FLOW SIMULATION OF AN UNGAUGED CATCHMENT USING DIFFERENT REGIONALIZATION PROCEDURES

DISSERTATION

Submitted in partial fulfillment of the requirement

for the award of degree

of

MASTER OF TECHNOLOGY

in

WATER RESOURCES DEVELOPMENT

by

MOHIT BHATIA

(Enrollment No. 17548014)

DEPARTMENT OF WATER RESOURCES DEVELOPMENT AND MANAGEMENT

INDIAN INSTITUTE OF TECHNOLOGY

ROORKEE- 247667 (INDIA)

MAY 2019

INDIAN INSTITUTE OF TECHNOLOGY, ROORKEE

CANDIDATE'S DECLARATION

I hereby declare that the work which is being presented in this end-term evaluation report entitled, **"Flow Simulation of an Ungauged Catchment Using Different Regionalisation Procedures"** in partial fulfilment of the requirement for the award of the degree of Master of Technology in **Water Resources Development**, submitted to the Department of Water Resources Development and Management, Indian Institute of Technology Roorkee, is an authentic record of my work carried out during the period of July 2018 to May 2019 under the supervision and guidance of **Dr. Deepak Khare, Professor,** Department of Water Resources Development and Management, IIT Roorkee and **Dr. Manohar Arora, Scientist D,** National Institute of Hydrology Roorkee, Roorkee.

The matter presented in this report has not been submitted by me for the award of any other degree.

……………………………

Date: 30.05.2019

Roorkee, Uttarakhand, India

Mohit Bhatia

Enrolment No: 17548014

CERTIFICATE

This is to certify that the above declaration made by a candidate is correct to the best of my knowledge.

……………………...

Dr. Manohar Arora
Scientists D,
NIH

……………………...

Prof. Deepak Khare
WRD & M,
IIT Roorkee

ACKNOWLEDGMENT

It is my great pleasure in expressing my heartfelt gratitude to my supervisors **Dr. Deepak Khare, Professor**, Department of Water Resources Development and Management, Indian Institute of Technology Roorkee and **Dr. Manohar Arora, Scientist D, National Institute of Hydrology Roorkee,** Roorkee for their valuable guidance, direction and infilling support towards completion of this report. I am highly obliged to them for their keen interest, able guidance and encouragement throughout the writing. Working under their guidance is a privilege, great opportunity and an excellent learning experience that I will flourish in my lifetime.

I am extremely thankful to other professors, staffs, and classmates from the Department of Water Resources Development and Management, IIT Roorkee and the National Institute of Hydrology Roorkee, Roorkee for their kind support, advice, encouragement, and cooperation.

…………………
(Mohit Bhatia)
Enrolment no. 17548014

ABSTRACT

The objective of this study to examine the effect of catchment characteristics that is catchment area(Ca), altitude(A) and (Ca/A^2) on streamflow characteristics for various sub-basins of upper Narmada river basin having catchment area ranging from1508 km^2 to 44548 km^2 located in Madhya Pradesh.10 daily flow data of 10 gauging sites varying from 10 to 30 years are utilized. To develop a regional relationship to estimate water availability 10 daily flow of eight gauging catchments are utilized and these relationships are validated using the remaining two test catchments. the physiographic and hydrologic characteristics of the region are derived from using ArcGIS tool and available literature. a simple linear regression model is used to predict regional equation of mean flow by correlating it with catchment characteristics. Three regionalization approaches based on regression are used to develop a regional relationship for the upper Narmada river basin. the first method is regionalization of parameters for individual gauged sites of selected probability distributions.second approach is regionalization of dependable flows and the third method is regionalization of parameters for the whole region of selected probability distribution these three methods are compared on the basis of percentage absolute error of dependable flows (PAEDF). It is observed that dependable flows increases with increase in the catchment area(Ca) and decreases with increase in altitude(A).

Table of Contents

LIST OF FIGURES

LIST OF TABLES

Chapter 1

INTRODUCTION

1.1 General

Estimation of water availability of a basin and its space and time distribution is necessary for planning, development, and operation of water resources development projects. Many factors like basin characteristics, land use land cover pattern, climatic conditions, surface vegetation, topography, drainage pattern, time and space distribution of rainfall, etc. affects the water availability of a basin. Water resources development on a basin depends upon the availability of hydrological data which is better available for gauged catchments.

The continuous increase in population and industrialization increases the requirement for proper planning and development of water resources which requires proper understanding of hydrological behavior of river basins. To understand the untapped potential of river basins requires information about hydrological data which requires new methodologies and approaches mostly in the case when catchments are poorly gauged and ungauged. Generally, most of the catchments are remained ungauged or poorly gauged not having required hydrological data because of inaccessible and rugged terrains, limited research works, etc. Streamflow estimation in an ungauged is one of the challenging tasks in surface water hydrology and water resources potential of the ungauged catchments are untouched due to inadequate hydrological data which creates problems for designers, planners and managers (Goswami et al. 2007).

1.1.1 River basins data availability gauged and ungauged catchments

Gauging of all sites on all available natural flow streams is not possible so it requires transferring of information available from one (gauged) to other (ungauged) sites because of similarity of streamflow characteristics among streams over fairly large regions which needs proper methodology. many methodologies have proposed but a method which relates stream flow parameters to climatic and topographic characteristics of river basins using regression principle shows promising results (Thomas and Benson 1975).

1.2 Background of the study

1.2.1 Flow duration curves and its application

Flow duration curve is a fundamental way to plot discharge against a percent of the time it can be equaled or exceeded. It provides fundamental information regarding dependable flows which provides a basis for the design of any hydropower project.

This curve is a cumulative distribution of daily stream flows at a site, firstly it is used by Clemens Hershel in about 1980. Flow duration curve is used in hydrologic studies for planning and design of hydropower, irrigation and water supply projects. With the growing demand for management of available water resources and planning, dependable design and development of new water resource projects, estimation of high dependable lows are required which needs the development of flow duration curves. Flow duration curves require an adequate amount of data to develop. Flow duration curve is also used for the study of reservoir sedimentation, management of water quality, estimation of low flows, calibration of the rainfall-runoff model. regional flow duration is mostly used to estimate dependable flows at poorly gauged and ungauged catchments (Manohar Arora, N.K. Goel, 2004) (Neil, M Vogel Richard, & Members, 1990).

There are various approaches to determine water availability of gauged catchments using empirical methods or continuous time series simulation approaches using water balance equation but these approaches required adequate availability of data which is absent for ungauged catchments.

One of the ways to estimate water availability potential of the ungauged catchment is to derive relationship of hydrological parameters of nearby gauged catchments in a region with their catchments characteristics using different regionalization techniques and then to generate the streamflow characteristics for ungauged catchments based on Regional relationships developed It provides a mechanism to obtain streamflow characteristics at ungauged catchments in a region by relating hydrological behavior of gauged catchments with physiographic characteristics of the region (Arora et al. 2004).

Regionalization based on regression is used to develop a regional regression equation by relating parameters of flow duration with basin characteristics of gauged catchments and these regional regressions are used to estimate stream flows at ungauged sites (Neil et al. 1990).

Regionalization is used as a standard hydrologic tool for many years, extrapolation from sites at which records have been collected to others at which data are required but unavailable (Riggs 1973). Considerable Effort has been invested in representative and experimental basins to predict hydrologic variables and parameters of complex distributed models in terms of catchment characteristics (Aston and Dunin 1979). However Continuous streamflow regionalization in ungauged catchments is contemplated as a challenging task. In a developing country like India where the subject of prediction in ungauged basins (PUB) is not prevalent (Swain and Patra 2017).

regionalization and multi-modal approach involving a rainfall-runoff model is developed to simulate streamflow in an ungauged catchment and different indexes are used to asses regionalization-model combination (Goswami et al. 2007).

1.2.2 Comparison of existing Regionalization approaches

Concept of regionalization can be applied to all methods which are aiming to estimate model parameters values of any gauged catchments in a definable region having a consistent hydrological response.

First kind of approach is Regionalization based on regression (Magette et al., 1976; Young, 2006) which develops a reasonable relationship between model parameters and catchment descriptors (physical and climatic) which are calibrated on gauged catchment sites then these established relations are used to determine the parameters of an ungauged catchment by sing its catchment descriptors. two hypotheses taken under this approach one is it considers there is well behave relationship exists between observed catchment characteristics and second is observed catchment characteristics used for regression provide relevant information about the behavior of ungauged catchment (Oudin et al. 2008).

The second regionalization approach is based on spatial proximity which is among the earliest approach to deal with ungauged catchments (Vandewiele et al. 1991). Geographic neighbors in a region are selected based on similar physical and climatic characteristics and parameters are calibrated for these neighbors. It uses these parameters for the whole region considering all neighbors behave similarly.

The third regionalization approach is considered to be the combination of regression-based and spatial proximity approach .it is based on the similarity between ungauged and gauged catchments and it transfers information between catchments in terms of catchment descriptors having similar catchment characteristics. Catchment descriptors are the same as the regression-based approach. this type of approach is known as physical similarity approach (Oudin et al. 2008).

1.3 Objective of the study

The main objective of this study to test the applicability of linear regression method for generalization of stream flow parameters over the complete range of upper Narmada basin and to understand the of accuracy in estimation of streamflow parameters at any ungauged site from the available long term flow records of nearby gauged sites.

Another objective to estimate topographic characteristics of the river basin to understand site to site variations in streamflow and also helps to know streamflow characteristics which help in the location of gauging stations (Thomas and Benson 1975). Streamflow and basin characteristics relation is studied in the upper Narmada basin using eight gauged catchments and two assumed ungauged catchments using linear regression approach.

Specific objectives for the current study include:

- To estimate different dependable flow values of a selected ungauged catchment using different regionalization procedures.
- To calibrate and validate the flow values of the specific duration of a selected ungauged catchment.
- To develop regional flow duration curves (FDC) for an ungauged catchment.
- To compare the results of these three regionalization procedures and choose best-fit regionalization procedure for the selected ungauged catchment.

1.4 Organization of dissertation

This thesis comprises of six chapters as organized below:

Chapter 1: Introduction

This chapters deals with the general background of the study, different approaches to deal with gauged and ungauged catchments as introductory knowledge, research gap and general and specific objectives of the study.

Chapter 2: a Literature review

This chapter deals with literature related to existing models and approaches to deal with ungauged catchments. Different regionalization approaches and their application to simulate flow data in an ungauged catchment. application of flow duration curve and development of regional flow duration curve.

Chapter 3: Study area and data collection

This chapter depicts the study area in terms of its location, physiographic characteristics, climate rainfall variability, etc. it also deals with various data used their type and source.

Chapter 4: Methodology

This chapter tells about different regionalization approaches based on regression is used to simulate flow in an ungauged catchment and comparison approach used for them to evaluate each method.

Chapter 5: Results and discussion

This chapter deals with different results obtained using these regionalization approaches and comparison of their results, followed by a discussion of their results.

Chapter6: Conclusion

This chapter shows the general conclusion from the research and some findings and also tells about the scope of future research.

Chapter 2

LITERATURE REVIEW

2.1 General

Singh et al. (2013) applied SWAT hydrological model in Tungabhadra Catchment, India for stream flow determination. The model gave excellent results for monthly calibration time steps and good results for daily calibration time step between the observed and simulated data.

2.2 Application of all existing regionalization approaches and statistical model

Singh et al. (2001) showed ungauged watershed is located in total 9 regions throughout India categorized from (A-I).formulation of models is done on the basis of data transfer between gauged watersheds of the same region. Using statistical normalization empirical relations is developed for each region. Performance of model developed for Himachal Pradesh which is categorized under region C is evaluated using 13 watersheds for calibration and 4 watersheds for validation purpose. statistical calibration approach to estimate quantiles which are non-dimensionally found to be satisfactory in both the calibration and validation process. these models can be used to estimate dependable flows of the desired level for ungauged watersheds of each identified regions. the simple power relation developed by relating mean flow with watershed area performs well in calibration but less satisfactorily in validation purpose because of a short length of data.

A. Bardossy (2007) used regionalization methods for transferring hydrological model parameters from the gauged catchment to ungauged catchment. One can accept that watershed with alike characteristics display alike hydrological behavior and therefore, can be modeled using alike model parameters. Parameter sets could be considered as movable if the equivalent model performance (NSE) on the donor and study area catchments are good. Finally, the results indicate that the parameters transferred based on the above principles accomplish well on the target watersheds.

(Blöschl and Sivapalan, 1995; Oudin et al., 2010) defined the regionalization as a way to transfer optimized model parameters (mean flow, standard deviation) from their respective gauged catchments to an ungauged catchment. This can be used to evaluate various hydrological process occurring within ungauged catchments.

Arora et al. (2004) mentioned that the Chenab river basin is considered as a study area to evaluate the effect of altitude of flow parameters. three different regionalization approaches are used, first is regionalization of parameters of individual gauged sites of a selected probability distribution. The second approach is regionalization of dependable flows and the third approach is regionalization of parameters for the whole region of a selected probability distribution. The total region is divided into 11 sub-basins out of which 9 is used for calibration and 2 based on highest and lowest altitude is used for validation purpose. It is found that the third approach of regionalization that is regionalization of parameters for the whole region of selected probability distribution was performed better than the other two approaches, but the third approach proves to be unsatisfactory for ungauged catchments having physiographic characteristics in extrapolation range.it can be concluded that dependable flows of region increases with catchment area and decreases with altitude.

Goswami et al. (2006) used a regionalization and multi-modal approach involving a suite of rainfall-runoff models and combination techniques. Daily observed hydrometeorological data for 12 French catchments are used. The Nash-Sutcliffe efficiency index (R2) is used for assessing and ranking the relative performances of the regionalization–model couples to identify the most appropriate couple for the region. The best regionalization-model couple is applied to a truly ungauged (13th) catchment in the region. Concluding that the pooling method of regionalization coupled with the conceptual soil moisture accounting and routing (SMAR) model is produced better results for simulating flow in an ungauged catchment in the region. The ultimate step of actually predicting the discharge in an ungauged (e.g. 13th) catchment within the region using the finally selected regionalization–model couple, is not
undertaken in this study.

Oudin et al. (2007) the study is carried out in France by taking 913 French catchments. In this, they compare different regionalization approaches to catchment model parameters. different approaches of regionalization compared are, regionalization based on regression, spatial proximity, and physical similarity. lumped rainfall-runoff model is applied over a large set of daily runoff data of 913 catchments to generalize conclusions. spatial proximity approach seems to perform better than the other two specified approaches. regression is least satisfactory whereas physical similarity approach is the median one. It seems that full model calibration provides far better results than these three approaches. spatial proximity combined with physical similarity approach seems to be an improvement over using any individual method.

Another regionalization procedure which uses catchment Characteristics to discover the similitude among gauged catchment(donor) and ungauged catchments(acceptor) is known as a physical similarity approach. The upside of physical comparability approach over regression method is that it doesn't take the presumption of linearity (Samuel et al. 2011).

Thirty-two catchments were determined so as to dissect nonstop streamflow estimation. Spatial closeness (Inverse Distance Weighted, Kriging, and worldwide mean), regression and physical similitude were the regionalization methodologies executed related to SWAT (Soil and Water Assessment Tool) for streamflow estimation in every catchment treated as ungauged thus. Kriging and IDW were the two strategies that created prevalent outcomes than other connected procedures as far as Nash-Sutcliff Efficiency (NSE), RMSE-perceptions standard deviation proportion (RSR) Percentage inclination (PBIAS) and Peak percent edge insights (PPTS). Physical similitude and relapse approaches, which depended on catchment qualities displayed preferable outcomes over worldwide mean methodology. (Swain and Patra 2017)

Exchange of streamlined model parameter set from at least one measured catchments to an ungauged catchment is an approach to evaluate different hydrological procedures happening inside the ungauged catchments. This procedure is called regionalization (Blöschl and Sivapalan 1995)

The qualities of the ungauged catchments which bear comparability with the checked catchments should be found and the succeeding advance is to average the model parameter estimation of the measured catchment to get the estimation of ungauged catchments. The means followed in this technique were like (Oudin et al. 2008).

2.3 Application of regression-based regionalization approaches

- Merz and Bloschl (2004) estimated the daily flow in ungauged catchments of Austria region. 308 catchments are taken ranging from 3 to 5000 km^2. Multiple regression is an estimate of the all model parameters couple with HBV hydrologic model. Uncertainty analysis is done using NSE which ranges from 0.63 to 0.67.
- Used lumped rainfall-runoff model HBV-96 to estimate discharge at ungauged catchments of Edessa sub-basin. he applied four regionalization methods to transfer model parameters values from gauged to ungauged catchments. model parameters are related to the physical characteristics of gauged catchments to develop the equation. These equations can be used to evaluate the flow parameters of ungauged catchments using their physiographic characteristics (Tamalew and Kemal 2016)

- Develop a regional hydrologic model to estimate the flow duration curve at gauged and ungauged catchments of Massachusetts regions using 23 sub-basins. Regionalization based on regression is used to relate lognormal parameters of gauged catchments to their basin characteristics. only basin relief and the watershed area are used to develop relations and to develop regional flow duration model. resulting regional flow duration curve seems to be satisfactorily at ungauged sites, considering the simplicity of the model (Fennessey et al. 1990).
- Dhar et al. (2000) studied on the regions of the Himalayas for high altitude and revealed that near the foot of the hills and at plain regions, precipitation is high. They showed that precipitation is starting increasing with its altitude but at some elevation, precipitation starts decreasing with altitude. Thus the altitude or elevation characteristics play an important role in the calculation of the flow data in the regional analysis.
- Regression One of the traditional methodologies of regionalization is to Calibration the hydrological model with various available gauged catchments and then relate each model parameter to the catchment characteristics using a regression approach (Wagener and Wheater 2006). In the present investigation relationship between catchment characteristics of all the ten catchment and calibrated model parameters is determined using a linear regression approach. Regression coefficients are estimated using ordinary least square method (Merz and Blöschl, 2004; Parajka et al. 2005; Samuel et al., 2011).

  The concept behind this technique is to perceive comparable catchments as per their characteristics where one might be the recipient (ungauged) catchment and different catchments are the contributors (measured) (Parajka et al., 2005; Oudin et al., 2008; Samuel et al., 2011; Razavi and Coulibaly, 2012). The subsequent stage is to transpose the parameters of the donor catchment upon the collector catchment. The characteristics of the ungauged catchments which bear comparability with the checked catchments should be found and the succeeding advance is to average the model parameter estimation of the measured catchment to get the estimation of ungauged catchments.

- ## 2.4 Gap identified

  The literature review shows that there are a number of researches and publication on hydrological modeling in watershed gauged the area in a different region of the world. but there are very limited works is found in the urban watershed or ungauged area. The requirement for strategies to manage ungauged catchments with the developing demand to harness the undiscovered capability of waterway water assets in numerous parts of the world, the need to devise new methodologies and techniques for appraisal of water assets from these sources is additionally expanding.

Chapter 3

STUDY AREA AND DATA COLLECTION

3.1 General

The Narmada is the longest west flowing river, lies in central India flows in a rift valley between Satpura and vindhyachal ranges. The Narmada is the longest river that flows entirely within India after the Godavari and Krishna.it is Called as the lifeline of Madhya Pradesh. The Narmada river originates from Amarkantak plateau of Maikal range in the shahdol district of Madhya Pradesh.

Narmada basin covers 92,672 km2 as its catchment area and it lies between longitudes 72° 38 'to 81°43'and longitude 21° 27' to 23° 37' which covert nearly 3% of the absolute geological region of the nation. The Narmada Basin covers enormous regions in Madhya Pradesh, Gujarat and a nearly smaller region in Maharashtra and Chhattisgarh. The waterway voyages a separation of 1,312 km before it falls into Gulf of Cambay in the Arabian Sea close to Bharuch in Gujarat. The initial 1,079 km of its run is in Madhya Pradesh. In the following length of 35 km, the waterway frames the limit between the States of Madhya Pradesh and Maharashtra. Once more, in the following length of 39 km, it frames the limit among Maharashtra and Gujarat. The last length of 159 km lies in Gujarat and a most extreme width of 234 km from north to south. The normal yearly water capability of the Narmada basin is 45.64 BCM. The Utilizable Surface Water in the basin records to 34.50 BCM.

The River has 41 tributaries. Out of these, 22 are on the left bank and 19 on the right. The significant tributaries/sub-bowls of the Narmada are Barna River, Ganjal River, Chhota Tawa River, Hiran River, and Jamtara River, Kolar River, Orsang River, Sher River, and Tawa River.

The basin is demarcated into 3 sub-basins. The Upper Narmada sub-basin, central and lower sub-basin with an aggregate of 150 watersheds. There is an aggregate of 21 hydrological precipitation stations is accessible. 19 significant tributaries alongside the primary stream the Narmada, channels a region of 92,672.42 Sq.km which is 3% of the all-outa topographical zone of the nation. The shape of the basin is elongated

3.2 Upper Narmada basin

3.2.1 Location

Upper Narmada basin is taken under study to develop regionalization procedure for flow simulation in the basin. The upper Narmada Basin is located Southern part of Madhya Pradesh with the extent of 22.48 km^2 (Fig. 3.1)

The elevation range of the upper Narmada basin varies from 100-1317m. The mean elevation of the basin is 650 m above mean sea level (MSL). The catchment area of upper Narmada basin up to hoshangabad, the lowermost gauging station in the basin, is 44548 km2. There is a total of 21 hydrological observations stations is available ranging from Dindori to Hoshangabad. The area representing the location of gauging sites is shown in Fig. 3.2.

