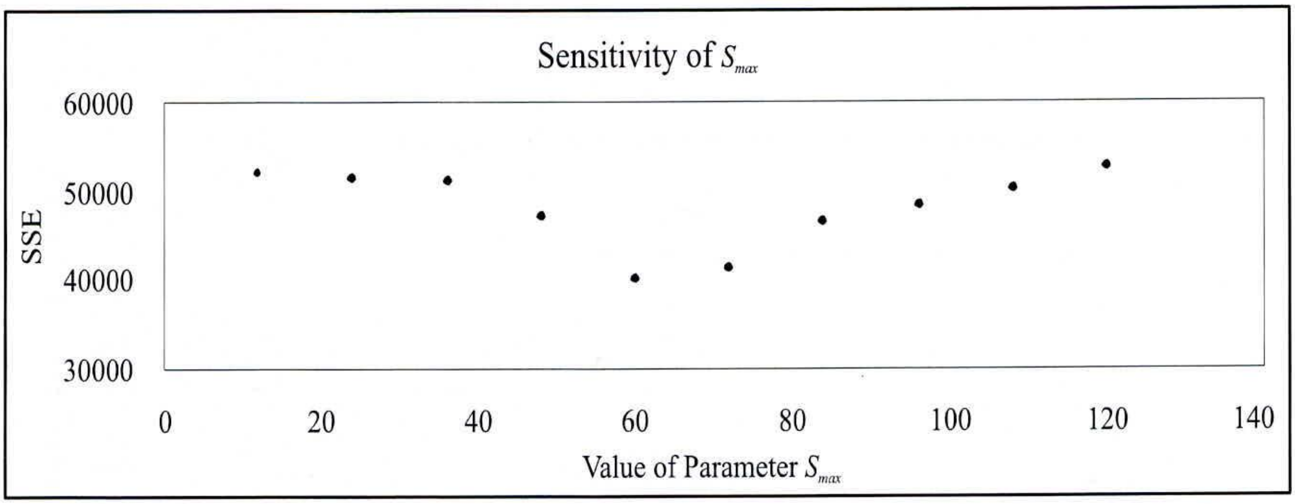


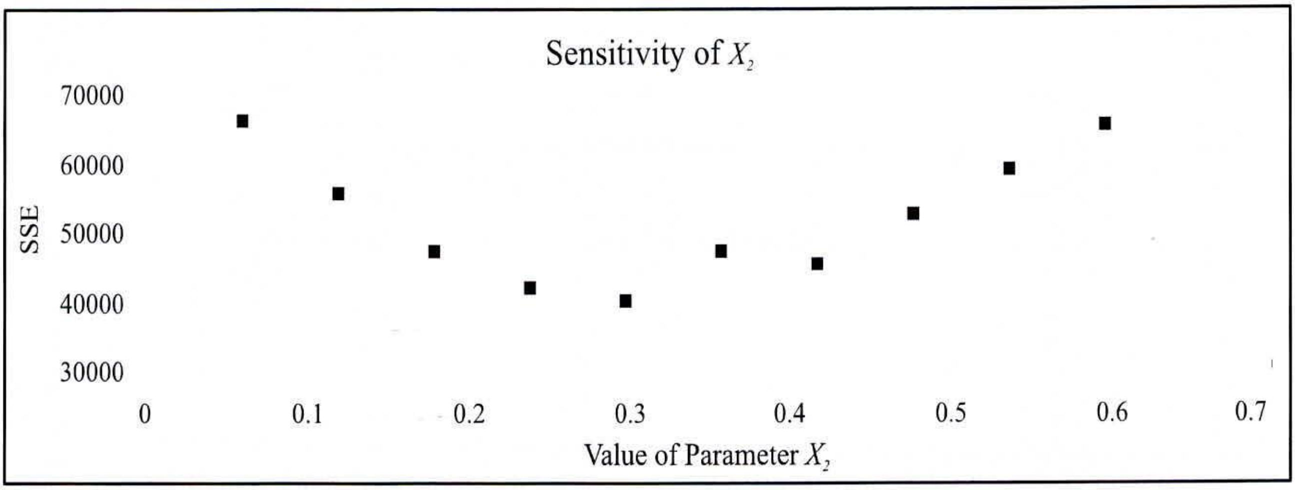
Fig. 6 : Comparison of the observed and simulated monthly runoff during validation

