FORMULATION AND VALIDATION OF HYBRID CONCEPTUAL MODELS FOR RUNOFF GENERATION

Ph.D. THESIS

by

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INDIAN INSTITUTE OF TECHNOLOGY ROORKEE
ROORKEE - 247 667 (INDIA)
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A THESIS

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CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in the thesis entitled "**FORMULATION AND VALIDATION OF HYBRID CONCEPTUAL MODELS FOR RUNOFF GENERATION**" in partial fulfilment of the requirements for the award of the degree of Doctor of Philosophy and submitted in the Department of Hydrology of the Indian Institute of Technology Roorkee, Roorkee, is an authentic record of my own work carried out during a period from December, 2010 to June, 2018 under the supervision of Dr. M. K. Jain, Associate Professor, and Dr. M. Perumal, Professor, Department of Hydrology, Indian Institute of Technology Roorkee, Roorkee.

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

(AJAY AHIRWAR)

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

(M. K. JAIN) Supervisor	(M. PERUMAL) Supervisor

Dated:

ABSTRACT

A number of well-established conceptual and physically based modelling approaches are available for the purpose of simulation of rainfall-runoff process of various catchments. In the development of such models, the runoff is generated based on infiltration excess runoff generation concept for separating excess rainfall that generates runoff from the uniformly distributed rainfall over the catchment. Although such models are used throughout the world, one school of thought attributes the failure of some of these models to their inability to reproduce the dynamic variation of the saturated areas within the catchment, particularly in the catchments located in the humid climatic zones. The non-linear nature of catchment response to storm events could be attributed to the dynamic variation in the accumulation and horizontal movement of water in the upper layers of the soil. Accordingly, the catchments produce runoff based on the saturation excess runoff concept which considers that the runoff from any point of the catchment is generated for the incident rainfall at that point only when the soil tension water capacity requirement at that point is fully satisfied by the incident rainfall. Also, the runoff is generated for a given rainfall only from that fraction of the area of the catchment wherein the soil tension water capacity requirement is fully satisfied.

Based on the Dunne’s concept of soil moisture replenishment, depletion and redistribution mechanism, many models have been developed. Notable among them is the Xinanjiang model, which is taken as the base model in the present investigation. The Xinanjiang model represents the dynamic variation of the saturated areas through a conceptual distribution function for reproducing the catchment response with a smaller number of quasi-physically meaningful parameters for large scale catchments in humid climatic zones. While catchments of humid climate zones may follow the saturation excess runoff generation mechanism, the catchments located in dry and average climate zones may still follow the infiltration excess runoff generation mechanism. Accordingly, Hu et al. (2005) applied the concept of combined, i.e., saturation excess and infiltration excess runoff generation mechanisms, for runoff generation of three catchments of China and they showed that the combined mechanisms of runoff generation is able to reproduce the observed runoff closely for humid and semi-humid catchments. A careful study of the interpretation of Hu et al. (2005) about the concept of Horton infiltration capacity leads to the inference that it is the lumped representation of the point variability of the infiltration capacity of the pervious area of the catchments at any time during the rainfall process. This interpretation enables one to consider the Horton infiltration capacity used in the infiltration excess runoff generation mechanism takes care of the point variability of the infiltration capacity rate

throughout pervious area of the catchment. Therefore, there is a necessity for studying runoff generation of the catchment based only on Horton's runoff generation mechanism based on its interpretation given by Hu et al., (2005) for rainfall-runoff modelling. The present study uses this interpretation for runoff generation. Besides the study also uses the combined mechanisms of runoff generation using SCS-CN method and as well as saturation excess method based on Zhao et al. (1992) approach. Therefore, in the present study, the following modifications in runoff generation mechanism of the Xinanjiang model have been proposed