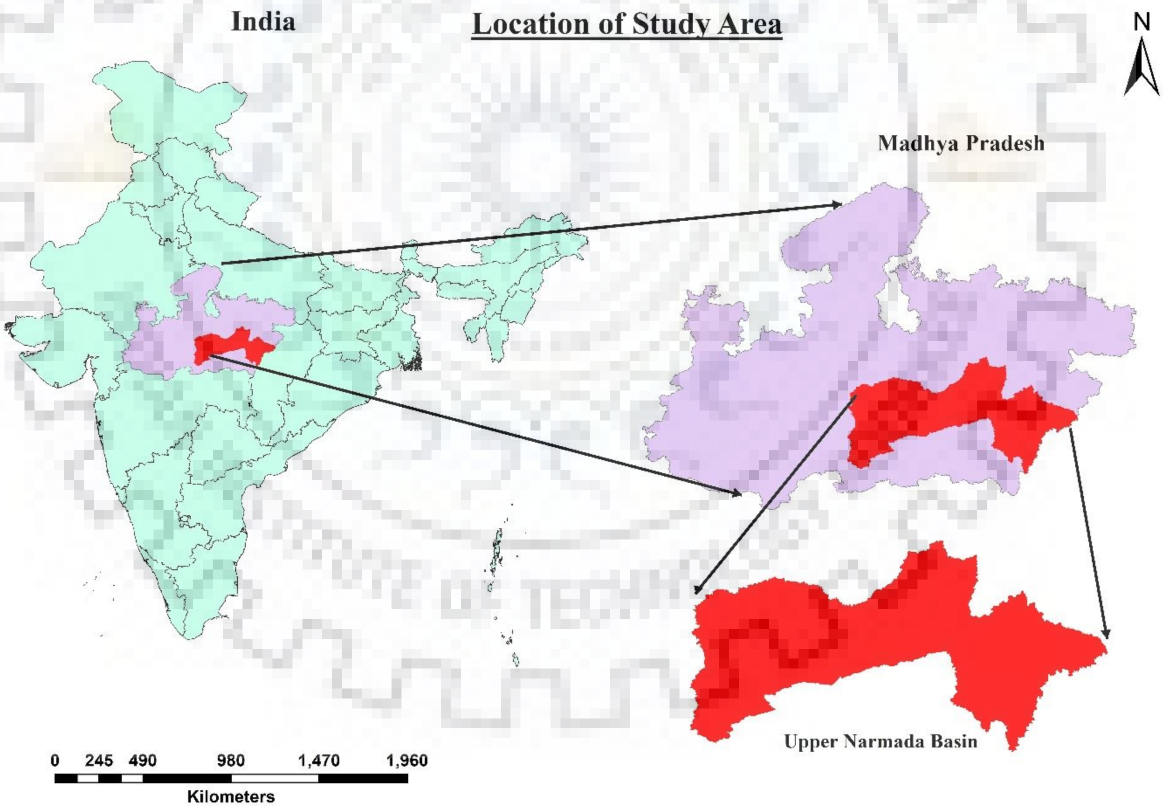


Fig. 3. 1 Study area map

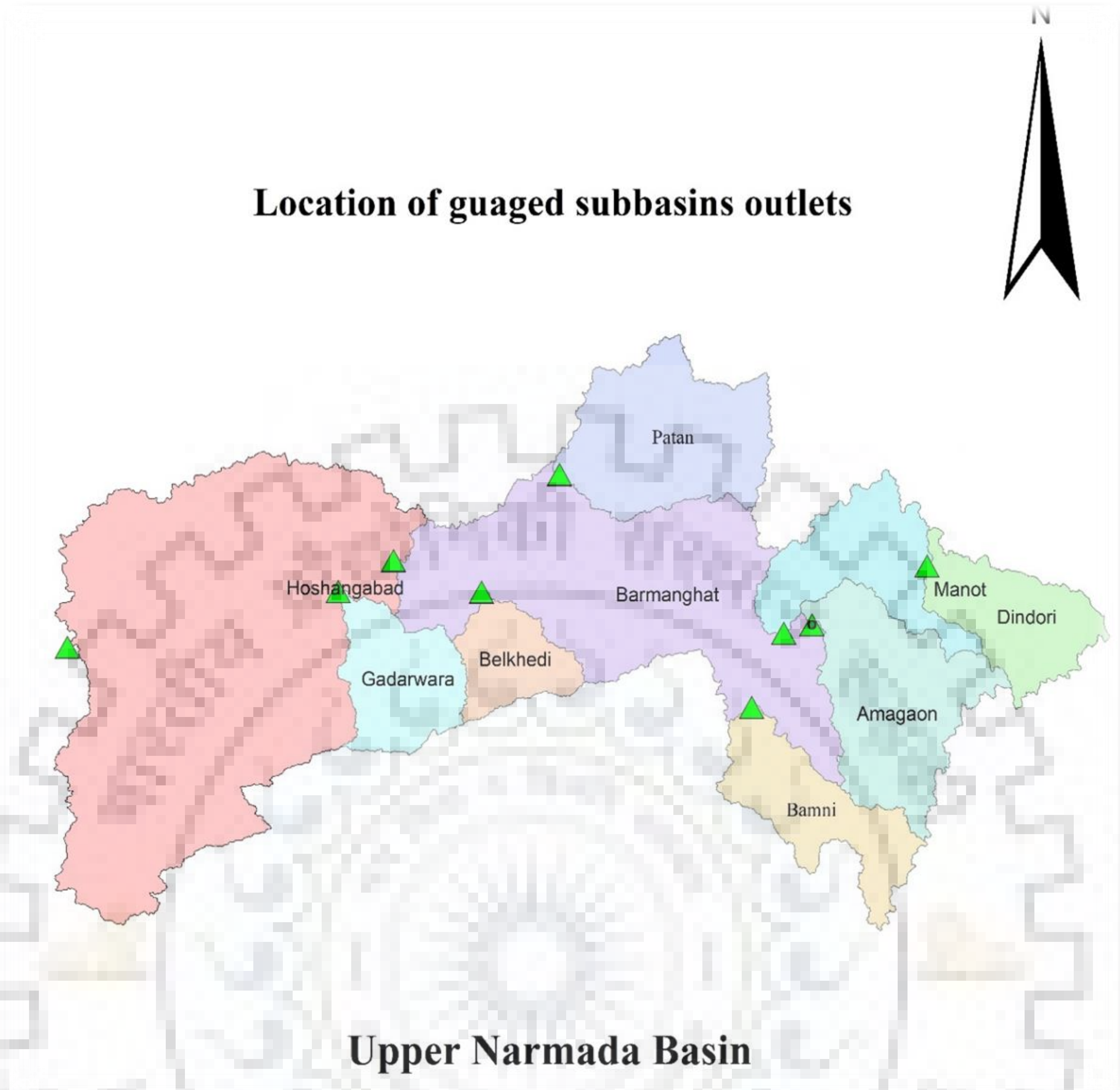


Fig. 3. 2 Subcatchment description

3.2.2 Physiographic characteristics: The Narmada basin has divided into five all-around characterized physiographic divisions. They are:

(1) The first division is classified under hilly area covering the Shahdol, Mandla, Durg, Balaghat and Seoni districts of Madhya Pradesh

(2) The second division is upper plains covering the areas of Jabalpur, Narsinghpur, Sagar, Damoh, Chhindwara, Hosangabad, Betul, Raisen and Sehore.

(3) The third division is middle plains covering the areas of Khandwa, some portion of Khargone, Dewas, Indore, and Dhar.

(4) The lower hilly zones covering some portion of the west Nimar, Jhabua, Dhulia, Narmada, and parts of Vadodara.

(5) the lower plains covering mostly the locale of Narmada, Bharuch, and parts of Vadodara. The slope areas are very much forested. The upper, center and lower fields are broad having good fertility for cultivation.

The Narmada Basin principally comprises of Black soils. The seaside fields in Gujarat are made out of alluvial dirt with a layer of black soils superficially.

3.2.2 Climate: In the region of the upper field Narmada basin crossed the Tropic of cancer and a noteworthy portion of the basin lies just beneath this line. In the year, four particular seasons happen in the basin. They are (I) cold Weather, (ii) hot weather, (iii) south-west monsoon and (iv) post-monsoon. The south-west storm sets in by the center of June and pulls back by the principal seven-day stretch of October. June to September is the rainiest months. In the post-rainstorm season, a couple of tempests happen, particularly in October. From that point, the weather clears up and dry wonderful weather wins all through the valley (Source: Report of Irrigation Commission,1972). The ordinary yearly precipitation for the basin works out to 1,178 mm. South-west storm (June to October) is the essential blustery season representing almost 94% of the yearly precipitation. About 60% of the yearly precipitation is received during July

3.2.3 Rainfall

Rainfall is substantial in the upper uneven and upper fields regions of the basin. It bit by bit diminishes towards the lower fields and the lower sloping territories and again increments towards the coast and south-western bits of the basin. In the upper sloping regions, the yearly precipitation, by and large, is in excess of 1400 mm however it goes up to 1650 mm in certain parts. In the upper fields, close Jabalpur to close Punasa dam site, the yearly precipitation diminishes from 1400 mm to under 1000 mm with the high precipitation zone around Pachmarhi where the yearly precipitation surpasses 1800 mm. In the lower fields, the yearly precipitation diminishes quickly from 1000 mm at the eastern and to under 650 mm around Barwani. This zone speaks to the aridest part of the Narmada Basin. In the lower slope territories, the yearly precipitation again increments to a little more than 750 mm (Source: www.nca.gov.in). A noteworthy bit of the precipitation in the basin happens amid the southwest rainstorm and records for about 85% to 95% of the all-out precipitation. The post-rainstorm represents about 9% of the precipitation through the winter and the pre-storm, together with a record for about a limit of 10% of the all-out precipitation. Every day precipitation information of the examination region was gathered from the India Meteorological Department (IMD) for the time of the year 1990–2011. Those downpour check stations were viewed as where a limit of 25% information is absent. Correspondingly, every day streamflow estimation records were gathered for a similar period from India-WRIS database (http://www.india-wris.nrsc.gov.in/). As indicated by the records kept up by the India Meteorological Department, there were ten rain-gauge stations in 1867 in the whole Narmada bowl. The number rose to 21 rain-gauge stations in the year 1891, the year from which distributed precipitation information is accessible. From there on, there has been a consistent development of the rain-gauge stations organize in the basin. The quantity of rain-gauge stations in the basin were 205 of every 1980. Of these, almost 120 rain-gauge stations have information for over 40 years. Around 50 self-recording precipitation check stations (SRRG) are kept up by IMD or different organizations like the flood anticipating division of CWC, state water system offices, and so on. The overflow factor for the 75% trustworthy progression of Narmada works out to be 0.29. The yearly precipitation in the upper piece of the Narmada catchment is in excess of 1,400 mm and in certain pockets, it surpasses 1,650 mm. The Narmada catchment up to Hoshangabad got extraordinary precipitation in 1999. In the catchment up to Hoshangabad, three noteworthy dams have been built: Bargi, Barna and Tawa. Thus, a huge piece of the Hoshangabad city stayed overwhelmed for an impressive time, causing serious harms.

3.3 Data type and source:

Major datasets required for this work

- DEM (digital elevation model) data. 90 X 90m resolution of Dem is downloaded from SRTM website and then it is projected to WGS 1984 UTM Zone 43N coordinate system DEM is processed in ArcGIS environment using watershed delineator.
- Discharge data the daily discharge data observed at different sub-basins varying from 5-30 yr. is used for the analysis purpose. Mostly 30 years of data are available at different sub-basins. India-WRIS database (http://www.india-wris.nrsc.gov.in/).
- Drainage Basin characteristics.in regionalization based on regression stream flow parameters of the gauged catchment are related to their catchment characteristics like catchment area (Ca), Altitude(A), basin relief (H).

Chapter 4

MATERIAL AND METHODOLOGY

4.1 General

The overall methodology followed in the study is shown in the form of a flowchart in Fig. 4.1. This chapter deals with three regionalization approaches that are used to compute dependable flows in an upper Narmada river basin. this chapter also tells about data collection required and its use as an input to derive regional regression model equations to calibrate and validate the modal. Model output depends upon the quality of input data and underlines the importance of data collection and processing.

4.2 Primary statistical analysis

The basic statistics like the arithmetic mean of flow values, standard deviation, variance, coefficient of variation and skewness coefficient is evaluated from the available historical flow data at each of the gauging sites at real space and in log space.

4.3 Regionalization approach based on regression

The procedure for the development of flow duration curves for the ungauged catchments is different as for gauged catchments. Regional flow duration curves for ungauged catchments are developed based on available long term rainfall runoff records of gauged catchment having a similar pattern of rainfall, runoff, and evaporation using different regionalization procedures

There are many regionalization procedures but in the present study, three regionalization procedures based on regression are adopted as mentioned below.

4.3.1 Method 1: Regionalization of the parameters of the chosen probability distribution for individual gauged sites.

This method results in the development of regional relations for the mean of log flows and coefficient of variation (Cv) of log flows by correlating them with physical characteristics of the catchment that is catchment area (Ca), altitude(A), and Ca/A^2 using linear regression. (Arora and Goel, 2004)

The developed relationships are in the following form as shown in equations (4.1 and 4.2)

$$\overline{\boldsymbol{Q}} = \mathbf{a_1}(\boldsymbol{Ca})^{\boldsymbol{b1}} \qquad (4.1)$$

$$\mathbf{CV_y} = \mathbf{a_2}(\boldsymbol{Ca})^{\boldsymbol{b2}} \tag{4.2}$$

$\bar{Q}$ and $\mathrm{CV_y}$ represents the mean and coefficient of variation of log flow respectively and a_1,b_1,a_2,$b_2$are the coefficients X represents the physiographic characteristics of the catchment.

the regional formula developed for the dependable flow computation is shown in figure (4.3)

$$\boldsymbol{Q_D} = \mathbf{k_1}^{(X)^{b1}} * \mathbf{k_2}^{(X)^{C1} Z_D} \tag{4.3}$$

$\boldsymbol{Q_D}$ is the D% dependable flow and $\mathbf{Z_D}$ is the normally reduced variate corresponding to D% dependable flow.

4.3.3Method 2: Regionalization of dependable flows.

In this method, dependable flows are correlated with the physiographic characteristics of the catchment and the regional relationship is developed. The developed relationships are of the following form as shown in equation (4.4)

In this method, dependable flows are correlated with the physiographic characteristics of the catchment and the regional relationship is developed. The developed relationships are of the following form

$$\boldsymbol{Q_D} = \mathbf{a_3}(\boldsymbol{Ca})^{\boldsymbol{b3}} \tag{4.4}$$

The relationship developed using Catchment area and (Ca/A^2) has shown good correlation coefficients as compared to the altitude. These relationships are used to compute respective dependable flows for 8 catchments which are used for calibration and 2 test catchments that are used for validation. The PAEDF has been computed for each of the site using the regionalization method.

4.3.3 Method 3: Regionalization of the parameters of chosen probability distribution derived for the region as a whole. with equations and some literature review (theory)

This method provides satisfactory results when the flow records of gauged catchments are not adequate or a number of gauged catchments are limited, in that condition above methods provides erroneous results. In this method, Non-dimensional flow series for the region is prepared by dividing flow series of each gauged sites by their respective mean flows and then these non-dimensional flow series of each gauged catchment are pooled together. This resulting non-dimensional flow series is analyzed and the best-chosen probability distribution is fitted which results in the parameters which are used as the regional parameters and dependable flows can find out for the gauged as well as ungauged catchments. For the development of the flow duration curve of ungauged catchment mean flow estimation is required which is then multiplied to non-dimensional flow series. The regional relationship developed of the following form as shown in equation 4.5

$$. \log Q_D/\bar{Q} = a_4 + b_4 Z_D \tag{4.5}$$

Mean flow of gauged catchments is correlated to physical characteristics of catchments using linear regression approach to develop a regional relationship for mean flow.

$$\bar{Q} = \mathrm{a}_5 (X)^{b5} \tag{4.6}$$

$\bar{Q}$ and CV_y represents the mean flow and coefficient of variation in normal space respectively and a_4, b_4, a_5, b_5 are the coefficients. X represents the physiographic characteristics of the catchment that is catchment area (Ca), altitude (A) and (Ca/A^2)

Comparison

of all three regionalization procedures are discussed in detail below. The above three regionalization methods are compared on the basis of percentage absolute error in dependable flows (PAEDF) which is computed using the relationship shown in equation (4.7)

$$PAEDF = \left|\frac{Q_D - \hat{Q}}{Q_D}\right| * 100 \tag{4.7}$$

where Q_D represents the dependable flow corresponding to D% dependability computed from the historical daily flow data. $\hat{Q}$ represents the D% dependable flow computed using any one of the three regionalization methods. The values of PAEDF are computed for each of the 10 sub-basins corresponding to each dependability considered.

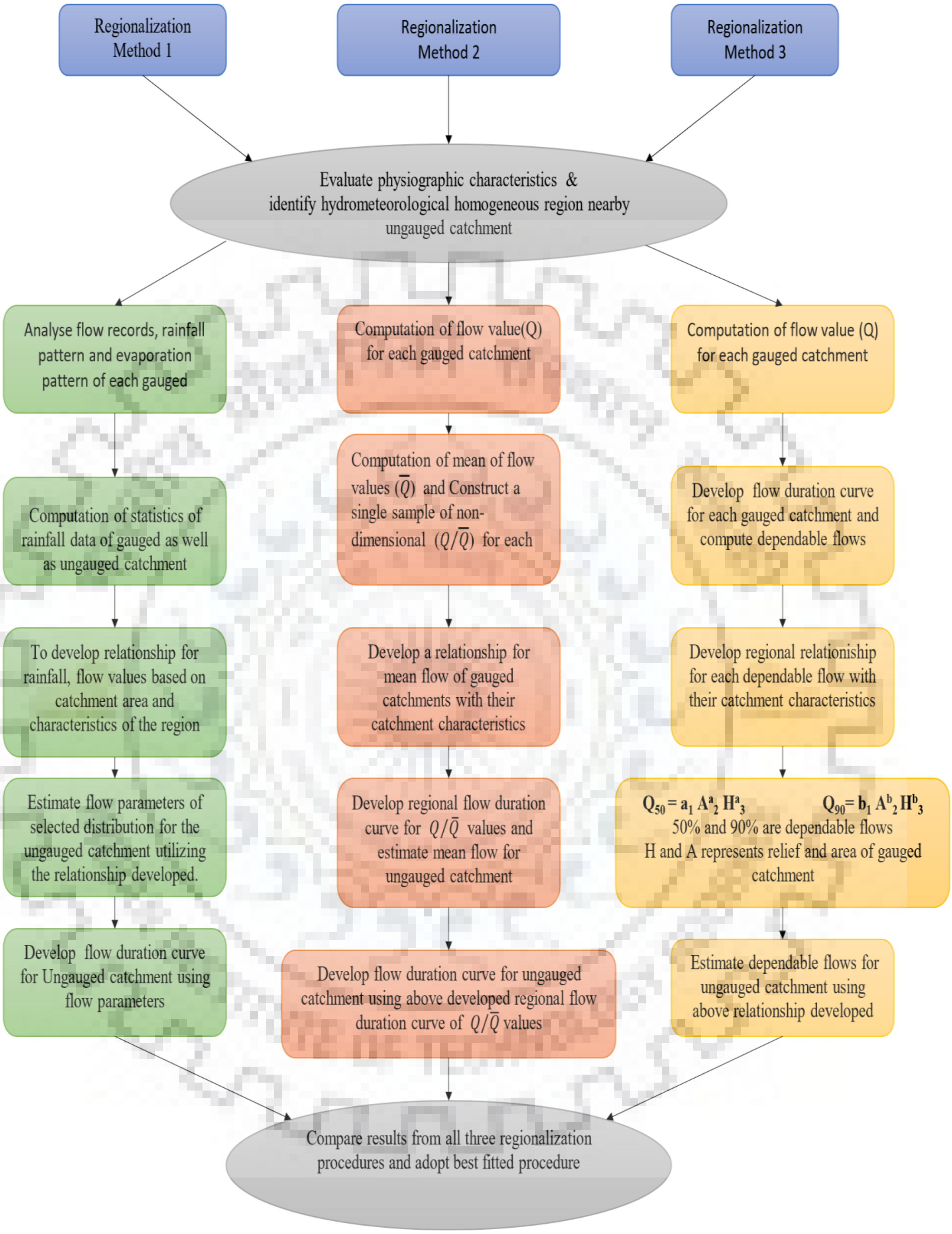


Fig. 4. 1 Flow chart of the methodology

4.4 Regression model setup

4.4.1 General

Linear regression model set up has been done it includes the following parameters as an input like DEM of the study area, statistical parameters of stream flow, physiographic characteristics of the catchment and basin discharge data. The output of the model depends upon the quality of input data.