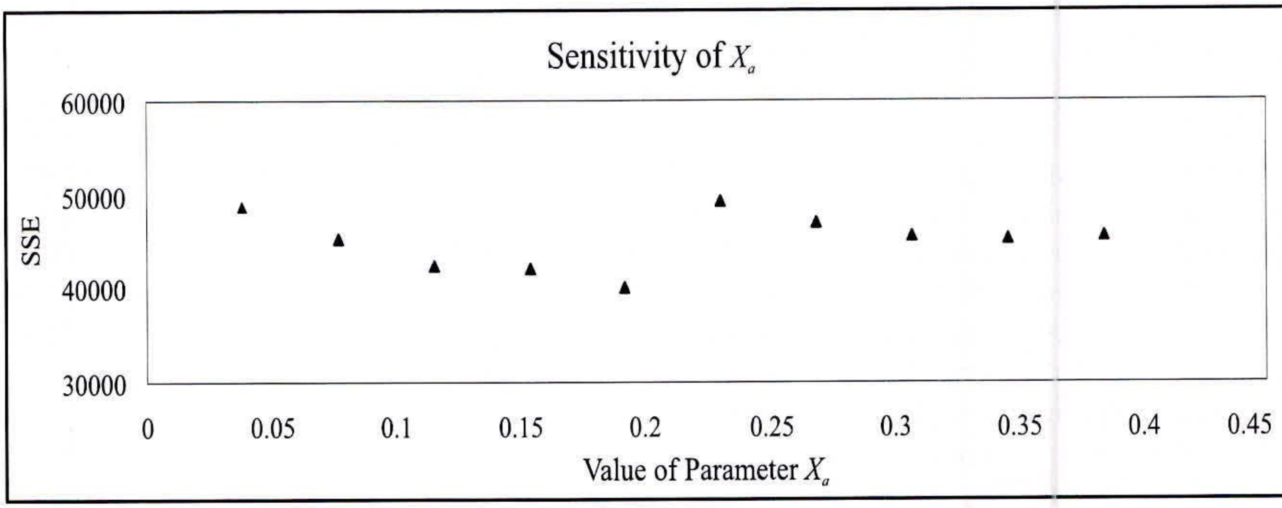
The model efficiency varies between 0.75 and 0.82 and the correlation coefficient between the observed and simulated flows varies between 0.90 and 0.95. The percentage difference in seasonal volume varies between –6.95% to –20.97%. The model is able to simulate the flows well with the evaluated set of parameters.