i) Incorporation of Soil Conservation Curve Number (SCS-CN) formulation for surface runoff generation to take care of infiltration excess runoff generation mechanism, which is ubiquitous in most of the catchments and missing in Xinanjiang model. In the proposed formulation, the spatial soil moisture capacity (WM) is considered as the function of the parameter S (maximum retention potential of soil in SCS-CN method) as proposed by Lin et al., (2014). Therefore, WM could be evaluated from average curve number of the watershed. For further computation, the parameter S is visualized as current soil water retention capacity and updated on daily basis as the difference of WM and W (which is nothing but the current soil moisture deficit of the soil), i.e. when the value of W becomes zero then S is equal to WM. Also when W reaches WM (state of saturation in soil water store zone) S is equal to zero or SCS-CN equal to 100, thus simulation of saturation excess runoff mechanism. In this way, the value of S is updated at each computational time step using the soil moisture updation procedure of Xinanjiang model. Under this model, the surface runoff is generated by SCS-CN method then remaining rainfall is infiltrates and add to the soil moisture and other components of total runoff are generated in the same way as in the original Xinanjiang model. The proposed SCS-CN inspired Xinanjiang model has been named as XIN-CN model.

ii) The proposed DVIC model is the modified form of the Hu et al. (2005) model. As the Hu et al. (2005) considered both the runoff generation mechanism i.e. saturation excess and infiltration excess runoff generation mechanism simultaneously, using both the distribution curve i.e. the distribution curve of tension water capacity and distribution curve of infiltration capacity. It is however seen that the Hu et al. (2005) model does not perform well as it was expected and also, the Hu et al. (2005) model is very complex in its runoff generation process as it uses six steps for generating surface runoff as well as ground water runoff. Therefore, a simplified and more realistic hybrid conceptual model is proposed in this study. The proposed DVIC model considers only the distribution of infiltration capacity curve for surface runoff generation, which uses only two steps for surface runoff generation and ground water runoff is generated when soil moisture exceeds the field capacity of the soil moisture. As $F_{m\Delta t}$ is the function of point soil infiltration capacity ($F'_{\Delta t}$) and the value of $F'_{\Delta t}$ is variable in nature because it varies from 0 to $F'_{m\Delta t}$ therefore, the proposed model (DVIC) shows its variability in terms of infiltration capacity distribution curve. Also the average time interval infiltration capacity $F_{m\Delta t}$, itself changes in each time interval (or daily) therefore, the proposed model (DVIC) is dynamic in nature, therefore, the model has been named as Dynamic Variable Infiltration Capacity (DVIC) model.

The performance of both the proposed hybrid XIN-CN and DVIC models and four existing variants of the Xinanjiang model viz. Zhao (1992), Nirupama (1996), Hu et al. (2005) and Lin et al. (2014) have been evaluated using observed data from 20 watersheds of different size and shape situated in different climatic zones of India. Available observed hydrological data have been split into two groups, data in one group has been used to calibrate parameters of the model, and data in other group have been used to validate the performance of the calibrated model. The performance of the models has been assessed using the statistical indices NSE, R^2, SE and RE (as %) as well as on the basis of visual assessment of hydrographs. To evaluate performance of selected models, the watershed selected for this study have been grouped into three categories as wet, average and dry based on average value of runoff coefficient. Accordingly, the watershed having a runoff coefficient more than 0.65 has been classified as a wet watershed, the watershed having a runoff coefficient between 0.36 and 0.65, has been classified as average watershed and the watershed having a runoff coefficient less than or equal to 0.35, has been classified as a dry watershed (Gan et al., 1997) representing humid, average and dry climatic conditions respectively.

Analysis of results obtained reveals that the Xinanjiang model and its other variants studied herein performs relatively poorly in estimating the discharge in catchments located in average and dry climatic zones which are mostly dominated by the infiltration excess runoff generation mechanism compared to those in humid zones, which are primarily dominated by the saturation excess runoff generation mechanism. This inference clearly indicates the inadequacy of the runoff generation mechanism adopted in the Xinanjiang model. The proposed hybrid conceptual models (XIN-CN and DVIC) can account for both infiltration excess as well as saturation excess runoff generation mechanisms based on watershed soil water status thus making them amenable

for use in all categories of catchments. Comparative evaluation of results obtained using proposed and existing four existing versions of the Xinanjiang model on hydrological data of 20 watersheds located in different climatic zones of India clearly indicate better performance of proposed models. The observed peak runoff is better simulated by proposed models. Better results in terms of close visual match between observed and model computed discharge obtained using DVIC and XIN-CN and high value on NSE both during calibration and validation periods indicate that the adoption and amalgamation of Hortonian runoff generation mechanism is very much need along with saturation excess mechanism to improve performance of the model for all catchments (i.e. in all climatic zones) in the present study. The overall performance ranking based on statistical evaluation indicators of the proposed models (DVIC and XIN-CN) and existing versions of the Xinanjiang model is indicated below