4.4.2 Model data inputs

- DEM (digital elevation model) (Fig. 4.2) show elevation map also contour map (Fig. 4.3)

DEM is defined as the raster data containing an array of pixels or cells having elevation value of every point in a given area at a particular resolution. DEM is used to delineate the network of river streams, stream characteristics and sub-basins parameters such as elevation, percentage slope, etc. in this report 90 X 90m resolution of Dem is downloaded from SRTM website and then it is projected to WGS 1984 UTM Zone 43N coordinate system DEM is processed in ArcGIS environment using watershed delineator. Dem data is used to describe the elevation of outlet points of gauged and selected ungauged catchments and their respective relief data.

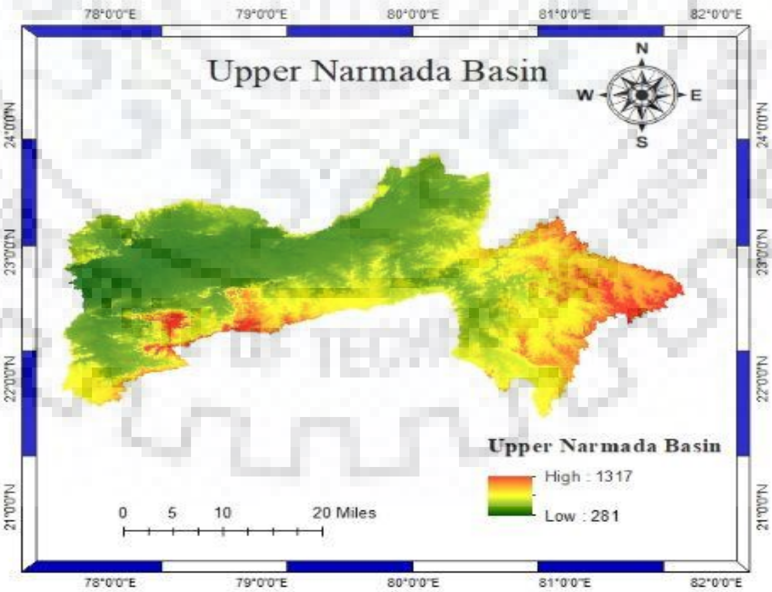


Fig. 4. 2 DEM Map

4.4.3 Evaluate Physiographic characteristics of the basin

The catchment area of each sub-basin is found by the delineation of the watershed which represents a contributing area for the outlet of each sub-basin. Watershed delineation was done using ArcGIS watershed and sub-basins are created with the help of DEM. On the basis of DEM data stream definition was carried out, followed by the direction of flow and the accumulation, on the basis of which steam network and outlets were created. Total 10 sub-basins were delineated with Dindori having the smallest area of 1508 km2 and Hoshangabad having highest catchment area 44548 km2. The catchment area and basin relief vary from 1508-44548 km^2 and 543-1030 m respectively.

Elevation of the outlet of sub-basins(A): With the help of DEM, 100 m contour interval map of upper Narmada basin id prepared in ArcGIS. elevation of the outlet of 10 sub-basins is estimated with the help of the contour map. From DEM it is noted that the maximum area of the basin falls in the 300-500m elevation range. The maximum elevation is observed in the uppermost region of the basin. The highest elevation in the basin is 1,317 m (SRTM DEM 90 m).

Basin Relief (H): Basin relief of each sub-basin is defined as the difference of elevation of the highest and lowest point of the basin.

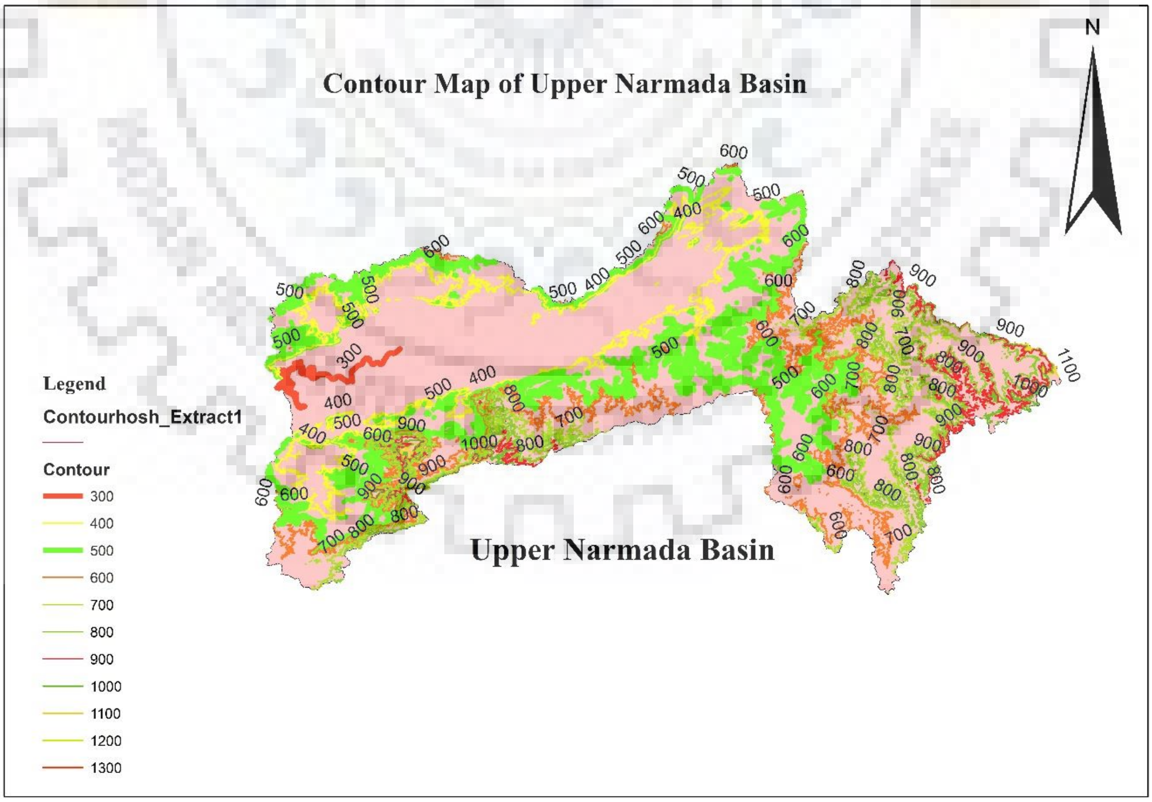


Fig. 4. 3 Contour Map

4.4.4 River Basin discharge data

Upper Narmada basin is divided into total 10 catchments out of which streamflow data of 8 gauged catchments are used for calibration and 2 virtually ungauged catchments are used for validation of linear regression model. Daily river flow data are available for all gauged catchments for the observation period of 1980 -2013 in Indian water information system(India-WRIS). the catchments having largest and smallest area are taken as ungauged catchments. details of all gauged catchments are shown in table from CWC report with latitude-longitude

4.4.5 Statistical parameters of discharge:

Statistical parameters are used to describe the variability of stream flows. the statistical parameters like arithmetic mean, standard deviation variance, coefficient of variation and skewness coefficient of 10daily stream flows of each 8 gauged catchments are estimated. The statistical parameters are estimated in both normal and log space. The normal and lognormal distributions are adapted to select appropriate distributions for annual stream flows. the lognormal distribution best fits the historical data

4.5 Model calibration and validation: theory from many theses

4.5.1 Model calibration

Model calibration the main purpose of model calibration is to get optimized parameters which have an impact on catchment response.it is done by comparing the observed data sets with the input parameters having the same conditions.

4.5.2 Model validation

Model validation this is was done to compare whether the calibrated model is efficiently comparing the simulated data with the observed data set after making the adjustments in the input parameters.

4.6 Comparison of all regionalization approaches

The performance of model parameters is evaluated on the basis of percentage absolute error in dependable flows (PAEDF) which is computed using the relationship

$$\text{PAEDF}= \left|\frac{Q_D-\hat{Q}}{Q_D}\right| * 100 \qquad (4.8)$$

Q_D **and** $\hat{Q}$ represents the observed dependable flows and the computed dependable flows respectively corresponding to D% dependability.

Chapter 5

RESULTS AND CONCLUSIONS

5.1 Physiographic characteristics:

Catchment characteristics like catchment area, altitude and relief are found out using ArcGIS tools. Physiographic characteristics of the study area are shown in Table 5.1.

Table 5. 1 Physiographic characteristics

Site no.	Name of sites	Area	Height(A)	Relief(H)	(C_a/A^2)
		(Km^2)	(m)	(m)	
1	Amagon	9344	438	701	48706.24
2	Bamani	1864	446	457	9370.79
3	Barmanghat	26453	314	825	268296.9
4	Dindori	2292	663	476	5214.198
5	Gadarwada	2270	327	822	21229.04
6	Manot	4667	447	253	23357.31
7	Mohgaon	3919	454	558	19013.57
8	Patan	3950	348	393	32616.59
9	Belkheri	1508	349	543	12380.85
10	Hoshangabad	44548	287	1030	540834.5

5.2 Statistical analysis of discharge data

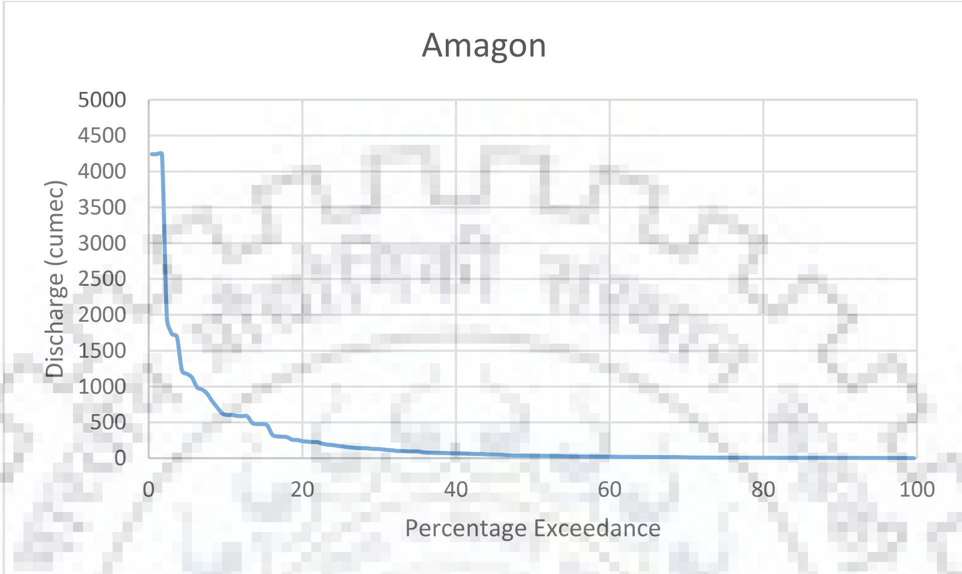
Table 5.2 describes the basic statistics of ten daily mean flow data in real and log domain. All other parameters like kurtosis, range, maximum and minimum flows are done in MS Excel mean sheet.

Table 5. 2 Basic statistics of ten daily mean flow data

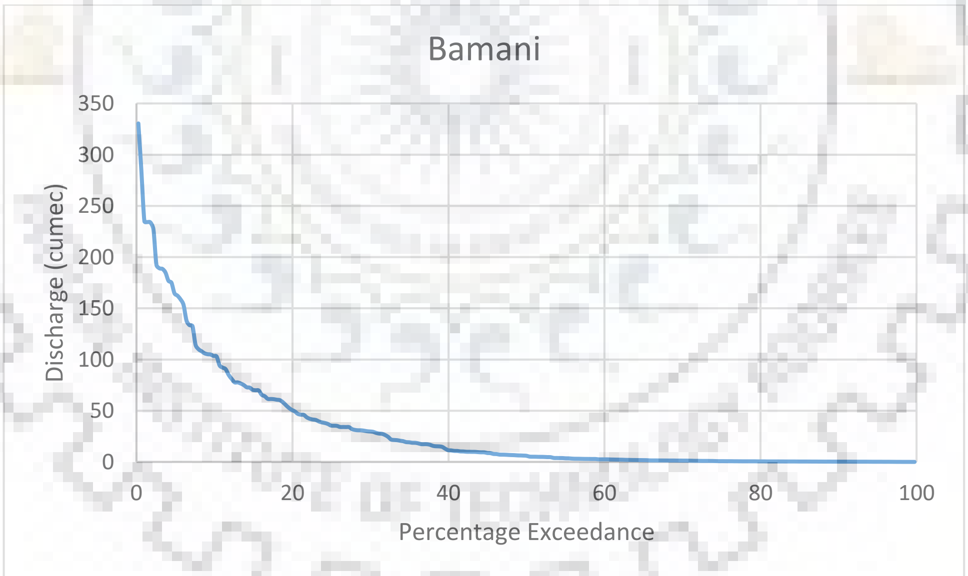
	Basic statistics of ten daily mean flow data in real and log domain												
Site no.	Name of sites		In real space							In log space			
		mean	mean(μ)	S.D	skewness	kurtosis	Range	mean	S.D	skew	C.V	Kurtosis	Range
		(cumec)	(cumec)	(cumec)	(Cs)	(Ck)		(cumec)	(cumec)				
1	Amagon	255.46	658.30	4.75	2.58	25.25	4239.95	3.75	1.95	0.16	0.52	-0.03	11.35
2	Bamani	31.63	54.89	2.60	1.74	7.36	330.57	1.68	2.23	-0.11	1.33	-1.04	9.41
3	Barmanghat	377.64	731.14	4.89	1.94	32.96	8754.19	5.02	1.34	-0.03	0.27	0.31	7.74
4	Dindori	41.26	81.71	4.06	1.98	23.32	850.60	2.49	1.55	0.39	0.62	-0.53	7.61
5	Gadarwada	45.21	118.09	7.13	2.61	88.06	2075.00	1.98	1.97	0.10	0.99	0.60	14.55
6	Manot	96.72	201.42	3.38	2.08	13.70	1568.00	2.70	2.13	0.04	0.79	-0.44	13.57
7	Mohgaon	75.19	160.24	3.65	2.13	17.69	1514.99	2.17	2.40	-0.05	1.10	-0.72	11.83
8	Patan	52.42	121.85	4.48	2.32	26.99	1368.99	2.38	1.79	0.22	0.75	-0.06	11.56
9	Belkheri	22.91	73.13	8.55	3.19	104.30	1118.99	0.76	2.17	0.68	2.84	-0.69	12.14
10	Hoshangabad	669.39	1324.55	4.46	1.98	26.30	13959.86	5.60	1.22	0.64	0.22	0.35	6.76

5.3 Development of flow duration curve of gauged catchments

With the available runoff data, flow duration curves have been made and shown in Fig. 5.1 to Fig. 5.3 for different gauging stations.

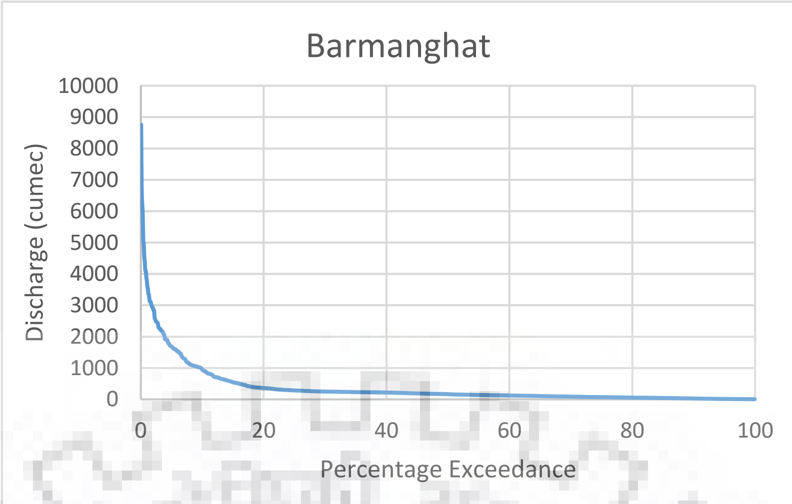


(a)

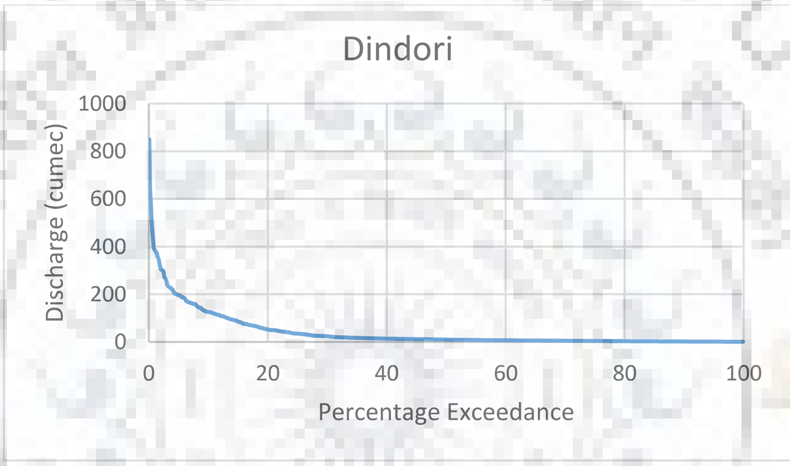


(b)

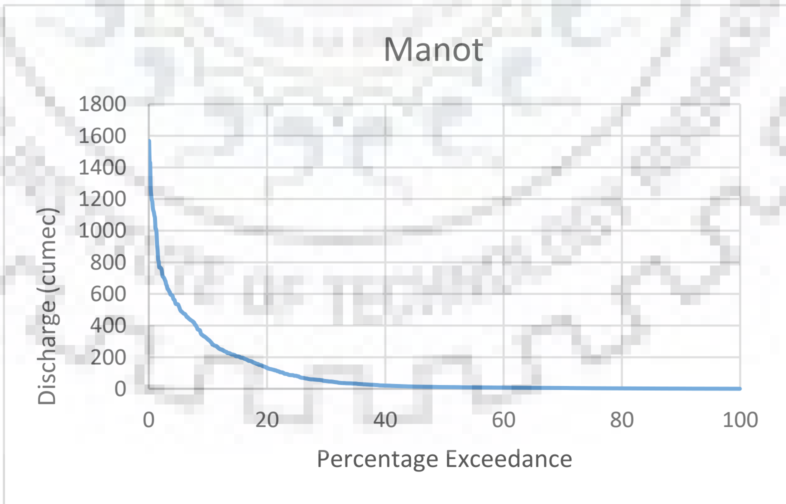
Fig. 5. 1 Flow-duration curves for (a) Amagaon & (b) Bamani



(a)

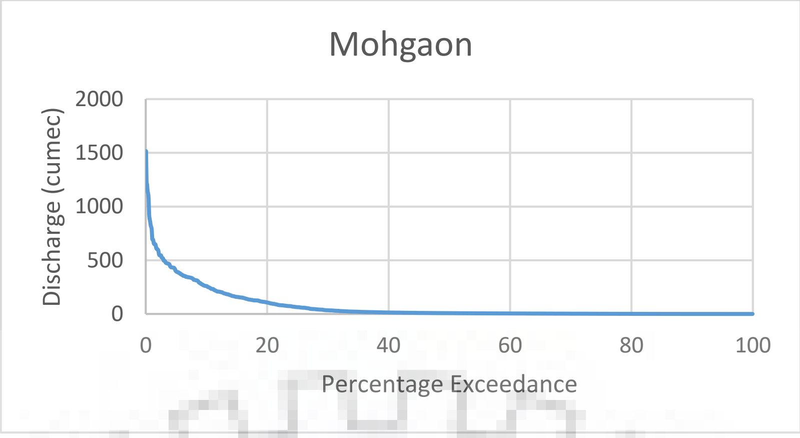


(b)

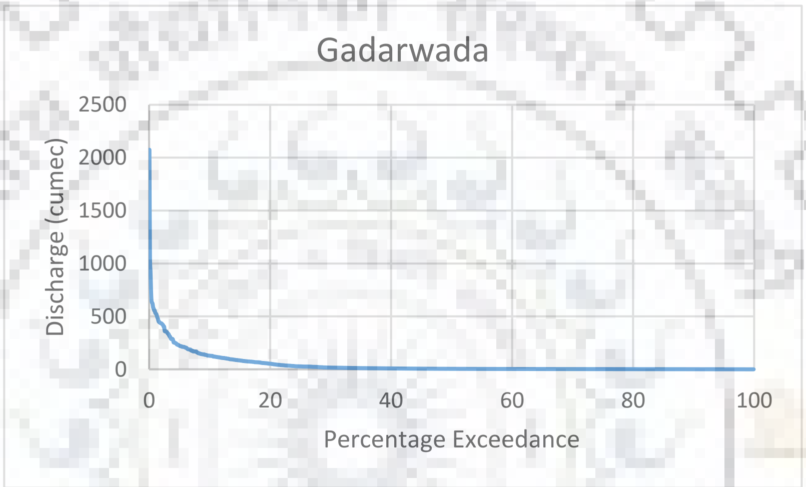


(c)