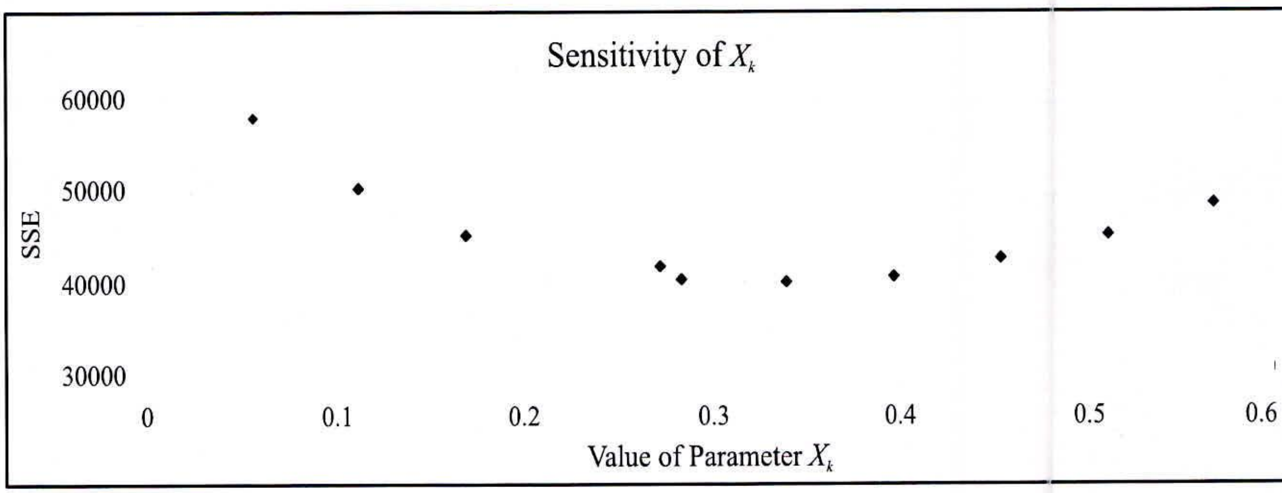
8.0 SENSITIVITY ANALYSIS

The sensitivity analysis has been performed to examine the sensitivity or responsiveness of the model with respect to important calibration parameters. The sensitivity analysis is aimed at identifying the parameters for which additional measurements are useful and the accuracy with which these measurements can be carried out. In each of the sensitivity runs, the response of the basin was simulated by changing just one parameter and keeping other parameters same as the calibrated parameter values. Each of the parameter was changed successively at a step of 20% from 0.20 to 2.00 times its optimized value, keeping the other parameters at their optimum values as obtained during the calibration and the resulting change in SSE and efficiency was computed. The parameter values were varied in steps of 20 % of the parameter value because the errors in the input data are assumed to be limited to be within this range. The plots depicting the sensitivity of the parameters S_{max}, X_2, X_a and X_k are presented in Fig. 7. S_{max} is the most important parameter influencing the runoff response from the catchment.






Sensitivity of X_a
60000
50000
40000
30000
SSE
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
Value of Parameter X_a


Sensitivity of X_k
60000
50000
40000
30000
SSE
0
0.1
0.2
0.3
0.4
0.5
0.6
Value of Parameter X_k

9.0 CONCLUSIONS

For water resources planning and management in Wainganga basin where few projects are being planned, an attempt has been made to develop a conceptual rainfall runoff model. The model with two component storages is sufficient to model the flows in the basin. The model is simple in structure with input data requirement of only rainfall and potential evapotranspiration. Dynamic response characteristics of the catchment can be explained by its quick or fast response and slow response. Fast response mainly depends on the volume of rainfall and catchment characteristics. Even though the model has six parameters, it well defines the response of the catchment in general. The runoff generation process on monthly scale is strongly dependent on volume of rainfall and soil moisture. The model efficiency during calibration period varies between 0.67 and 0.83 whereas the seasonal difference in volume varies between –14.59% and 25.65%. During validation period the model efficiency varies between 0.75 and 0.82, whereas the difference in volume varies between –6.95% and –20.97%. These results show that the choice of the model parameters is pertinent and the model is capable of simulating the stream flow in the semi-arid climatic zone with a fair degree of accuracy. It is felt that the model performance may improve significantly if the parameters are estimated from sufficiently longer length of data, which includes both the wet, and dry years. Further refinements can be made for the application of the model to hilly catchments where the response is rather very quick. Also studies are required to determine the size limit of the watersheds for which the runoff can be accurately modeled by applying the model to various watersheds of varying sizes.