XIN-CN > DVIC > ZHAO (1992) > NIRUPAMA (1996) > LIN (2014) > HU ET AL. (2005)

The proposed models have simple structure and can simulate both infiltration excess and saturation excess runoff generation mechanisms based on catchment wetness status and can be used as a flexible tool for rainfall runoff modeling in all categories of catchments.

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NOTATIONS

The following symbols are used in this thesis:

Symbol	**Particulars**	**Dimensional Unit**
P	= Rainfall	[L]
EM	= Pan evaporation	[L]
QE	= Estimated discharge at outlet	[L]
ET	= Total Evapotranspiration	[L]
EU	= Evapotranspiration from upper soil moisture layer	[L]
EL	= Evapotranspiration from lower soil moisture layer	[L]
ED	= Evapotranspiration from lower soil moisture layer	[L]
W'	= Point tension water storage	[L]
W, W_o	= Areal mean tension water storage	[L]
WU	= Areal mean tension water storage of upper layer	[L]
WL	= Areal mean tension water storage of lower layer	[L]
WD	= Areal mean tension water storage of deeper layer	[L]
S'	= Point free water storage	[L]
S, SF	= Areal mean free water storage	[L]
R	= Total runoff	[L]
RS, R_S	= Surface Runoff	[L]
RI	= Contribution to Interflow	[L]
RG, R_g	= Contribution to Groundwater	[L]
TS	= Discharge from single linear reservoir of surface runoff	[L]
TI	= Discharge from single linear reservoir of interflow runoff	[L]
TG	= Discharge from single linear reservoir of groundwater flow runoff	[L]
K	= Coefficient of pan evaporation for calculating potential evapotranspiration	[-]
X	= Coefficient for calculating upper soil moisture layer capacity (UM)	[-]
Y	= Coefficient for calculating lower soil moisture layer capacity (LM)	[-]
C	= Coefficient for deep evaporation	[-]
WM	= Areal mean tension water storage capacity	[L]
B	= A parameter used in generating tension water storage capacity curve which also responsible for showing the heterogeneity of the soil surface of the watershed.	[-]
cm	= A parameter used in generating infiltration capacity curve	[-]
W'M	= The point soil tension water capacity	[L]
MM	= Maximum of point soil tension water capacity	[L]
S'M	= Capacity of point soil free water storage	[L]
MS	= Maximum of point soil free water storage capacity	[L]
SM	= Areal mean free water storage capacity	[L]
EX	= A parameter in exponent of the tension free water storage capacity curve it is similar to parameter B	[-]
KG	= Coefficient for Ground water generation	[-]
KI	= Coefficient for Inter flow generation	[-]