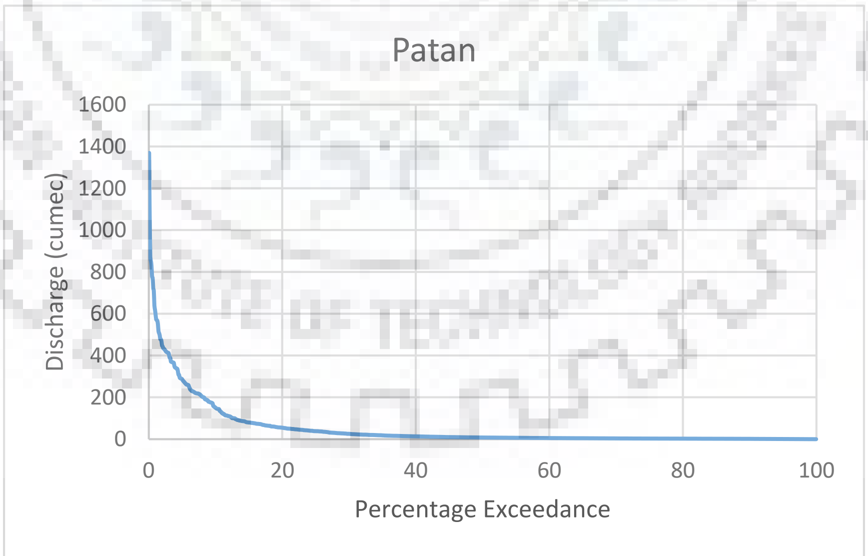
Fig. 5. 2 Flow duration curves for (a) Barmanghat (b) Dindori & (c) Manot



(a)



(b)



(c)

Fig. 5. 3 Flow-duration curves for (a) Mohgaon (b) Gadarwada & (c) Patan

5.4 Results of regionalization method

5.4.1 Method 1

Development of an empirical regional model

Mean flow $\bar{Q}$ and $\mathbf{CV_y}$ is computed using the relationship developed by correlating mean flow with catchment area(Ca), Altitude(A) and (Ca/A^2) using a linear regression approach as shown in equation (5.1 to 5.5)

$$\bar{Q} = .1042(Ca)^{0.383}, r = .95 \quad (5.1)$$

$$\bar{Q} = 23.95(A)^{-0.367}, r = .25 \quad (5.2)$$

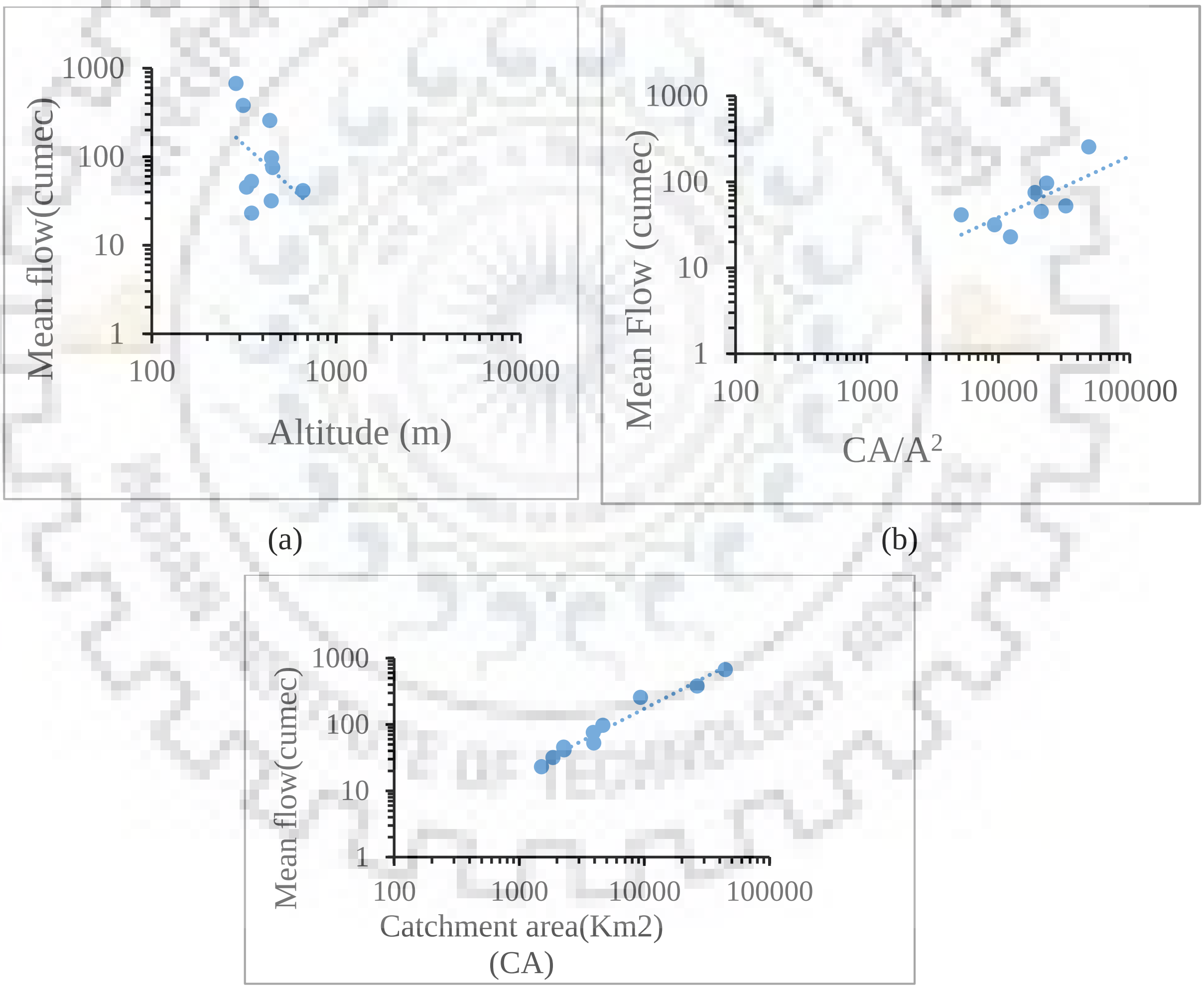
$$\bar{Q} = .2167(Ca/A^2)^{0.245}, r = .81 \quad (5.3)$$

$$CV_y = 49.41(Ca)^{-.502}, r = .87 \quad (5.4)$$

$$CV_y = .0395(A)^{-.482}, r = .23 \quad (5.5)$$

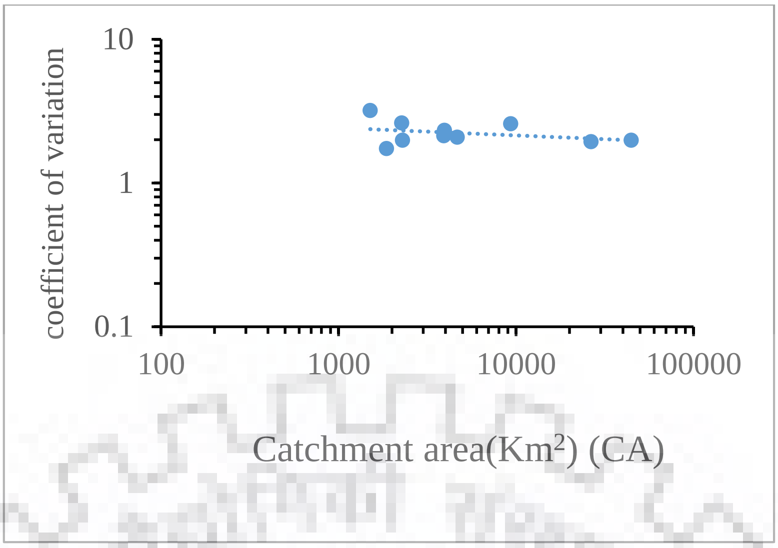
$$CV_y = 18.93(Ca/A^2)^{-.321}, r = .75 \quad (5.6)$$

Development of Regional model for the upper Narmada region is done by correlating mean ($\bar{Q}$) of log flows and coefficient of variation (Cv) of log flows with physical characteristics of the catchment that is catchment area (Ca), altitude (A), and Ca/A^2 using linear regression is shown by equations (5.1 to 5.6). A regional model for the upper Narmada region is developed using selected 8 gauged catchments for calibration purpose. r is the correlation coefficient which is an index of goodness of fit. The higher values of r show better performance and vice versa. From the equations (5.1, 5.2 and 5.3), it is observed that there is a good correlation between the mean of the observed flows and the catchment area as the correlation coefficient is 0.95. mean flow also depends on altitude A and Ca/A^2 but their correlation coefficient is not so satisfactory as it is 0.25 and 0.82 respectively. It can be concluded as a catchment area and Ca/A^2 increases, mean of observed flow increases and mean flow decreases with an increase in altitude. Derived relation for the basin is shown in figure 5.4. It is clearly seen from the fig. that regional relationship developed for mean flow relating catchment area, most of the data points lie in an around the line of best fit. But it does not seem satisfactory for regional relation derived relating mean of flow with other drainage characteristics that are altitude (A) and (Ca/A^2). (Ca/A^2) is a non-dimensional measure computed for all 8 sub-basins and it is treated as in dependable variable for model development. It considers the impacts of both catchment and altitude on hydrologic data of basin. Its values vary from 5214 to 540834. A similar analysis of the same parameters can be done with reference to the coefficient of variation as in Fig. 5.5. Also, computational and observed dependable flows are tabulated below in Table 5.3. Fig. 5.6 to Fig. 5.8 show the regional flow duration curves prepared. Evaluation of model performance using Method I is well depicted in Fig. 5.9. Percentage of absolute errors are shown in Table 5.4.

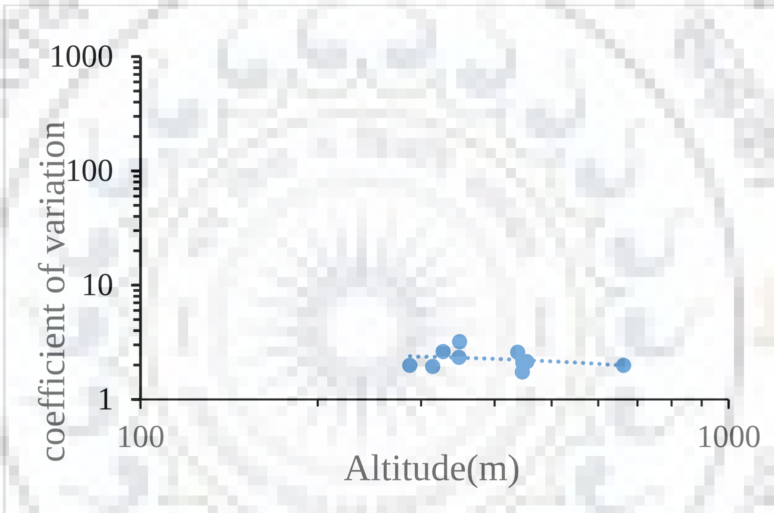


(c)

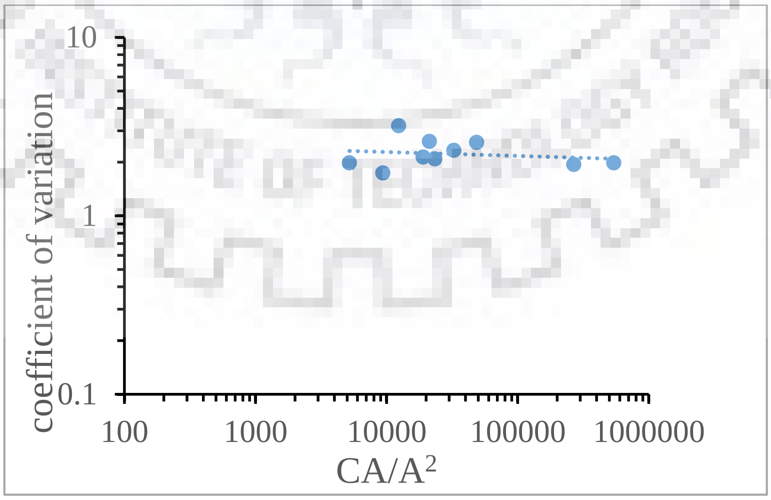
Fig. 5. 4 Mean flow V/s altitude, catchment area and CA/A^2 respectively



(a)



(b)



(c)

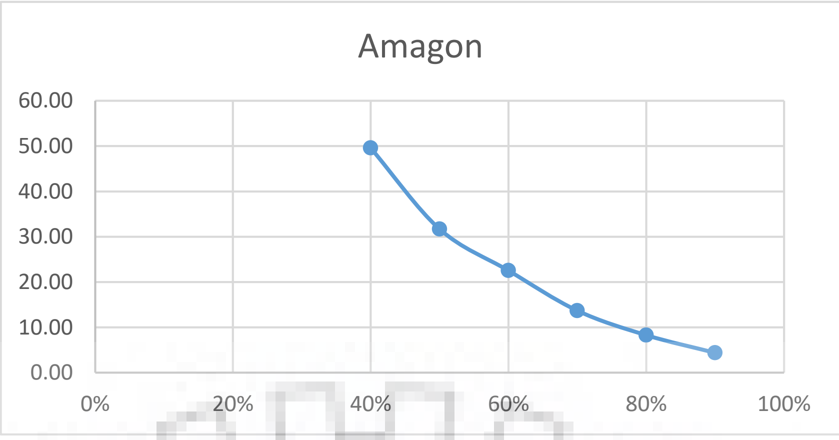
Fig. 5. 5 Coefficient of variation v/s altitude, catchment area and CA/A2respectively

- Development of flow duration model theory

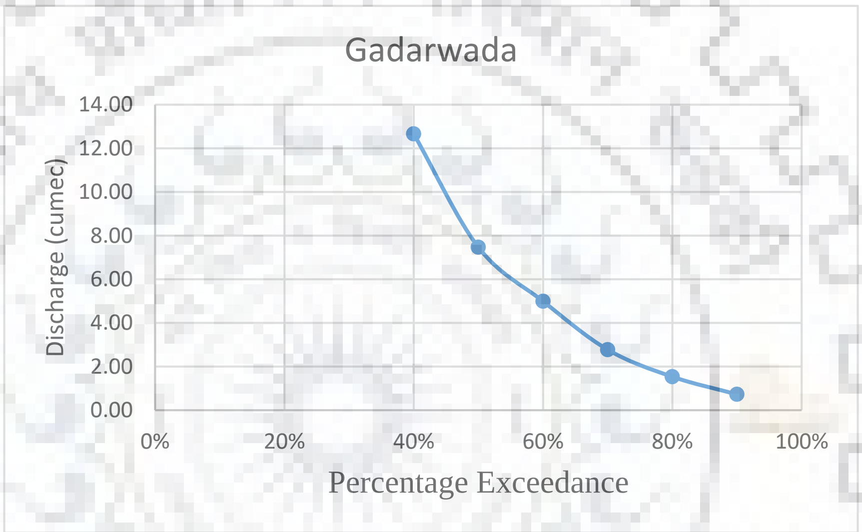
  The Q_D quantiles for various dependabilities ranging from 40% to90% for the whole region is estimated using this characteristic of series resembles a normal distribution and these are shown in table 5.3 Regional flow curve computed using this regional model is shown in fig 5.6 to 5.9.

Table 5. 3 computation and observed dependable flows

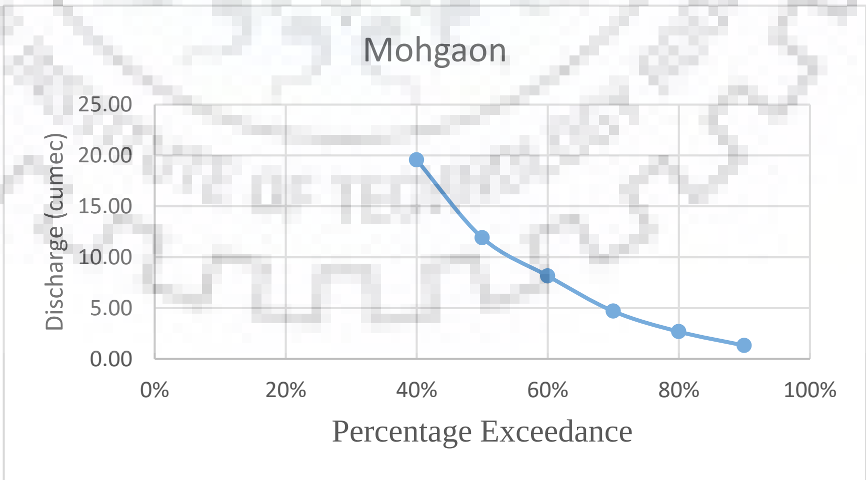
Computed and Observed Dependable Flows															
		Computed								Observed					
			Dependable flows								Dependable flows				
			$\hat{Q}$ (Cumec)								Q_D (Cumec)				
		mean	40%	50%	60%	70%	80%	90%	mean	40%	50%	60%	70%	80%	90%
Site	Name	(cumec)							(cumec)						
number															
			(a)calibration												
1	Amagon	3.46	49.58	31.69	22.52	13.68	8.28	4.38	3.75	66.98	33.78	21.50	11.82	5.87	4.63
2	Bamani	1.86	11.07	6.45	4.27	2.34	1.27	0.59	1.68	11.43	6.02	2.52	1.28	0.55	0.27
3	Barmanghat	5.15	255.86	172.16	127.24	81.84	52.44	29.86	5.02	216.50	164.10	122.40	86.36	55.59	27.40
4	Dindori	2.02	12.74	7.52	5.03	2.79	1.55	0.73	2.49	13.70	9.73	6.57	4.87	3.18	1.73
5	Gadarwada	2.01	12.66	7.46	4.99	2.77	1.53	0.72	1.98	8.51	4.58	3.12	2.30	1.67	0.99
6	Manot	2.65	22.98	14.14	9.76	5.69	3.30	1.65	2.70	20.33	10.92	7.39	5.02	2.51	1.02
7	Mohgaon	2.48	19.55	11.91	8.16	4.70	2.70	1.33	2.17	13.30	7.57	4.63	2.61	1.13	0.33
8	Patan	2.49	19.69	12.00	8.23	4.74	2.72	1.35	2.38	13.60	8.11	5.32	3.73	2.56	1.61
			(b) Validation												
9	Belkheri	1.72	9.70	5.58	3.66	1.97	1.06	0.48	0.76	2.02	0.85	0.59	0.45	0.33	0.25
10	Hoshangabad	6.29	779.38	536.96	404.07	266.80	175.57	103.39	5.60	284.00	239.70	184.00	142.00	108.00	71.88



(a)

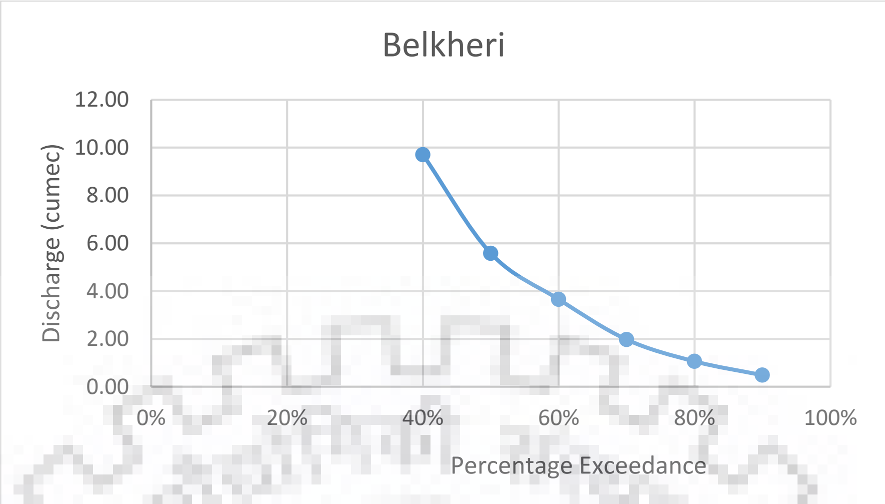


(b)

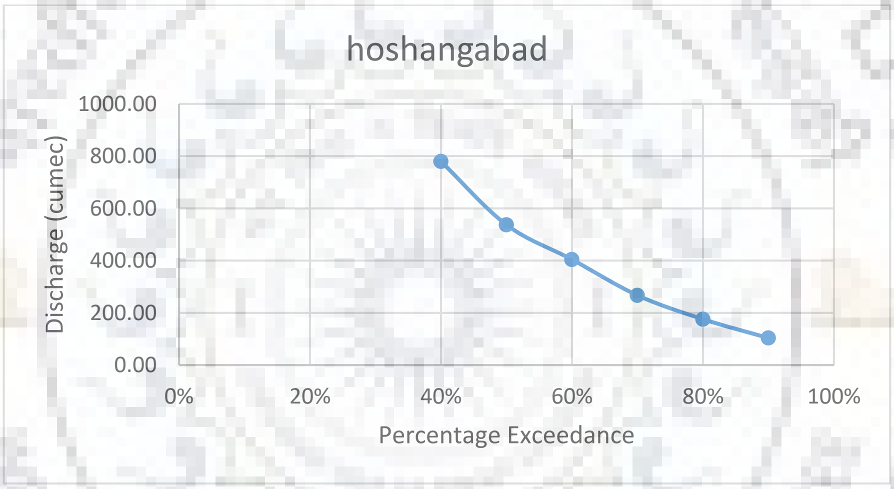


(c)