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Table 1 : Relationship between monsoon rainfall and runoff

Year	Monsoon Rainfall (mm)	Monsoon Runoff (mm)	Runoff Coefficient
1992	923.60	556.71	0.60
1995	939.55	422.19	0.45
1996	750.80	295.46	0.39
1998	921.30	587.18	0.64
1999	1312.30	928.26	0.71
2001	687.80	265.96	0.39
2002	1126.15	532.65	0.47

Table 2: Monthly mean evapotranspiration at Seoni

S. N	Month	Evapotranspiration (mm)	S. No.	Month	Evapotranspiration (mm)
1.	Jan	80.00	7.	Jul	101.0
2.	Feb	100.0	8.	Aug	98.00
3.	Mar	145.0	9.	Sep	104.0
4.	Apr	170.0	10.	Oct	116.0
5.	May	196.0	11.	Nov	87.00
6.	Jun	152.0	12.	Dec	72.00

Table 3 : Final calibrated parameters of the proposed model

S. No.	Parameter name	Parameter value
1.	S_{max}	60.25 mm
2.	X_a	2.00 mm
3.	X_1	0.192
4.	X_2	0.298
5.	X_3	0.050
6.	X_k	0.284

Table 4 : Comparison of the observed and simulated monthly runoff during calibration

Year	Month	Precipitation (mm)	Observed Runoff (mm)	Computed Runoff (mm)	Surface Runoff (mm)	Baseflow (mm)
1993	June	142.25	45.24	61.57	49.58	11.99
	July	356.20	221.66	191.10	153.69	37.42
	August	162.00	89.10	68.24	68.24	0.00
	September	196.80	106.19	111.40	83.05	28.36
	October	65.90	94.52	57.48	25.85	31.63
1995	June	0.00	0.00	0.00	0.00	0.00
	July	484.20	195.60	235.69	201.07	34.61
	August	262.25	111.94	152.04	112.58	39.46
	September	167.45	99.68	70.66	70.66	0.00
	October	25.65	14.97	39.14	7.94	31.20
1996	June	0.00	0.00	0.00	0.00	0.00
	July	201.85	91.44	76.12	76.12	0.00
	August	238.95	71.38	99.36	96.95	2.41
	September	252.50	103.26	121.44	108.29	13.14
	October	57.50	29.38	41.64	22.27	19.37
1998	June	81.75	19.38	20.83	19.61	1.22
	July	225.15	145.57	104.32	96.24	8.08
	August	224.20	136.49	110.23	95.82	14.41
	September	308.50	237.37	163.53	132.86	30.67
	October	81.70	48.37	68.51	32.68	35.83
1999	June	0.00	0.00	0.00	0.00	0.00
	July	226.80	136.29	87.50	87.50	0.00
	August	223.50	214.60	95.41	92.18	3.23
	September	660.00	357.07	364.62	285.48	79.14
	October	202.00	220.30	142.67	86.00	56.67

Table 5 : Comparison of the observed and simulated seasonal runoff during calibration

Year	Precipitation (mm)	Observed Runoff (mm)	Simulated Runoff (mm)	Efficiency	Difference in Vol. (%)	Correlation Coefficient
1993	923.65	556.71	489.79	0.83	12.02	0.94
1995	939.55	422.19	497.54	0.82	-17.85	0.96
1996	750.80	295.46	338.56	0.80	-14.59	0.94
1998	921.30	587.18	467.43	0.72	20.39	0.93
1999	1312.30	928.26	390.19	0.67	25.65	0.92

Table 6: Comparison of the observed and simulated runoff during validation

Year	**Month**	**Precipitation (mm)**	**Observed Runoff (mm)**	**Computed Runoff (mm)**	**Surface Runoff (mm)**	**Baseflow (mm)**
2001	June	181.60	49.68	85.85	67.8	18.05
	July	248.60	129.98	131.16	106.88	24.58
	August	146.00	44.74	61.13	61.13	0.00
	September	111.60	41.56	43.58	43.58	0.00
	October	0.00	0.00	0.0	0.00	0.00
	Seasonal	*687.8*	*265.96*	*321.72*	*279.39*	*42.63*
2002	June	240.60	65.79	118.38	93.81	24.57
	July	99.60	8.67	40.55	40.55	0.00
	August	642.60	302.0	355.29	272.24	83.05
	September	127.60	143.7	52.95	52.95	0.00
	October	15.75	12.49	2.53	2.53	0.00
	Seasonal	*1126.15*	*532.65*	*569.70*	*462.08*	*269.70*