CG = Coefficient for Ground water concentration [-]
CI = Coefficient for Inter flow concentration [-]
CS = Coefficient for Surface flow concentration [-]
f/F = Fraction of the saturated area to the pervious area [-]
FR = The current runoff producing area which occurs when runoff (R) is produced [-]
f/FR = Fraction of the saturated area to the runoff producing area [-]
$\Delta W, \Delta W_o$ = Change in average soil moisture storage [L]
$\Delta S, \Delta SF$ = Change in free water storage [L]
$\Delta RSB, \Delta RI, \Delta RG$ = Change in storage due to surface, interflow, groundwater flow [L]
$W'M \sim \alpha$ = For showing saturation excess capacity curve [-]
$F'_{\Delta t} \sim \beta$ = For showing infiltration excess capacity curve [-]
B = Area fraction in which the soil infiltration capacity is less than or equal to $F'_{\Delta t}$ [-]
CN = Curve Number [-]
Ia = Initial abstraction in SCS-CN method [L]
λ = Initial abstraction coefficient varies from 0 to ∞ [-]
S = Maximum potential retention in SCS-CN method [L]
Pe = Effective rainfall after subtracting the initial abstraction [L]
Q, RCN = Runoff from SCS-CN method [L]
a = A parameter in modified SCS-CN method [-]
b = A parameter related to rainfall storm and watershed characteristics in derivation of modified SCS-CN method [-]
P5 = Antecedent rainfall of five days [L]
LU = Land Use cover practice [-]
κ = Seasonal parameter in terms of time and temperature [-]
T_s = Storm duration T
K_h = Soil index parameter [-]
N = An integer [-]
f = Rate of infiltration $[LT^{-1}$
f_c = Final constant infiltration rate $[LT^{-1}]$
f_o = Initial infiltration rate $[LT^{-1}]$
t = Time [T]
k = Decay coefficient $[LT^{-1}]$
i_o = Uniform rainfall intensity at time t = 0 $[LT^{-1}]$
i_e = Effective rainfall intensity $[LT^{-1}]$
PK = Rainfall after deducting the runoff by SCS-CN method [L]
RSB = Combined surface runoff [L]
RCN = Runoff by Curve Number Method [L]
TS, TI and TG = Represents the surface, interflow and ground water outflow discharge from the single linear reservoirs respectively [L]
QE = The total discharge at the outlet [L]
$F'_{\Delta t}$ = Point soil infiltration capacity [L]
$F'_{m\Delta t}$ = Maximum point soil infiltration capacity [L]
$F_{m\Delta t}$ = Average time interval infiltration capacity [L]
FC = Field capacity [L]
WP = Wilting point [L]
CW = A coefficient for obtaining wilting point [-]

a_1, a_2, a_3, and a_4 = Parameters used in updating Horton’s infiltration components [-]

R^2 = Coefficient of determination [-]

°C = Degree Celsius [-]

ABBREVIATIONS

The following abbreviations are used in this thesis:

amsl = Above Mean Sea Level

ANN = Artificial Neural Network

CNGRIDS = Curve Number Grids

CWC = Central Water Commission

DVIC = Dynamic Variable Infiltration Capacity

ECCHE = East China College of Hydraulic Engineering

EcoHAT = Ecohydrological Analysis Tools

GIS = Geographic Information System

GP = Genetic Programming

HEC-GeoHMS = Hydrologic Engineering Center-Geospatial Hydrologic Modeling System

HEC-HMS = Hydrologic Engineering Center-Hydrologic Modeling System

IQR = Inter Quartile Range

ISRO = Indian Space Research Organization

IWRM = Integrated Water Resources Management

KWXAJ = Kinematic Wave Xinanjiang Model

LARSIM = Large Area Runoff Simulation Model

LASCAM = Large Scale Catchment Model

LCC = Lambert Conformal Conic

MLP = Multi-Layer Perceptron

MODIS-LAI = Moderate Resolution Imaging Spectroradiometer-Leaf Area Index

NAM = Nedbor Afstromnings Model

NSE = Nash and Sutcliffe Efficiency

PSO = Particle Swarm Optimization

RBF = Radial Basis Function

RC = Runoff Coefficient

RE = Relative Error

RMSE = Root Mean Square Error

SCE-UA = Shuffled Complex Evolution - The University Of Arizona

SCS-CN = Soil Conservation Service Curve Number

SIMHYD = Simplified Hydrolog

SMAR = Soil Moisture Accounting and Routing

TIGGE = THORPEX Interactive Grand Global Ensemble

TRMM = Tropical Rainfall Measuring Mission

USA = United States of America

USDA = United States Department of Agriculture

VIC = Variable Infiltration Capacity

VSC = Varying Storage Capacity

WGS = World Geodetic System
WRIS = Water Resources Information System
XIN-CN = Xinanjiang Curve Number
XXT = Xinanjiang Hybrid Topmodel