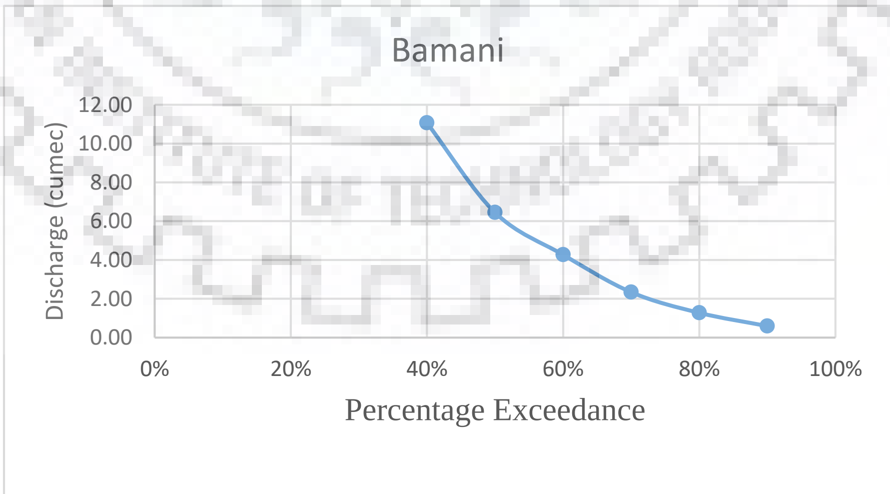
Fig. 5. 6 Regional flow duration curve for (a) Amagaon (b) Gadarwada & (c) Mohgaon



(a)

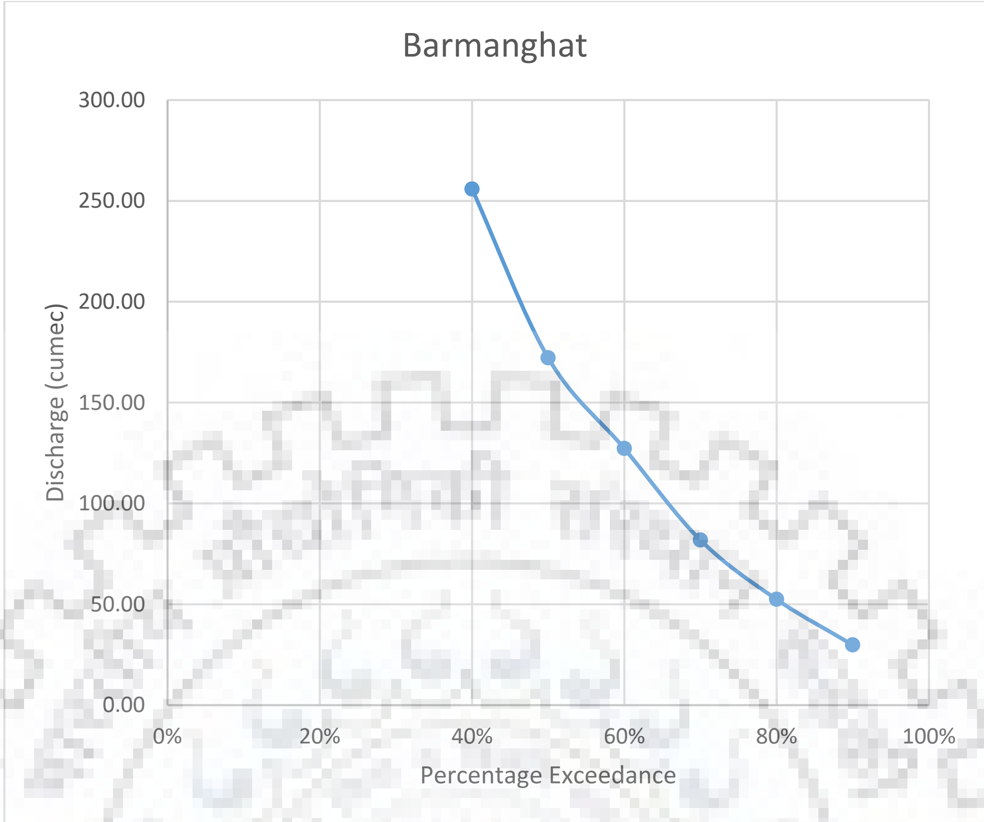


(b)

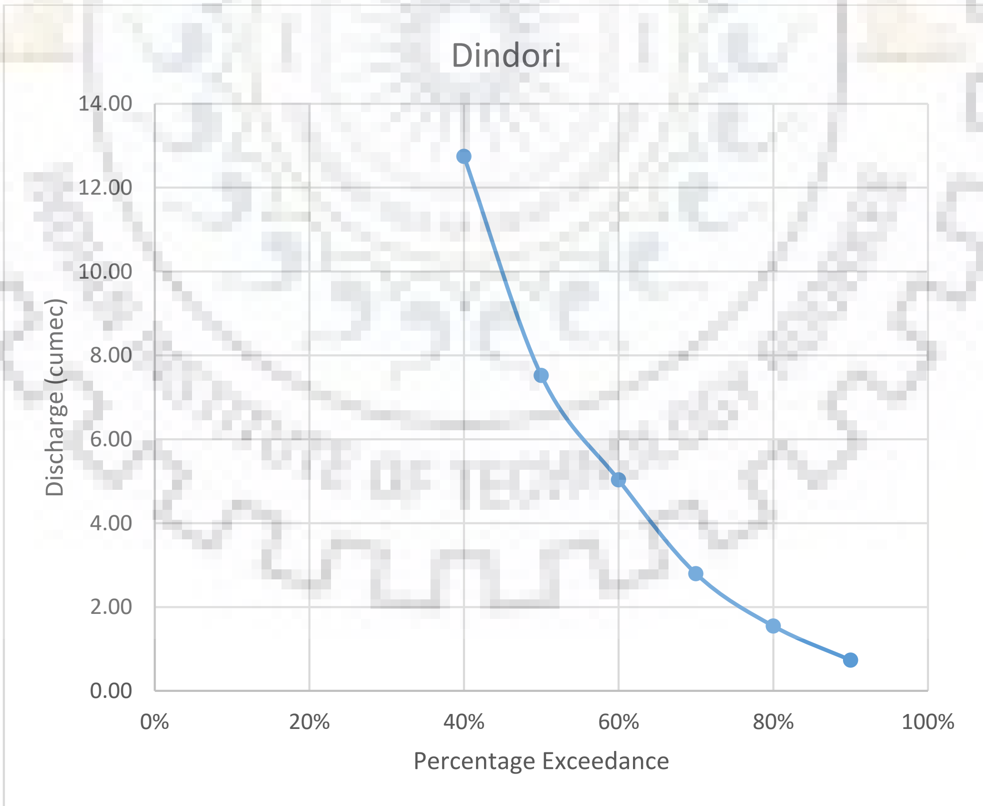


(c)

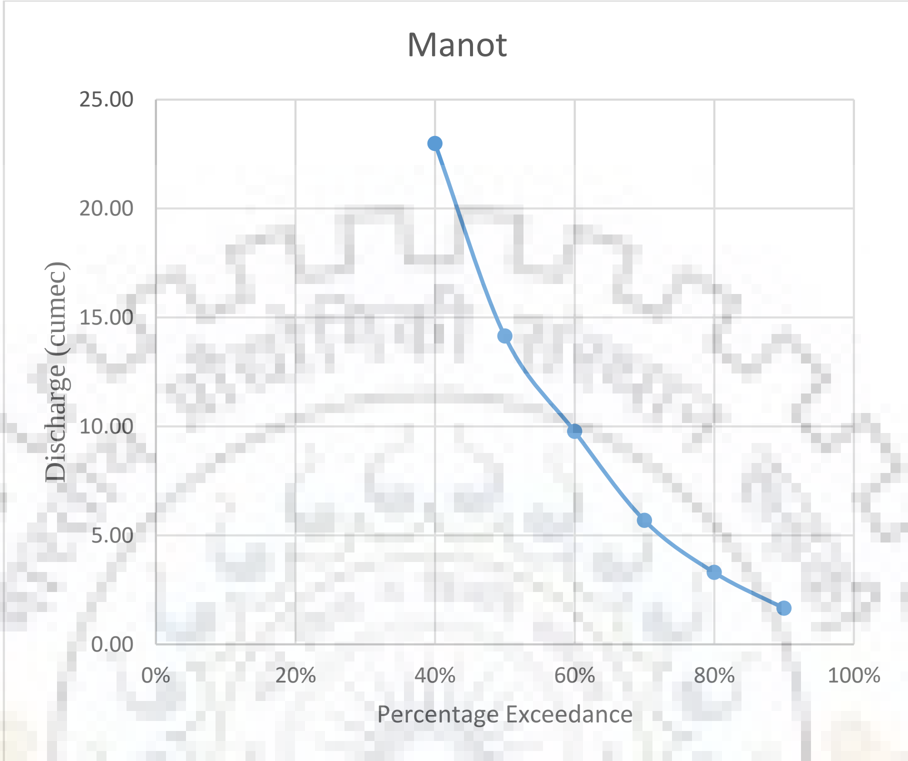
Fig. 5. 7 Regional flow duration curve for (a) Belkheri (b)Hoshangabad & (c) Bamani


Barmanghat
300.00
250.00
200.00
150.00
100.00
50.00
0.00
Discharge (cumec)
0%
20%
40%
60%
80%
100%
Percentage Exceedance

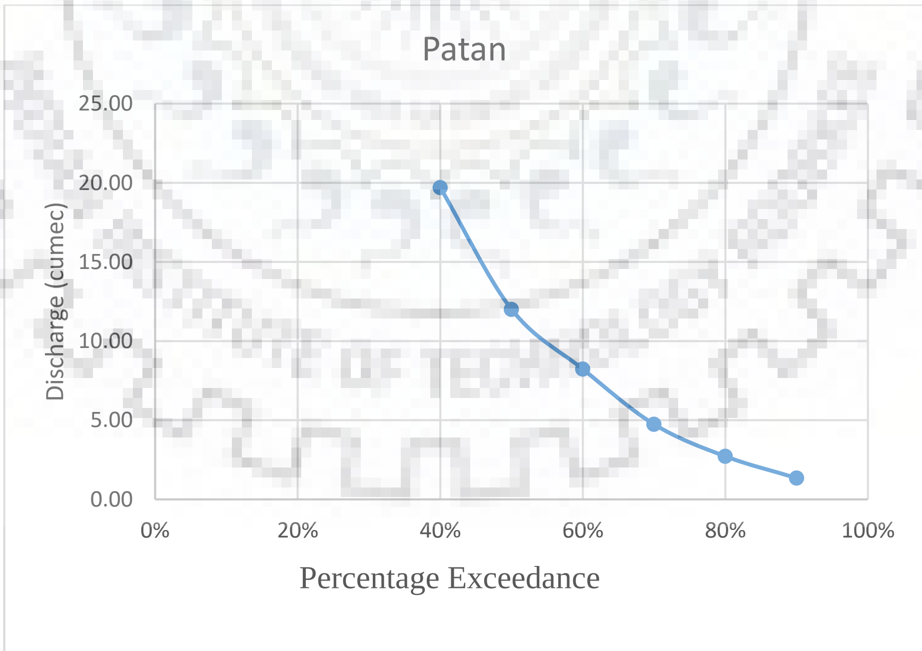
(a)


Dindori
14.00
12.00
10.00
8.00
6.00
4.00
2.00
0.00
Discharge (cumec)
0%
20%
40%
60%
80%
100%
Percentage Exceedance

(b)



(c)



(d)

Fig. 5. 8 Regional flow duration curve for (a)Barmanghat (b) Dindori (c) Manot & (d) Patan

- Evaluation of model performance for mean flow computation

  Mean flow Q is computed using the relationship developed by correlating mean flow with catchment area(Ca) using a linear regression approach as shown in equation 5.8 and it is compared with the mean flows computed using the available flow series and it is shown from figure 5.1 that coefficient of correlation (r^2) comes as 0.98 which shows that linear regression model performs well for computation of mean flow.

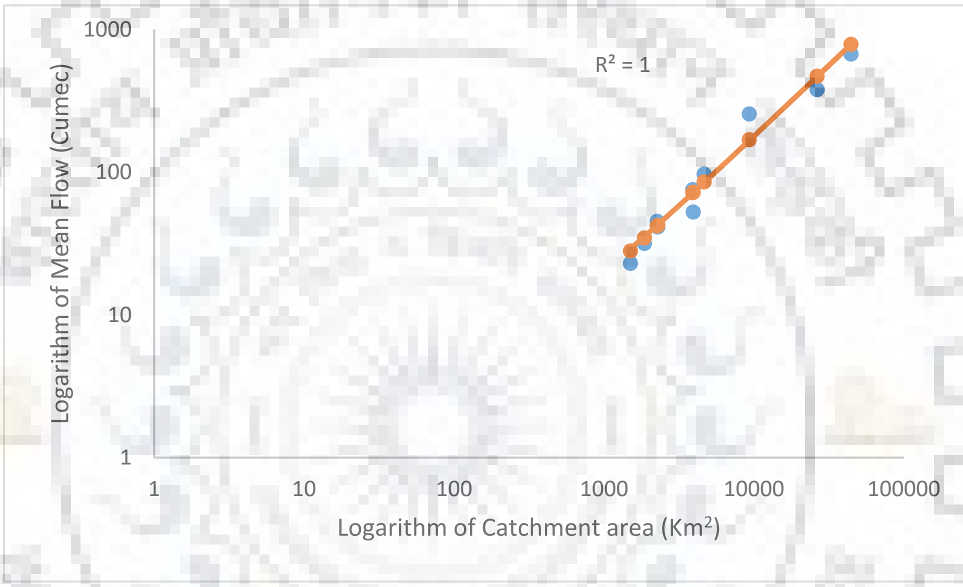


Fig. 5. 9 Evaluation of model performance using Method I

- Evaluation of model performance for dependable flows

  The performance of model parameters is evaluated on the basis of percentage absolute error in dependable flows (PAEDF) which is computed using the relationship as shown as equation 5.13

$$\left|\mathbf{PAEDF} = \frac{Q_D - \hat{Q}}{Q_D}\right| * \mathbf{100} \qquad (5.13)$$

$\boldsymbol{Q_D}$ **and** $\boldsymbol{\hat{Q}}$ represents the observed dependable flows and the computed dependable flows respectively corresponding to D% dependability. The computed percentage of absolute errors are well depicted in Table 5.4.

Table 5. 4 Computed percentage absolute errors

Computed percentage absolute errors (PAEDF)								
Site no.	Name of sites	(PAEDF) in mean flows($\bar{Q}$)	Computed percentage absolute errors in dependable flows (PAEDF)					
			40%	50%	60%	70%	80%	90%
				Calibration				
1	Amagon	7.89	25.98	6.18	4.76	15.75	40.93	5.36
2	Bamani	10.73	3.14	7.15	69.38	82.15	131.35	116.40
3	Barmanghat	2.47	18.18	4.91	3.96	5.24	5.66	8.99
4	Dindori	18.89	6.99	22.74	23.41	42.65	51.33	57.69
5	Gadarwada	1.46	48.76	63.05	59.80	20.45	8.32	26.69
6	Manot	1.96	13.02	29.51	32.10	13.32	31.55	62.14
7	Mohgaon	13.95	47.01	57.39	76.17	80.12	139.14	305.14
8	Patan	4.53	44.78	48.01	54.81	27.09	6.05	16.42
9	Belkheri	125.19	379.87	560.02	524.79	340.23	220.87	94.35
10	Hoshangabad	12.16	174.43	124.01	119.60	87.89	62.56	43.84

5.4.2 Method 2

- Development of empirical regional model: Regional flow duration curves have been derived from the Equations shown in Table 5.5. dependable flows are related to (CA) show good results

Table 5. 5 Empirical equations for making regional flow duration curve

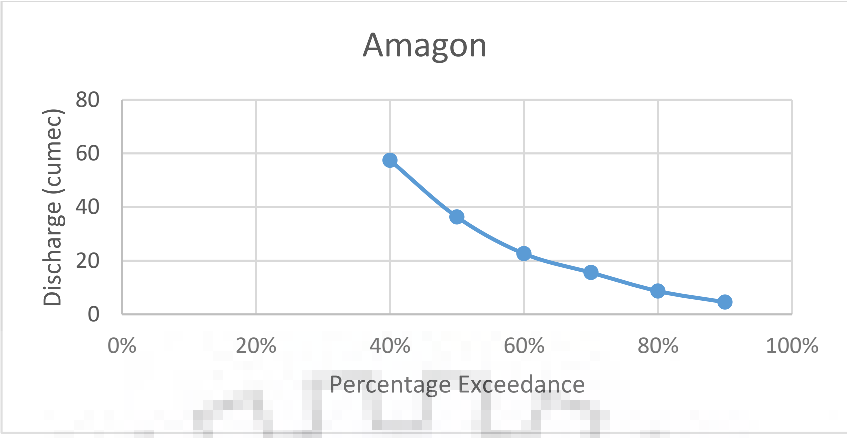
Dependability	**Relation using CA**	**Relation using A**	**Relation using CA/A^2**
40%	$Q_D = 0.0009x^{1.21}$	$Q_D = 143303x^{-1.45}$	$Q_D = 0.0068x^{0.79}$
	r= 0.96	r = .32	r = .85
50%	$Q_D = 0.0003x^{1.28}$	$Q_D = 71602x^{-1.423}$	$Q_D = 0.0028x^{0.83}$
	r = 0.96	r = .29	r = .83
60%	$Q_D = 0.000020x^{1.42}$	$Q_D = 122283x^{-1.56}$	$Q_D = 0.0008x^{0.91}$
	r = .91	r = .30	r = .85
70%	$Q_D = 0.000043x^{1.39}$	$Q_D = 141470x^{-1.69}$	$Q_D = 0.0005x^{0.923}$
	r = .94	r = .31	r =.84
80%	$Q_D = 0.000020x^{1.42}$	$Q_D = 494343x^{-1.98}$	$Q_D = 0.0002x^{0.961}$
	r = .91	r = .35	r = .82
90%	$Q_D = 0.000008x^{1.451}$	$Q_D = 798867x^{-2.18}$	$Q_D = 0.00006\ x^{0.995}$
	r = .86	r = .36	r = .79

- Development of flow duration model theory

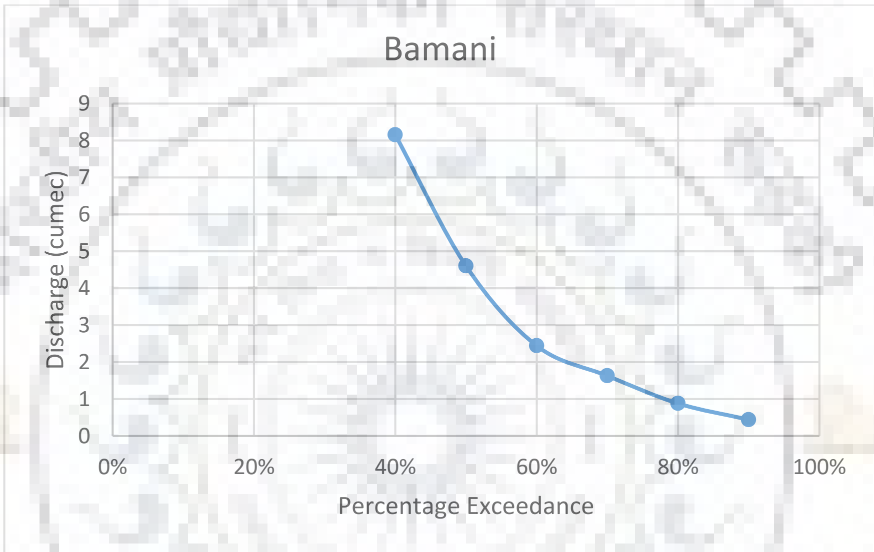
  Computed and observed dependable flows are shown well in Table 5.6 and regional flow duration curves made are shown in Fig. 5.10 to 5.12.