1

INTRODUCTION

1.1 GENERAL

With the increasing demand for water with rising population over the years, and the increasing anthropogenic activities resulting in land use and climate changes the availability of usable water in the world is shrinking. As a consequence, water is becoming a scarce resource over the years and the worst scenario is in store for the future. Due to impending bleak scenario of water availability in the forthcoming years, it is essential that careful planning for utilizing and safeguarding the available water resources is very much needed. In this regard, assessment of the available water in a river basin becomes an essential component for proper water resources planning and management. Water resources management is a continuous process and, therefore, can be considered as a dynamic field of research among the scientific communities, where new objectives are constantly emerging to resolve the challenges posed with the increment in the difficulties related to water management issues (Tayfur et al., 2017; Akter and Babel, 2012). Therefore, a systematic study, proper planning and optimal operation of the water resources system are need of the hour (Ray and Sarma; 2016). To achieve this purpose, better understanding and inclusion of various hydrological processes of the rainfall-runoff process is essential. The major components of this process are the infiltration and runoff which are considered to be highly fluctuating with space and time (Sarma et al., 2016). Among these, the infiltration has been identified as a complex phenomenon which is controlled by different soil and climatological variables (Kale and Sahoo, 2011; Corradini et al., 2011). The capability of a model to simulate the rainfall-runoff process of a catchment system depends on factors such as, proper representation of catchment processes, especially, the runoff generation processes, including infiltration and evapotranspiration over the catchment system and also its absolute delineation by input parameters of the model (Jain and Singh, 2005; Tripathi et al. 2006). Therefore, a proper hydrological modelling is required for sustainable management of water resources for a better understanding of the actual runoff generation process of the catchment.

1.2 HYDROLOGICAL MODELLING

Presently, a number of well-established conceptual and physically based modeling approaches are available for the purpose of simulation of rainfall-runoff process of various catchments. In the development of such models, generally, two schools of thoughts exist for runoff generation: 1) rainfall excess mechanism and, 2) saturation excess mechanism. While the former mechanism was proposed by Horton in 1930's, the latter was introduced by Dunne (1969). The concept of runoff generation is based on infiltration excess runoff generation mechanism by which rainfall is separated in excess of the infiltration rate which in turn generates runoff from the incident rainfall over the catchment. Although such models are used ever-since the rainfall-runoff modeling exercise started throughout the world, the second school of thought attributes the failure of some of these models to reproduce the dynamic variation of the saturated areas within the catchment (Dunne, 1970). Dunne (1970) attributed this behaviour to the non-linear nature of catchment response to storm events causing the dynamic variation in the accumulation and horizontal movement of water in the upper layers of the soil. He argued that addition of more and more process components and parameters to the model may fail to reproduce the actual runoff phenomenon and reduce the model to extremely complex black boxes with an exceedingly high number of parameters to be estimated from historical data. As per the proposition of Dunne (1970), catchment produce runoff based on the saturation excess runoff concept which considers that the runoff from any point of the catchment is generated for the incident rainfall at that point only when the soil tension water capacity requirement at that point is fully satisfied by the incident rainfall. Accordingly, the runoff is generated for a given rainfall only from that fraction of the area of the catchment wherein the soil tension water capacity requirement is fully satisfied. Based on the Dunne's concept of soil moisture replenishment, depletion and redistribution mechanism, many models have been developed. Notable among them are the Xinanjiang model and its modified versions (Zhao et al., 1980; Zhao, 1992; Jayawardena and Zhao, 2000), the Variable Infiltration Capacity (VIC) model and its variants (Wood et al., 1992; Dumenil and Todini, 1992; Liang et al., 1994, 1996a; Sivapalan and Woods, 1995) and the ARNO model (Todini, 1996). These models represent the dynamic variation of the saturated areas through a conceptual distribution function for reproducing the catchment response with fewer semi-physically significant parameters for mesoscale catchments in humid climatic zones. While the catchments of humid climate zones may follow the saturation excess runoff generation mechanism, the catchments of dry and average climate zones may still follow the infiltration excess runoff generation mechanism (Beven et al., 1995; Franchini et al., 1996; and Choi and Beven, 2007; Chapi et al. 2015; Huang et al. 2016). As a storm event may not always be evenly distributed over the catchment, even in the presence of homogeneous soil characteristics over the entire catchment, it is possible some part of the catchment may follow the saturation excess mechanism, some may follow the infiltration excess mechanism and the remaining may follow both the mechanisms of runoff generation. In essence, the runoff from a catchment when subjected to a storm event may follow both the runoff generation mechanisms. Considering this concept into consideration, Hu et al. (2005) proposed a catchment model built on the concept of combined, i.e., a hybrid model based on both infiltration excess and saturation excess) mechanisms of runoff generation and tested its performance on three catchments of China and showed that the combined mechanisms of runoff generation is able to reproduce the observed runoff more closely for humid and semi-humid catchments.

1.3 SCOPE FOR INVESTIGATION OF THE XINANJIANG MODEL WHILE CONSIDERING IT AS A DYNAMIC VARIABLE INFILTRATION CAPACITY MODEL WHEN COUPLING WITH THE SCS-CN METHOD

The hybrid model given by Hu et al. (2005) is basically a modified form of the Xinanjiang model, which amalgamated the infiltration excess runoff mechanism concept with the existing saturation excess mechanism of runoff generation. But the main feature of this modified Xinanjiang model which has not been explored in detail is that the incorporation of infiltration capacity, which is varying according to soil moisture deficit (which arise from the consideration of heterogeneous nonlinearly varying saturation excess area of assumption of the Xinanjiang model) and changes on each time interval. Therefore, the concept of spatially lumped infiltration capacity itself may be considered as a most powerful feature to represent the runoff generation processes in the Xinanjiang model. In view of this perspective, there is a scope for reconsidering this hybrid Xinanjiang model, as a model which enables to consider that the infiltration capacity (Dynamic variable infiltration capacity) concept can take care of the runoff generation mechanism.

The Xinanjiang model has been developed for humid and semi-humid catchments and also it has been modified by different researchers in the past as mentioned above in the Section 1.1, but whatever modifications that were made in the Xinanjiang model, it becomes more complex and less effective for runoff production in dry catchments. Also, the modification done by Hu et al. (2005) was found to be less effective for runoff generation process even in semi-arid catchments (Ren et al. 2009). The Xinanjiang model was also modified by combining with the SCS-CN method by Lin et al. (2014) to check the change in environmental flow in different time duration by using a new relationship between maximum potential retention (S) of the SCS-CN method and the areal mean tension water capacity (WM) of the soil, used in the Xinanjiang model. Here, they proposed a good relationship between S and WM, but used it for environmental flow processes only, while that relationship could be used for runoff generation mechanism processes in the Xinanjiang model. The main aspect of the SCS-CN method for runoff generation is that it depends on the value of S. If the value of S is available then the runoff can be produced in the SCS-CN method. Basically, in the SCS-CN method, S represent the current status of the moisture deficit in the soil, which is readily available in the Xinanjiang model, i.e., the difference between WM and W (soil moisture), which is nothing but the deficit present in the soil. As the SCS-CN method works on the concept of infiltration excess runoff generation mechanism and the Xinanjiang model works on the concept of saturation excess runoff generation mechanism, then if the SCS-CN method is coupled with Xinanjiang model for the generation of runoff as the infiltration excess runoff, then the Xinanjiang model can be transformed into a hybrid-Xinanjiang model which can be more effective even for dry catchments as the SCS-CN method is known to be a more powerful method for runoff generation process.

1.4 OBJECTIVES

Keeping in view the above facts, the specific objectives of the present study are:

1. To study different models with saturation excess and infiltration excess runoff generation processes.
2. To replace the distribution curve for tension water storage capacity in the Xinanjiang model by the distribution curve of infiltration capacity for runoff generation,
3. To amalgamate the SCS-CN and Xinanjiang models for development of a hybrid model to take into account of both the infiltration and saturation excess runoff generation mechanisms.
4. To evaluate the performance of these models using hydrological data from different climatic zones in India.

1.5 SCOPE OF THE STUDY

The Xinanjiang rainfall-runoff model is a popular model applied extensively in the humid and sub-humid regions of the world for forecasting of flood, large scale hydrological study including climate change studies, and water resources planning, management and assessment. However, its performance in the Indian climatic conditions have not been extensively studied except the Kneis et al. (2014) who evaluated the quality of tropical rainfall measuring mission data for the lower Mahanadi River basin, India, in which they used the Xinanjiang model for the purpose of runoff production only. So this study will be helpful to understand the Xinanjiang model more in detail by modifying it in a systematic way as a hybrid-Xinanjiang model with SCS-CN method and remodifying its one of the modified version.