Table 5. 6 Computed and observed dependable flows

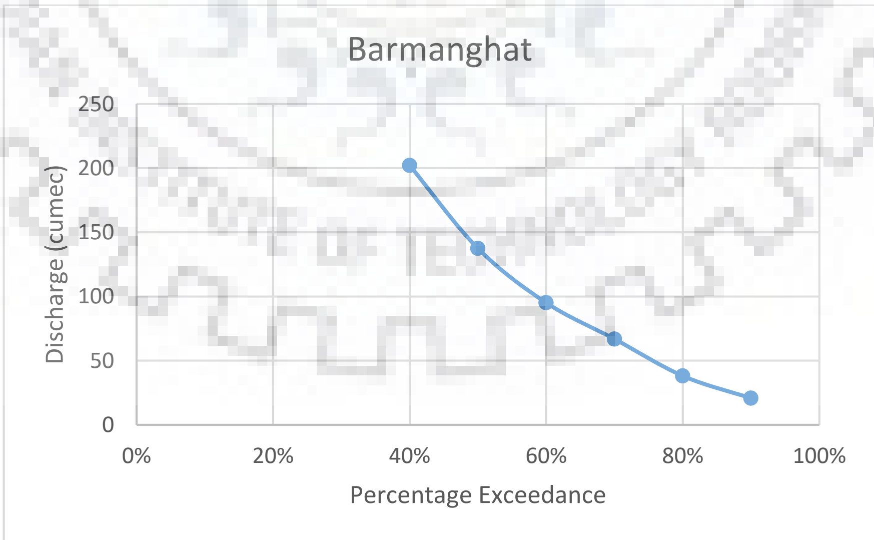
Computed and Observed Dependable Flows														
			Computed						Observed					
			Dependable flows						Dependable flows					
			$\hat{Q}$(Cumec)						Q_D(Cumec)					
			Q_D =a*(power(Ca,b))											
			40%	50%	60%	70%	80%	90%	40%	50%	60%	70%	80%	90%
Site Sl.	Name	Area(Ca)	a= 0.0009	a=0.0003	a=0.000	a=0.0000	a=0.0000	a=0.000008						
number		(Km2)	b=1.21	b=1.28	b=1.38	b=1.40	b=1.42	b=1.45						
							(a)calibration							
1	Amagon	9344	57.36	36.26	22.61	15.57	8.69	4.57	66.98	33.78	21.50	11.82	5.87	4.63
2	Bamani	1864	8.16	4.61	2.44	1.63	0.88	0.44	11.43	6.02	2.52	1.28	0.55	0.27
3	Barmanghat	26453	202.04	137.37	95.08	66.82	38.10	20.69	216.50	164.10	122.40	86.36	55.59	27.40
4	Dindori	2292	10.47	6.00	3.25	2.18	1.18	0.60	13.70	9.73	6.57	4.87	3.18	1.73
5	Gadarwada	2270	10.35	5.93	3.21	2.15	1.17	0.59	8.51	4.58	3.12	2.30	1.67	0.99
6	Manot	4667	24.76	14.91	8.68	5.89	3.24	1.67	20.33	10.92	7.39	5.02	2.51	1.02
7	Mohgaon	3919	20.04	11.92	6.82	4.61	2.53	1.30	13.30	7.57	4.63	2.61	1.13	0.33
8	Patan	3950	20.24	12.04	6.89	4.66	2.56	1.31	13.60	8.11	5.32	3.73	2.56	1.61
							(b) Validation							
9	Belkheri	1508	6.31	3.51	1.82	1.21	0.65	0.32	2.02	0.85	0.59	0.45	0.33	0.25
10	Hoshangabad	44548	379.60	267.68	195.18	138.62	79.87	44.04	284.00	239.70	184.00	142.00	108.00	71.88



(a)

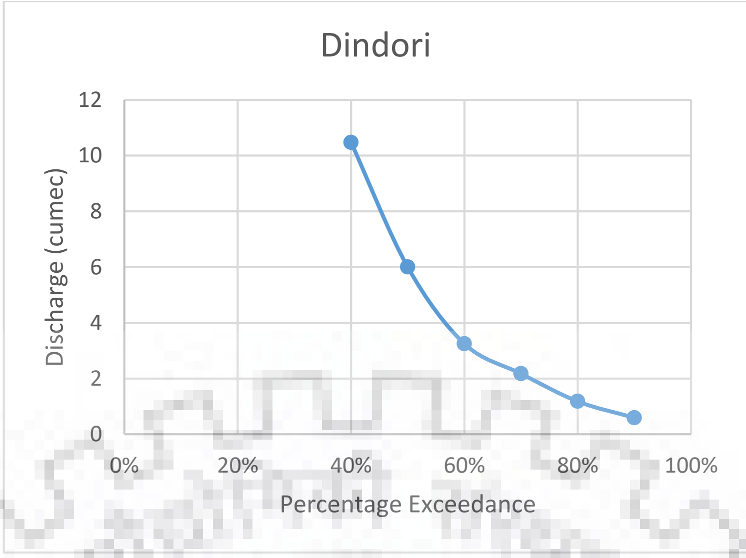


(b)

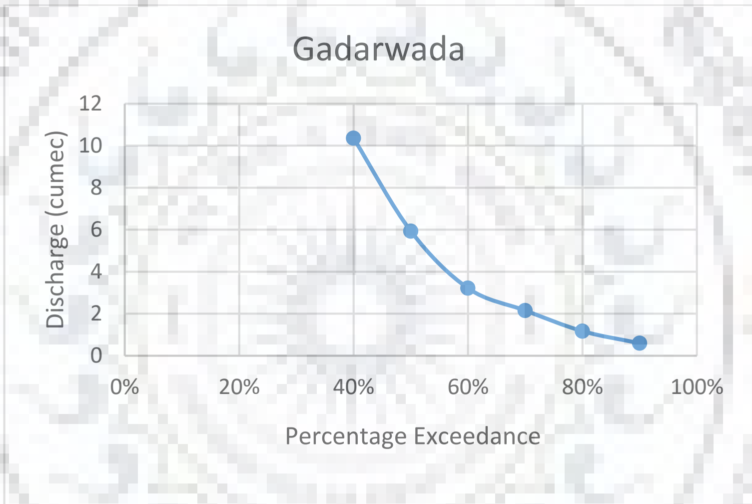


(c)

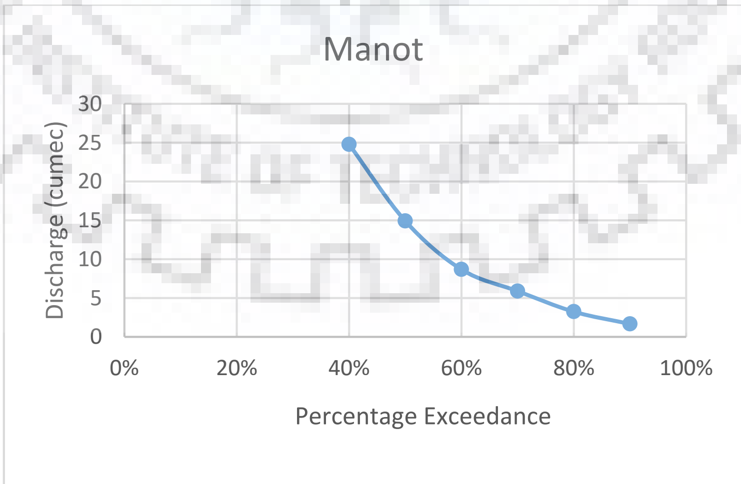
Fig. 5. 10 Regional flow duration curve for (a)Amagon (b)Bamani & (c) Barmanghat



(a)

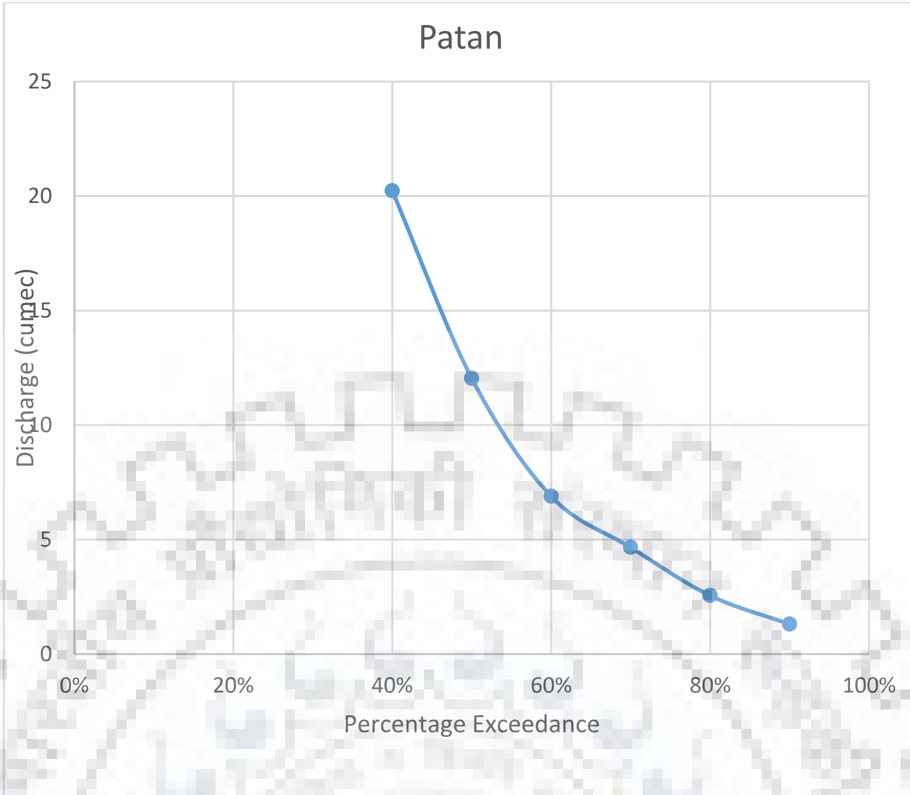


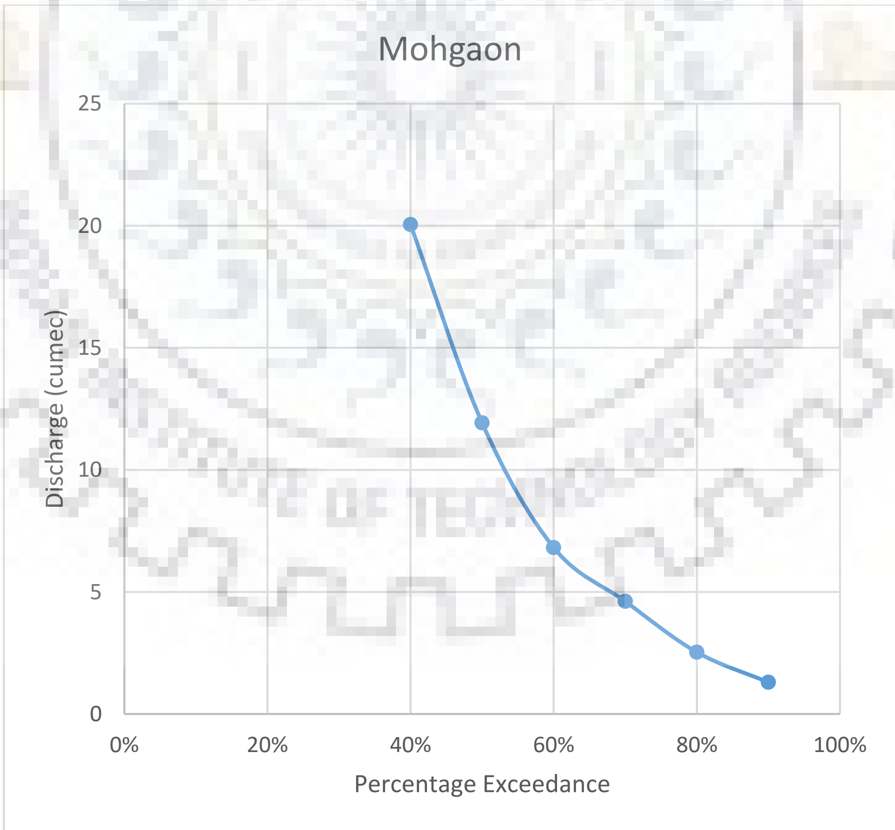
(b)

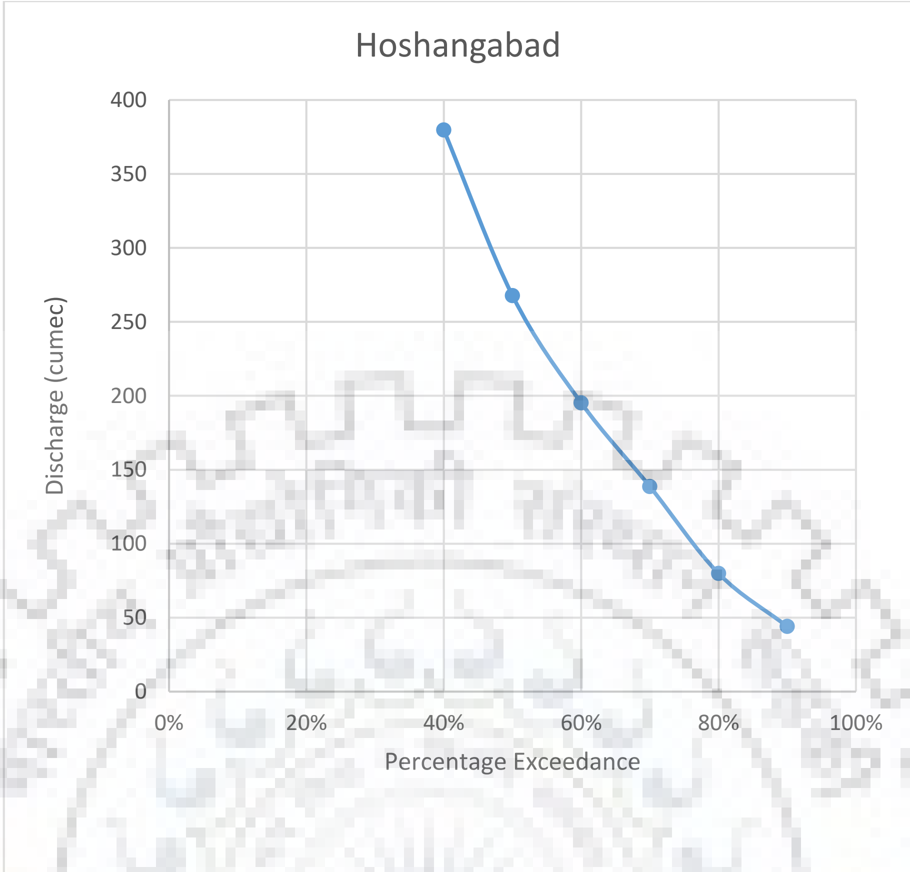


(c)

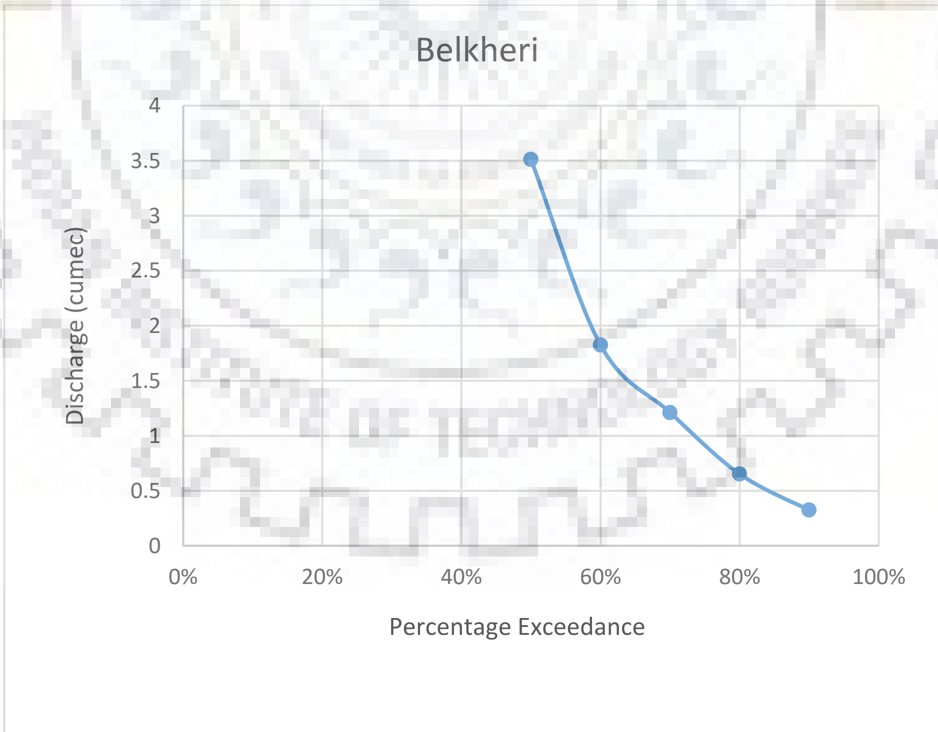
Fig. 5. 11 Regional flow duration curve for (a) Dindori (b) Gadarwada & (c) Manot


Patan
Discharge (cumec)
Percentage Exceedance
0
5
10
15
20
25
0%
20%
40%
60%
80%
100%
(a)


Mohgaon
Discharge (cumec)
Percentage Exceedance
0
5
10
15
20
25
0%
20%
40%
60%
80%
100%
(b)



(c)



(d)

Fig. 5. 12 Regional flow duration curve for (a) Patan (b) Mohgaon (c) Hoshangabad & (d) Bekhedi

- Evaluation of model performance and also the performance of all equations all tables The performance of model parameters are evaluated on the basis of percentage absolute error in dependable flows (PAEDF) which is computed using the relationship as shown as equation 5.13

$$\left|\mathbf{PAEDF} = \frac{Q_D - \hat{Q}}{Q_D}\right| * \mathbf{100} \qquad (5.13)$$

Q_D **and** $\hat{Q}$ represents the observed dependable flows and the computed dependable flows respectively corresponding to D% dependability. The computed percentage of absolute errors are well depicted in Table 5.7

Table 5. 7 Computed percentage absolute errors

Computed percentage absolute errors (PAEDF)							
Site no.	Name of sites	Computed percentage absolute errors in dependableflows Q_D (PAEDF)					
			Calibration				
		40%	50%	60%	70%	80%	90%
1	Amagon	14.37	7.34	5.19	31.70	48.02	1.19
2	Bamani	28.64	23.48	3.02	26.92	59.92	61.66
3	Barmangha	6.68	16.29	22.32	22.62	31.46	24.50
4	Dindori	23.55	38.35	50.46	55.33	62.78	65.46
5	Gadarwada	21.68	29.47	2.79	6.64	30.20	40.37
6	Manot	21.80	36.54	17.37	17.38	29.44	63.91
7	Mohgaon	50.71	57.50	47.13	76.71	124.60	294.46
8	Patan	48.79	48.51	29.68	25.02	0.17	18.47
			Validation				
9	Belkheri	212.12	315.55	211.96	170.37	97.63	31.01
10	Hoshangab	33.66	11.67	6.08	2.38	26.05	38.73

5.4.3 Method III

The Regional flow-duration curves for an ungauged site in an Upper Narmada basin is developed by transferring the non-dimensional hydrologic data between the gauged catchments of the same hydro meteorological homogeneous region. Non-dimensional flow series for the region is prepared by dividing 10 daily flow series of each gauged sites by their respective mean flows and then these non-dimensional flow series of each gauged catchment are pooled together. This resulting non-dimensional flow series is normalized using log-normal transformation for the estimation of quantiles.

Assume that Q and q respectively represent the original and non-dimensional flow series for a watershed. Then

$$q = \frac{Q}{\bar{Q}} \qquad (5.7)$$

- Development of empirical regional model theory

A regional model for the upper Narmada region is developed by relating mean flow to the drainage characteristics (catchment area (Ca), altitude (A) and (Ca/A^{2}) using selected 8 gauged catchments. The empirical equations developed are shown below. r is the correlation coefficient which is an index of goodness of fit. The higher values of r show better performance and vice versa. From equation 5.8, it is observed that there is a good correlation between the mean of the observed flows and the catchment area as the correlation coefficient is 0.97. mean flow also depends on altitude A and Ca/A^2 but their correlation coefficient is not so satisfactory as it is 0.35 and 0.87 respectively (Equation 5.10 & 5.11). It can be concluded as a catchment area and Ca/A^2 increases mean of observed flow increases and mean flow decreases with an increase in altitude. Derived relation for the basin is shown in figure 5.13. It is clearly seen from the fig that regional relationship developed for mean flow relating catchment area, most of the data points lie in an around the line of best fit. But it does not seem satisfactory for regional relation derived relating mean to flow with other drainage characteristics that are altitude (A) and (Ca/A^2).

Mean flow Q is computed using the relationship developed by correlating mean flow with catchment area (Ca) using a linear regression approach as shown in equation 5.8 and equation for dependable flows are shown below as 5.9

$$\bar{Q} = 0.0209(Ca)^{0.984}, r = 0.97 \qquad (5.8)$$

$$Q_D = 0.0041e^{1.967 Z_D}(Ca)^{0.984} \qquad (5.9)$$

Above two equations 5.8 and 5.9 are combined to compute regional dependable flows

Above equation 5.9 is used for computation of dependable flows for 8 catchments taken for calibration and two catchments considered for validation.

Mean flow is also correlated with altitude and ratio of catchment area to altitude in the following manner as shown in equation 5.10 and 5.11

$$\bar{Q} = 218540(A)^{-1.305}, r = 0.35 \qquad (5.10)$$

$$\bar{Q} = .1009(Ca/A^2)^{0.66}, r = 0.87 \qquad (5.11)$$

- Evaluation of model performance for mean flow computation

Mean flow Q is computed using the relationship developed by correlating mean flow with catchment area(Ca) using a linear regression approach as shown in equation 5.8 and it is compared with the mean flows computed using the available flow series and it is shown from figure 5.13 that coefficient of correlation (r^2) comes as 0.97 which shows that linear regression model performs well for computation of mean flow.

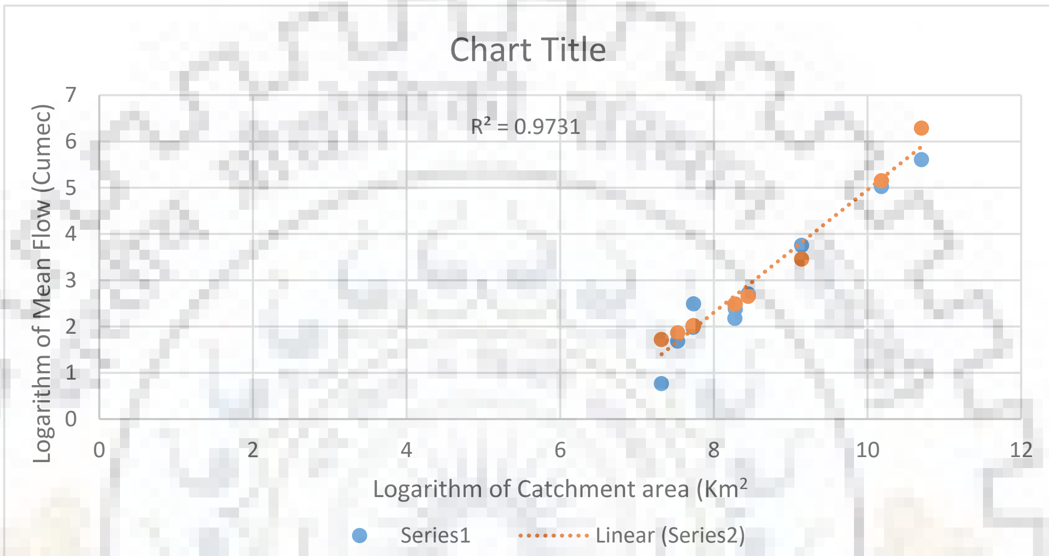


Fig. 5. 13 Evaluation of model performance using Method

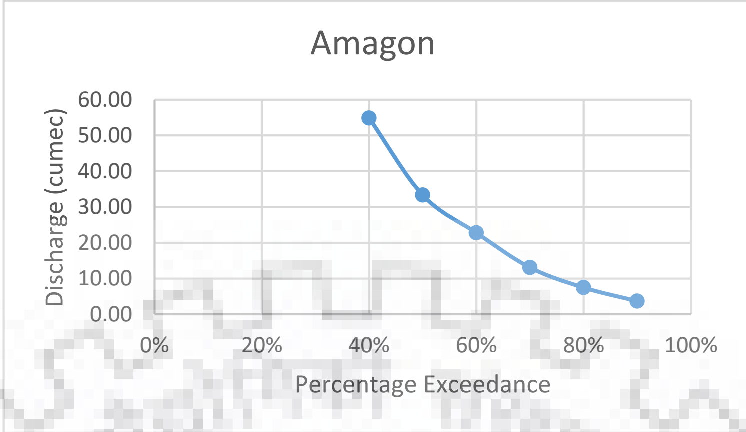
- Development of flow duration model

The non-dimensional flow series is derived from data transfer between the eight gauged watersheds of upper Narmada Basin. This series is transformed using normal and lognormal transformations. The derived statistical characteristics are shown in the table. evidently, the lognormal transformed series closely resembles a normal distribution. The Q_{D-} quantiles for various dependabilities ranging from 40% to 90% for the whole region is estimated using this characteristic of series resembles a normal distribution and these are shown in table 5.8. the result of the table and constitute a regional flow duration model for the upper Narmada basin. Two parameters lognormal distribution is fitted to the resulting non-dimensional flow series and the relationship is developed for the region as shown in equation 5.12

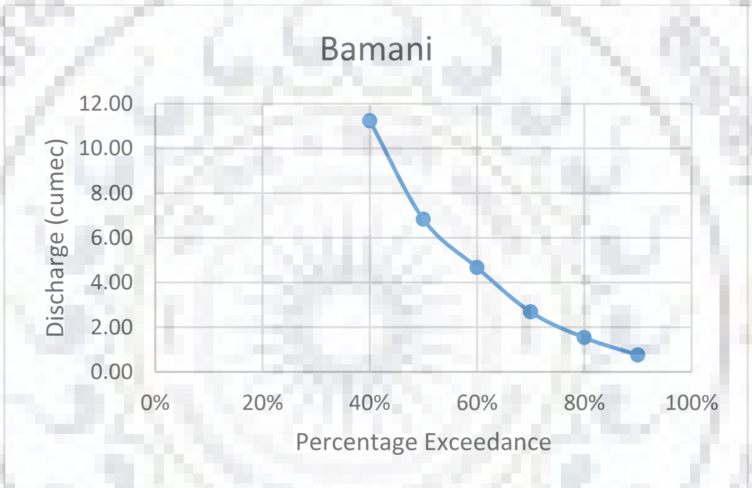
$$\log Q_D/\bar{Q} = -1.612 + 1.967\, Z_D, r = .92 \tag{5.12}$$

Table 5. 8 Computational and observed dependable flows

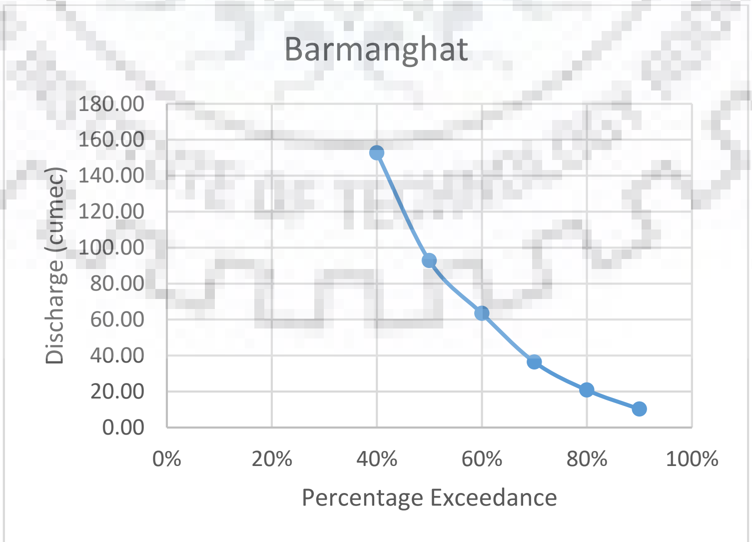
		Computed and Observed Dependable Flows													
		Computed							Observed						
		Dependable flows							Dependable flows						
		$\hat{Q}$ (Cumec)							Q_D (Cumec)						
		mean	40%	50%	60%	70%	80%	90%	mean	40%	50%	60%	70%	80%	90%
Site Sl.	Name	(cumec)							(cumec)						
number						(a)calibration									
1	Amagon	168.56	57.36	36.26	22.61	15.57	8.69	4.57	255.46	66.98	33.78	21.50	11.82	5.87	4.63
2	Bamani	34.51	8.16	4.61	2.44	1.63	0.88	0.44	31.63	11.43	6.02	2.52	1.28	0.55	0.27
3	Barmanghat	469.27	202.04	137.37	95.08	66.82	38.10	20.69	377.64	216.50	164.10	122.40	86.36	55.59	27.40
4	Dindori	42.29	10.47	6.00	3.25	2.18	1.18	0.60	41.26	13.70	9.73	6.57	4.87	3.18	1.73
5	Gadarwada	41.89	10.35	5.93	3.21	2.15	1.17	0.59	45.21	8.51	4.58	3.12	2.30	1.67	0.99
6	Manot	85.14	24.76	14.91	8.68	5.89	3.24	1.67	96.72	20.33	10.92	7.39	5.02	2.51	1.02
7	Mohgaon	71.69	20.04	11.92	6.82	4.61	2.53	1.30	75.19	13.30	7.57	4.63	2.61	1.13	0.33
8	Patan	72.25	20.24	12.04	6.89	4.66	2.56	1.31	52.42	13.60	8.11	5.32	3.73	2.56	1.61
						(b) Validation									
9	Belkheri	28.01	6.31	3.51	1.82	1.21	0.65	0.32	22.91	2.02	0.85	0.59	0.45	0.33	0.25
10	Hoshangabad	783.66	379.60	267.68	195.18	138.62	79.87	44.04	669.39	284.00	239.70	184.00	142.00	108.00	71.88



(a)

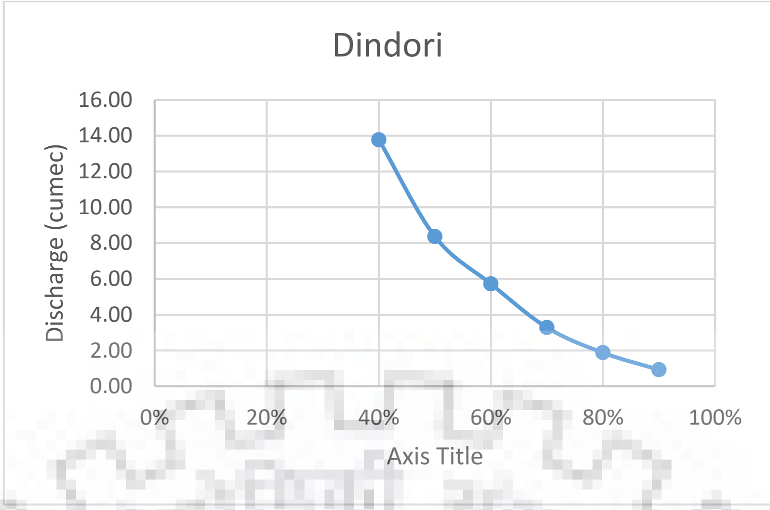


(b)

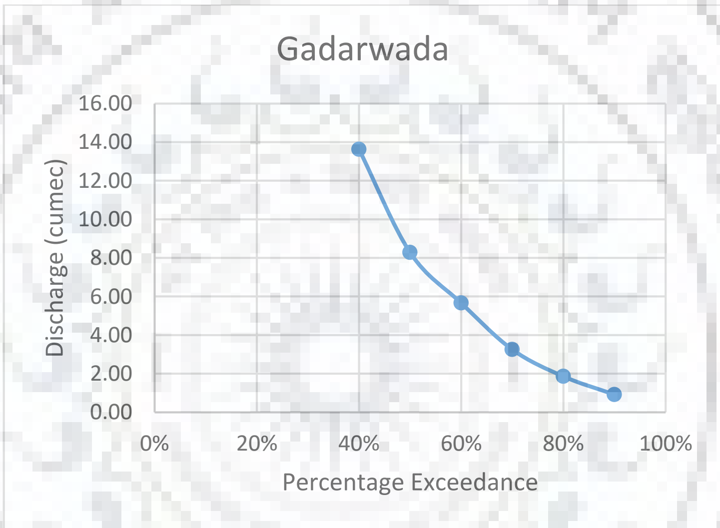


(c)

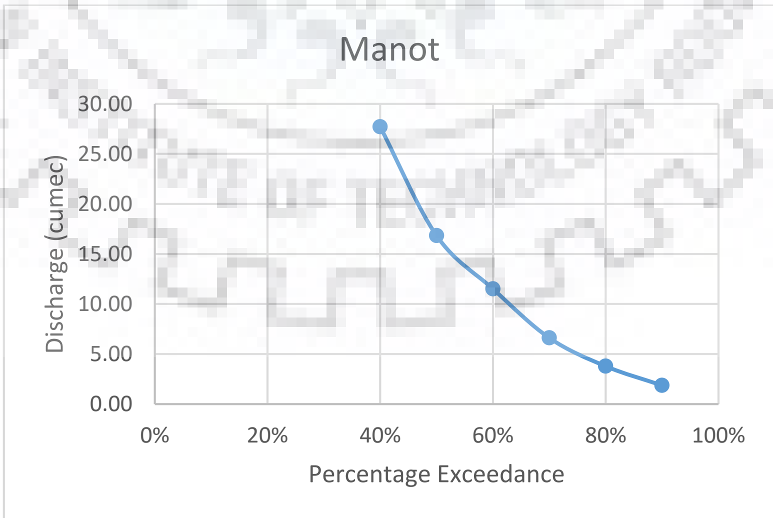
Fig. 5. 14 Regional flow duration curve for (a) Amagon (b) Bamani & (c) Barmanghat



(a)

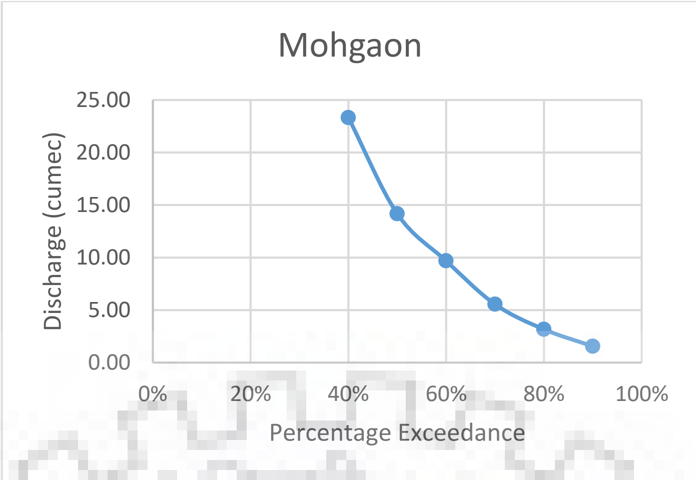


(b)

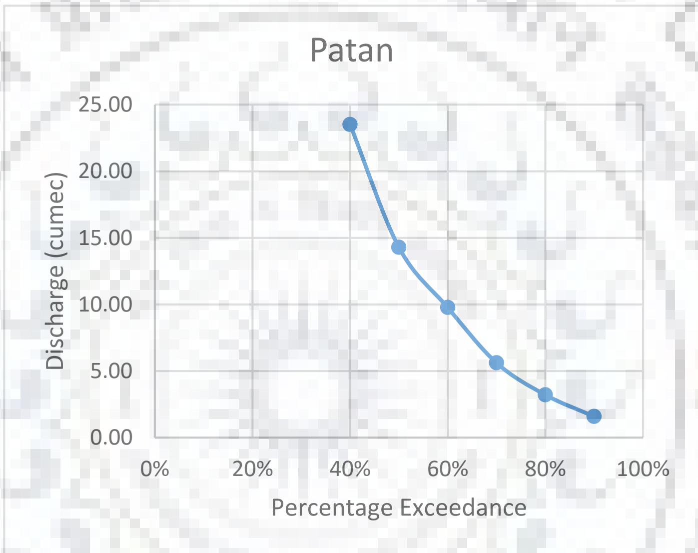


(c)

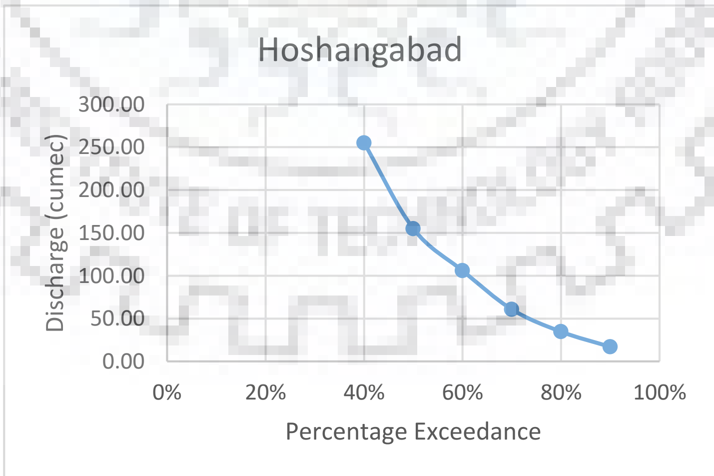
Fig. 5. 15 Regional flow duration curve for (a)Manot (b)Gadarwara & (c) Manot



(a)

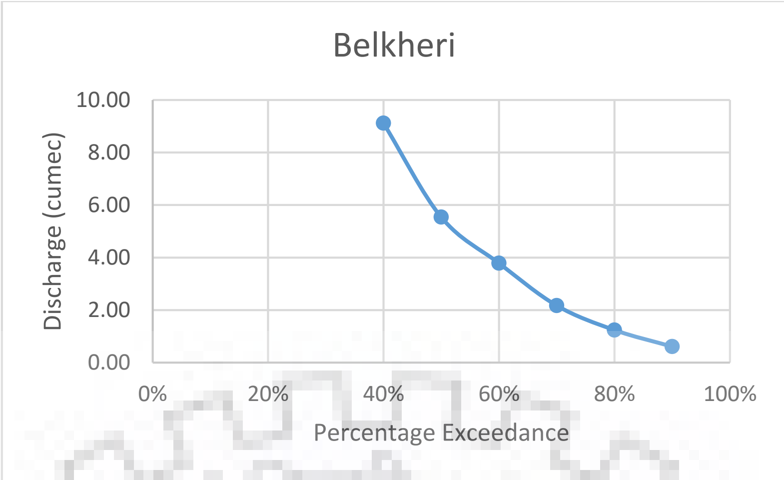


(b)



(c)

Fig. 5.15 Regional flow duration curve for (a)Mohgaon (b)patan (c) Hoshangabad (d)Belkhedi



(d)

Fig. 5. 15 Regional flow duration curve for (a)Mohgaon (b) patan (c) Hoshangabad (d)Belkhedi continued

- Evaluation of model performance

The performance of model parameters is evaluated on the basis of percentage absolute error in dependable flows (PAEDF) which is computed using the relationship as shown as equation 5.13

$$\left|\mathbf{PAEDF} = \frac{Q_D - \hat{Q}}{Q_D}\right| * \mathbf{100} \qquad (5.13)$$

Q_D **and** $\hat{Q}$ represents the observed dependable flows and the computed dependable flows respectively corresponding to D% dependability. Computed percentage absolute errors are shown in Table 5.9.

Table 5. 9 Computed percentage absolute errors

Computed percentage absolute errors (PAEDF)								
Site no.	Name of sites	(PAEDF) in mean flows($\bar{Q}$)	Computed percentage absolute errors in dependableflows Q_D(PAEDF)					
			40%	50%	60%	70%	80%	90%
				Calibration				
1	Amagon	34.02	18.12	1.35	5.97	10.65	27.25	20.49
2	Bamani	9.09	1.76	13.35	85.03	108.54	177.69	175.76
3	Barmanghat	24.26	29.47	43.46	48.18	57.84	62.57	62.60
4	Dindori	2.49	0.45	14.10	12.92	32.65	40.94	46.49
5	Gadarwada	7.33	60.22	80.91	81.38	41.33	11.22	7.21
6	Manot	11.97	36.26	54.13	55.68	31.64	50.63	82.29
7	Mohgaon	4.65	75.39	87.23	109.12	113.13	182.05	375.90
8	Patan	37.82	72.86	76.13	83.75	50.29	24.94	1.99
				Validation				
9	Belkheri	28.01	350.80	555.43	547.29	385.18	276.39	146.70
10	Hoshangabad	783.66	10.22	35.36	42.43	57.18	67.83	76.19

- Selection of watershed for error analysis

  The limited number of gauged watersheds prevented the discarding of any gauged watershed in the development of the models. Therefore, hydrological data of 10 watersheds of upper Narmada basin are used to evaluate performance (Table 5.1). Relative errors are computed for mean flows and flow quantiles. the observed flows and the derived mean and dependable flows are computed and shown. The computed relative errors are given in Table 5.9.

- Performance of equation

  Performance of equation 5.10 is also evaluated using Relative error besides correlation coefficient (r) for consistency. Table 5.9 indicates that the results of calibration while computing mean flow varies from one watershed to another as absolute relative error varies from 2% to 37%. Which shows satisfactory performance and in case of validation using 2 virtually ungauged catchments this absolute relative error varies from 17% to 22%. It can be noted that simple models perform less satisfactory invalidation as compared to calibration.

  Performance of complete regional flow duration model. The complete regional flow duration model is evaluated on the basis of relative errors in the computation of dependable flows. Total 10 watersheds are selected in upper Narmada basin, eight of them are gauged used in calibration and 2 is considered as ungauged and they are used for calibration purpose. On different watersheds, the absolute error for 40% dependable flow in calibration varies from 1.7% to 75%., for 50% dependability error range varies from 1.3% to 87%.for 60% and above dependable flows this error ranges from 2% to 370%. For some watersheds, a higher percentage of relative error may result from less availability of data for calibration. Invalidation using 2 watersheds, the absolute error for 40% dependable flow varies from 10% to 350% and for 50% dependable flow it varies from 35 % to 500%.

  For dependability 60% and higher, the absolute relative error varies from 40% to 500%., which don't show satisfactory results invalidation. These higher values of error in validation are primarily attributed to the short length of flow data (mention table) which results in non-representative mean flows.

5.7 comparison of all three regionalization procedures

All three regionalization methods are compared on the basis of percentage absolute error in the computation of dependable flows (PAEDF) in the upper Narmada basin. observed dependable flows are analyzed from the available historical data of 10 gauging sites ranging from 10 to 30 years. The computed PAEDF values of each regionalization method and plotted in figures (5.16 to 5.18). It is found regionalization method II that is regionalization of dependable flows perform more satisfactorily than the other two methods and shows good results for calibration but invalidation of Belkhedi sites results comes in much higher side .it suggests that regionalization method II is more suitable for the selected region and dependable flows can be computed for ungauged sites of the selected region.

$$\mathbf{PAEDF} = \left|\frac{Q_D - \hat{Q}}{Q_D}\right| * \mathbf{100} \qquad (5.14)$$

Q_D **and** $\hat{Q}$ represents the observed dependable flows and the computed dependable flows respectively corresponding to D% dependability. The PAEDF values are computed for each of 10 sub-basins corresponding to D% dependability ranging from 40% to 90%.

The dependable flow derived from analyzing the available flow data at various sub-basins are compared with the computed dependable flows from these regionalization methods. The percentage absolute error in Dependable flows (PAEDF) computed analytically and graphs for different dependability of flows are shown in Figure 5.10 to Figure 5.12. It is observed from the figures that the PAEDF values for regionalization method 2 are lowest for most of the catchments that indicates that method 2 performs well for the upper Narmada river basin.

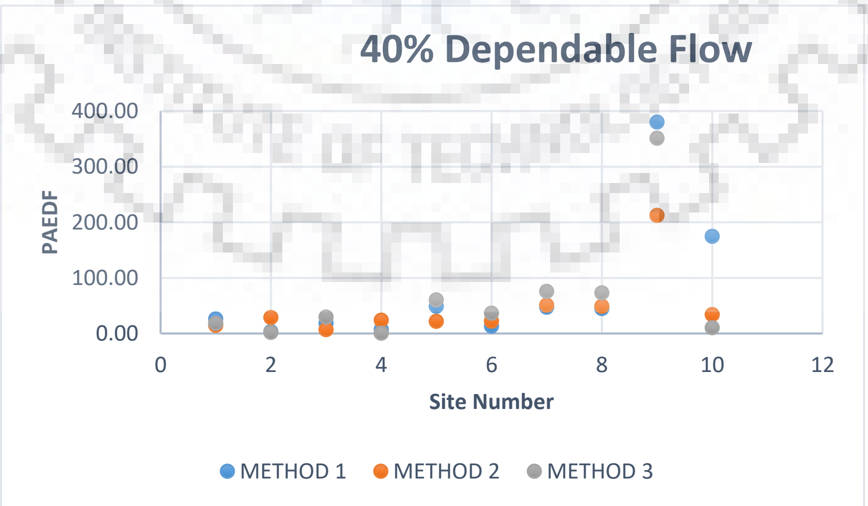
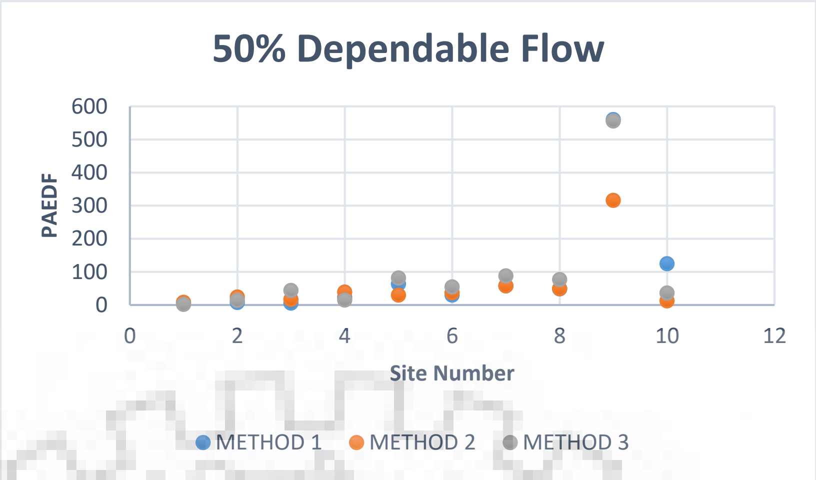
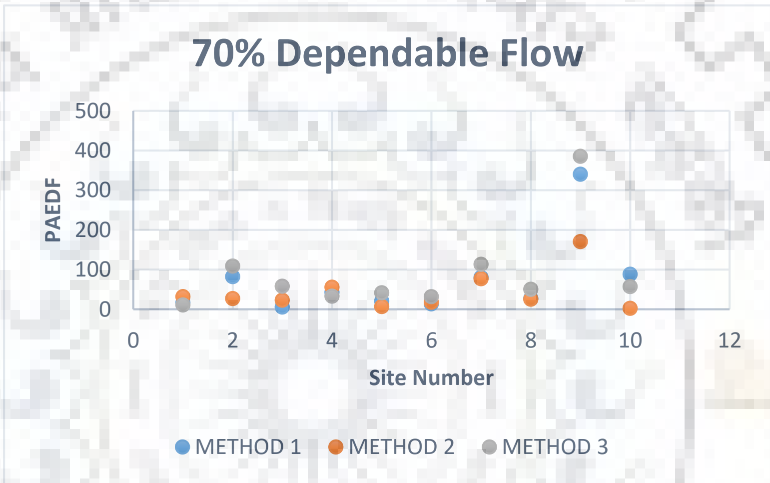


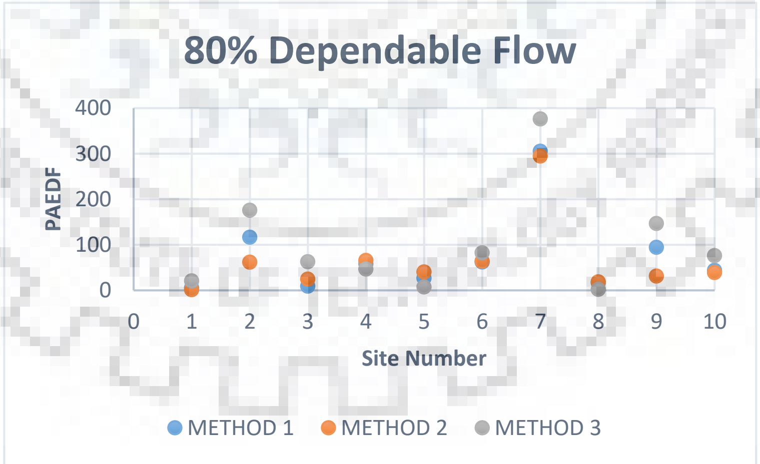
Fig. 5. 16 PAEDF for 40 % dependable flow



(b)



(c)



(d)

Fig. 5. 17 PAEDF for (a) 60%, (b) 70% & (c) 80% dependable flow

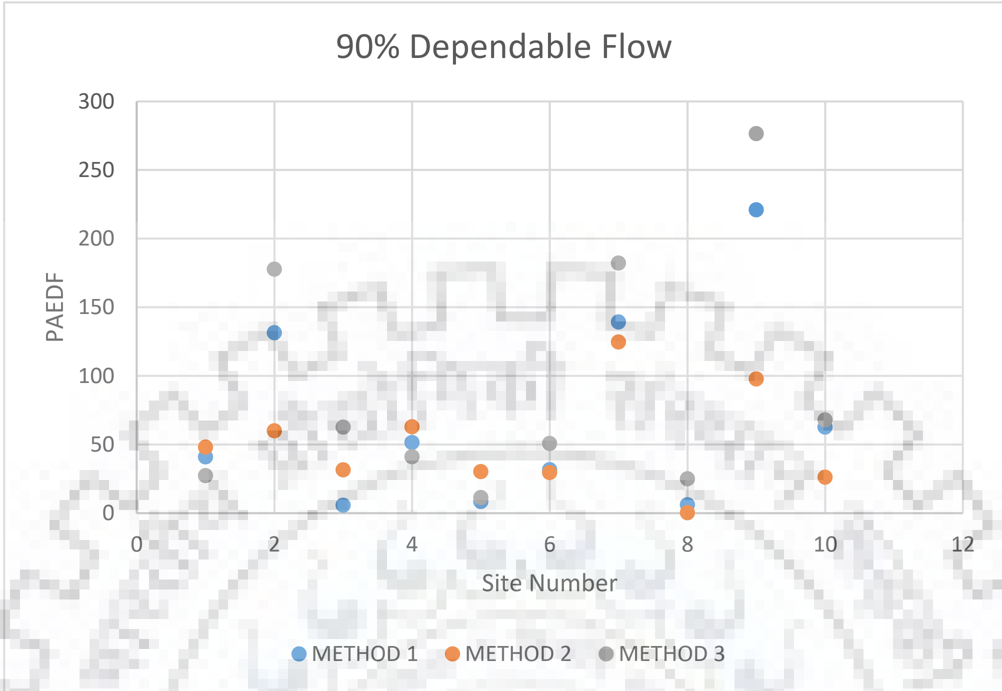


Fig. 5. 18 PAEDF for 90 % dependable flow

Chapter 6

CONCLUSIONS

6.1. CONCLUSIONS

Based on the present study following conclusions can be drawn;

1. Three regionalization methods are used to develop a regional flow duration curve of the upper Narmada river basin. total 10subbasin are selected in upper Narmada basin having an area ranging from 1508 to 44548 km^2 sub-basins are selected for calibration of the regional model developed and 2 test catchments are selected for validation purpose. 2 test catchments are selected on the basis of the catchment area with one having largest catchment area and other having the lowest catchment area. In regionalization method I parameters resemble lognormal distribution are regionalized for individual gauging sites, in regionalization method II dependable flows are regionalized for individual gauging sites and in regionalization method III parameters resemble lognormal distribution is regionalized for the whole region. All three methods are compared on the basis of percentage absolute error in the computation of dependable flows. It is found that regionalization method II that is regionalization of dependable flows performs more satisfactorily than the other two methods and shows good results for calibration but in the validation of Belkhedi sites results come in much higher side and for Hoshangabad sites, it performs well. it suggests that regionalization method II is more suitable for the selected region and dependable flows can be computed for ungauged sites of the selected region.
2. The effect of the catchment area, Altitude and (Ca/A^2) over the flow parameters are studied and it can be concluded flow parameters increases with increase in the catchment area (Ca) and decreases with increase in altitude(A).
3. On different watersheds, the absolute error for 40% dependable flow in calibration varies from 1.7% to 75%., for 50% dependability error range varies from 1.3% to 87%.for 60% and above dependable flows this error ranges from 2% to 370%. For some watersheds, a higher percentage of relative error may result from less availability of data for calibration. Invalidation using 2 watersheds, the absolute error for 40% dependable flow varies from 10% to 350% and for 50% dependable flow it varies from 35 % to 500%. For dependability 60% and higher, the absolute relative error varies from 40% to 500%., which don't show satisfactory results invalidation. These higher values of error

in validation are primarily attributed to the short length of flow data (mention table) which results in non-representative mean flows.

4. It can be concluded that regionalization method II predicts the mid-range of flows characteristics more accurately than high-flow characteristics and low-flow characteristics.in this study, it is found that catchment characteristics mainly catchment area(Ca) a is mostly related to streamflow characteristics having a coefficient of correlation(r) between mean flow and catchment area is .95 to .97. the linear regression studies have shown that the midrange of flow is more accurately estimated than the high- or low-flow characteristics. It might, therefore, be found that mean flows can be estimated from regression relations within satisfactory accuracies but that high and low flows cannot

5. 10 daily data are used to predict regional equation of mean flow by correlating it with catchment area and neglecting other catchment characteristics thus this model is not fully warranted. this model is a simple linear regression model but the results can be improved by using multiple linear regression model considering more independent variables or rainfall-runoff model coupled with a multilinear regression model.

6.2. FUTURE SCOPE

In this study, a simple linear regression model is used to evaluable dependable flows for the upper Narmada basin based on physiographic catchment characteristics only.

1. These dependable flows can be obtained more satisfactorily when multiple regression model coupled with a rainfall-runoff model is used or using other methods which involve more catchment characteristics to compute the mean flow of a region. This simple linear regression approach can be applied to whole Narmada river basin considering more gauged catchments for calibration and ungagged catchments for validation purpose.
2. The results of the simple linear regression model can be improved by using long runoff data of gauged catchments and involving more catchment characteristics in the regression model.

REFERENCES

Bloschl, G. and Sivapalan, M., (1995). Scale issues in Hydrological modeling: Hydrological Processes, Vol. 9, 251-290.

Gebeyehu,

Cheng, C.C. (1988). Hydrologic regionalization based on flow duration curve. Ph.D. dissertation, Syracuse University, NY, Unpublished

Dingman, S.L. (1978). Synthesis of flow-duration curves for unregulated streams in New Hampshire. Wat. Res. Bull., 14(6), 1481–1502

Goel N.K., 2011. Stochastic Hydrology. Lecture notes, Dept. of Hydrology, IIT Roorkee.

Goswami, M., O'Connor, K.M., 2005. Application of a conceptual rainfall-runoff simulation model to three European catchments characterised by non-conservative system behaviour. In: Proceedings of the International Conference Hydrological Perspectives for Sustainable Development, Roorkee, India, vol. 1, pp. 117–130.

Goswami, M., O'Connor, K. M., & Bhattarai, K. P. (2007). Development of regionalisation procedures using a multi-model approach for flow simulation in an ungauged catchment. *Journal of Hydrology*, *333*(2), 517–531.

Ming Li., Quanxi Shao, Lu Zhang, Francis H.S. Chiew, 2012. A new regionalization approach and its application to predict flow duration curve in ungauged basins, Journal of Hydrology, 389 (23 May 2010), 137-145.

Merz, R., and G. Blo¨schl (2004), Regionalisation of catchment model parameters, J. Hydrol., 287, 95–123.

Merz, R., G. Blo¨schl, and J. Parajka (2006), Regionalisation methods in rainfall-runoff modelling using large samples, in Large sample basin experiments for hydrological model parameterisation, edited by V. Andre´assian et al., IAHS publication n°307, Wallingford.

Neil, F., M Vogel Richard, & Members. (1990). Regional flow-duration curves for ungauged sites in Massachusetts, *116*(4), 530–549.

Oudin, L., Andréassian, V., Perrin, C., Michel, C., & Le Moine, N. (2008). Spatial proximity, physical similarity, regression, and ungauged catchments: A comparison of regionalization approaches based on 913 French catchments. *Water Resources Research*, *44*(3), 1–15. https://doi.org/10.1029/2007WR006240

Quimpo, R. G., Alejandrino, A. A., and McNally, T. A. (1983). "Regionalized flow duration curves for the Philippines." J. Water Res. Ping, and Mgmt., ASCE, 109(4), 320-330.

Riggs, H. C. (1972). "Low-flow investigations." U.S. Geological Survey Techniques of Water-Resources Investigations, Book 4, U.S. Geological Survey, Washington, D.C.

Riggs, H. C, et al. (1980). "Characteristics of low flows." J. Hydr. Engrg., ASCE, 106(5), 717-731.

Singh, R. ., Mishra, S. ., & Chowdhary, H. (2001). Regional flow - duration models for large number ungauged Himalayan catchments for planning micro-hydro projects. *Journal of Hydrologic Engineering - J HYDROL ENG*, *6*(1), 310–316.

Swain, J. B., & Patra, K. C. (2017). Streamflow estimation in ungauged catchments using regionalization techniques. *Journal of Hydrology*, *554*, 420–433. https://doi.org/10.1016/j.jhydrol.2017.08.054

Tamalew, C., & Kemal, A. (2016). Estimation of Discharge for Ungauged Catchments Using Rainfall-Runoff Model in Didessa Sub-Basin : the Case of Blue Nile River. *International Journal of Innovations in Engineering Research and Technology [Ijiert]*, *3*(9), 62–72. https://doi.org/10.1177/154193120605001782

Thomas, D. M., & Benson, M. A. (1975). Generalization of streamflow characteristics from drainage-basin characteristics. *USGS WaterSupply Paper*, *Water-Supp*, 55.

Vandewiele, G.L., Elias, A., 1995. Monthly water balance of ungauged catchments obtained by geographic regionalization. J. Hydrol. 170, 277–291.

Vogel, R. M., and Kroll, C. N. (1989). "Low-flow frequency analysis using prob- ability-plot correlation coefficients." J. Water Res. Ping. andMgmt., ASCE, 115(3), 338-357.

Vogel, R.M. and Fennessey, N.M. (1994). Flow duration curves. I: New interpretation and confidence intervals. J. Wat. Res. Plann. Mngmnt., 120(4), 485–505.

Vogel, R.M. and Fennessey, N.M. (1995). Flow duration curves. II: A review of applications in water resources planning. Wat. Res. Bull., 31(6), 1029–1039.

Wagener, T. and Wheater, H., (2006). Parameter estimation and regionalization for continuous. Journal of Hydrology, 320(1-2): 132-154.

Wright, C. E. (1970). ‘‘Catchment characteristics influencing low flows.’’ J. Water and Water Engrg., 468–471.

Razavi, T., Coulibaly, P. (2013a). “Streamflow prediction in ungauged basins: Review of regionalization methods.” ASCE J. Hydrol. Eng., 8(8): 958-975.

Razavi, T., Coulibaly, P. (2013b).”Classification of Ontario watersheds based on physical attributes and streamflow series.” J. Hydrol., 493: 81-94

Appendix

Comparison of all three regionalization procedures for computation of dependable flows using PAEDF

	40% Dependable Flow			
PAEDF	SITE	METHOD 1	METHOD 2	METHOD 3
0	1	25.98	14.37	18.12
100	2	3.14	28.64	1.76
200	3	18.18	6.68	29.47
300	4	6.99	23.55	0.45
400	5	48.76	21.68	60.22
500	6	13.02	21.80	36.26
600	7	47.01	50.71	75.39
700	8	44.78	48.79	72.86
	9	379.87	212.12	350.80
	10	174.43	33.66	10.22
	50% Dependable Flow			
PAEDF	SITE	METHOD 1	METHOD 2	METHOD 3
0	1	6.1811865	7.3355613	1.348762631
100	2	7.15326425	23.481284	13.35020673
200	3	4.9132416	16.289375	43.46473458
300	4	22.744251	38.35404	14.10285148
400	5	63.0480269	29.466845	80.91433639
500	6	29.5077031	36.542233	54.13404818
600	7	57.3867815	57.50332	87.23377481
700	8	48.0114799	48.506233	76.12700867
	9	560.020212	315.54519	555.4314883
	10	124.012783	11.674324	35.36481835

60% Dependable Flow				
PAEDF	SITE	METHOD 1	METHOD 2	METHOD 3
0	1	4.7633447	5.1860408	5.973138504
100	2	69.3842391	3.0151785	85.0315933
200	3	3.95682013	22.322498	48.17746267
300	4	23.4061821	50.463799	12.92220306
400	5	59.795848	2.7883862	81.37939438
500	6	32.0984892	17.373882	55.6794682
600	7	76.1696862	47.125211	109.1202636
700	8	54.8055904	29.676711	83.74503756
	9	524.786459	211.96024	547.2919697
	10	119.604777	6.0782561	42.43065887
70% Dependable Flow				
PAEDF	SITE	METHOD 1	METHOD 2	METHOD 3
0	1	15.750685	31.703386	10.6484629
100	2	82.1524402	26.91931	108.5366131
200	3	5.23903969	22.621425	57.83849915
300	4	42.6493108	55.325301	32.64598506
400	5	20.4473215	6.6365655	41.32585299
500	6	13.3158921	17.379085	31.64102216
600	7	80.1207235	76.71496	113.1278701
700	8	27.0919038	25.024624	50.29296803
	9	340.228247	170.36615	385.18423
	10	87.8884852	2.3798194	57.17973576

80% Dependable Flow				
PAEDF	SITE	METHOD 1	METHOD 2	METHOD 3
0	1	5.35602624	1.194391	20.4915887
100	2	116.40118	61.657896	175.764853
200	3	8.99252209	24.503281	62.5967502
300	4	57.6933392	65.456974	46.4867679
400	5	26.6859243	40.371956	7.20945159
500	6	62.1391321	63.905915	82.2858409
600	7	305.144852	294.45569	375.900388
700	8	16.4195074	18.467661	1.99396445
	9	94.3529343	31.014768	146.697197
	10	43.836754	38.72507	76.1899217

90% Dependable Flow				
PAEDF	SITE	METHOD 1	METHOD 2	METHOD 3
0	1	40.9320252	48.022118	27.2526029
100	2	131.351193	59.923242	177.689561
200	3	5.66111146	31.459428	62.5720677
300	4	51.3324074	62.778745	40.9403522
400	5	8.32457476	30.197618	11.2235605
500	6	31.549164	29.444203	50.6276324
600	7	139.135349	124.60269	182.046458
700	8	6.04588482	0.1656831	24.9376364
	9	220.868228	97.626856	276.386956
	10	62.5640096	26.049298	67.8280233