1.6 LIMITATIONS OF THE STUDY

The Xinanjiang model is a semi-distributed conceptual rainfall-runoff model, which has been applied throughout the world for different purposes of the hydrological modeling in a semi-distributed as well as in a lumped manner, as per availability of input data required to the model. Since the Xinanjiang model works in a semi-distributed manner with help of channel routing module present in the model, which can be applied in a whole basin of river simultaneously by adjoining the inflows from sub-watershed of the basin by channel routing processes however, in the present study, the Xinanjiang model has been applied in the lumped manner due to the unavailability of required input data.

1.7 ORGANIZATION OF THESIS

The thesis is arranged in Seven chapters as follows.

Chapter 1: The first chapter introduces the research problem and sets the objectives, Scope and limitations.

Chapter 2: This chapter deals with the review of literature that supports the research work of this study.

Chapter 3: This chapter deals with description of the proposed methodology of the study in terms of modification in the Xinanjiang model in a systematic manner.

Chapter 4: This chapter deals with description of the study area, compilation and processing of available data for application of existing and proposed models.

Chapter 5: This chapter deals with the results obtained through analysis of the Xinanjiang model and its modified version.

Chapter 6: This chapter summarizes and concludes the study along with its major research contributions and provides scope for future research work.

2 REVIEW OF LITERATURE

2.1 GENERAL

For planning and management of water resource, hydrological simulation models play an important role. Available hydrological models may be categories based on spatial representation of catchment (e.g. lumped, distributed), scale (e. g. space, time), process representation (e.g. empirical, physically based) technique of solution (numerical, analog, analytical) as well as based on their runoff generation mechanism. Review of literature reveals that two major runoff generation mechanisms are in use i.e. infiltration excess also known as Hortonian runoff generation mechanism or saturation excess mechanism known popularly as Dunne runoff generation mechanism or a combination of both. Horton (1933) developed a theory of infiltration for estimation of rainfall excess and improved hydrograph separation techniques. Contemporaneous with Horton's work, Lowdermilk (1934), Hursh (1936), and Hursh and Brater (1944) perceived that in humid regions, a major component of storm flow hydrograph is constituted by subsurface water movement. Later, Horton (1939) studied overland flow processes and developed a semi – empirical formula. Followed by an experimental analysis, Horton (1945) developed a theory of erosional land-form development and streamflow generation dominated by infiltration excess. Roessel (1950) detected dynamic changes in streamside groundwater flow. Based on the works of, Nielsen et al. (1959), Remson et al. (1960), Hewlett (1961a, b) among others, it was then accepted that downslope unsaturated flow can contribute to streamside saturated areas and thus generate streamflow.

For continuous stream flow simulation, Linsley and Crawford (1960) developed one of the first conceptual hydrological model for assessment of increase in the capacity of one of the water supply reservoirs of the Stanford University, USA. At the same time, a research group in the China led by Zhao and Zhuang (1963) at the East China College of Hydraulic Engineering (ECCHE) developed a probability-distributed function based approach for representation of dynamic variation of soil moisture storage capacity in a catchment (ECCHE, 1977); Zhao et al., 1980). This concept of distribution of soil moisture storage capacity was later adopted in the Xinanjiang model (Zhao et al., 1980; 1992) because it gave best agreement with observed rainfall and runoff data. It also gives a straightforward explanation for the heterogeneity of soil moisture storage capacity. This chapter deals with the brief review of the Xinanjiang model with its modifications and applications in different part of the world along with the concept of hybrid hydrological modelling.

2.2 THE XINANJIANG MODEL

The Xinanjiang model is a semi distributed conceptual rainfall runoff model developed by Zhao et al. (1980, 1992). It has been applied extensively in the humid/sub-humid regions of the world for forecasting of flood, climate change studies and water resources assessment, planning and management of water resources (Gan et al. 1997; Jayawardena, 2000; Hu et al. 2005, Lin et al .2014). The Xinanjiang model works on the concept of runoff formation on repletion of point soil tension water storage. The model has been framed in a simple structure which has been divided into four basic sub-modules as evapotranspiration, runoff production, runoff separation and runoff concentration as shown in Fig. 2.1.

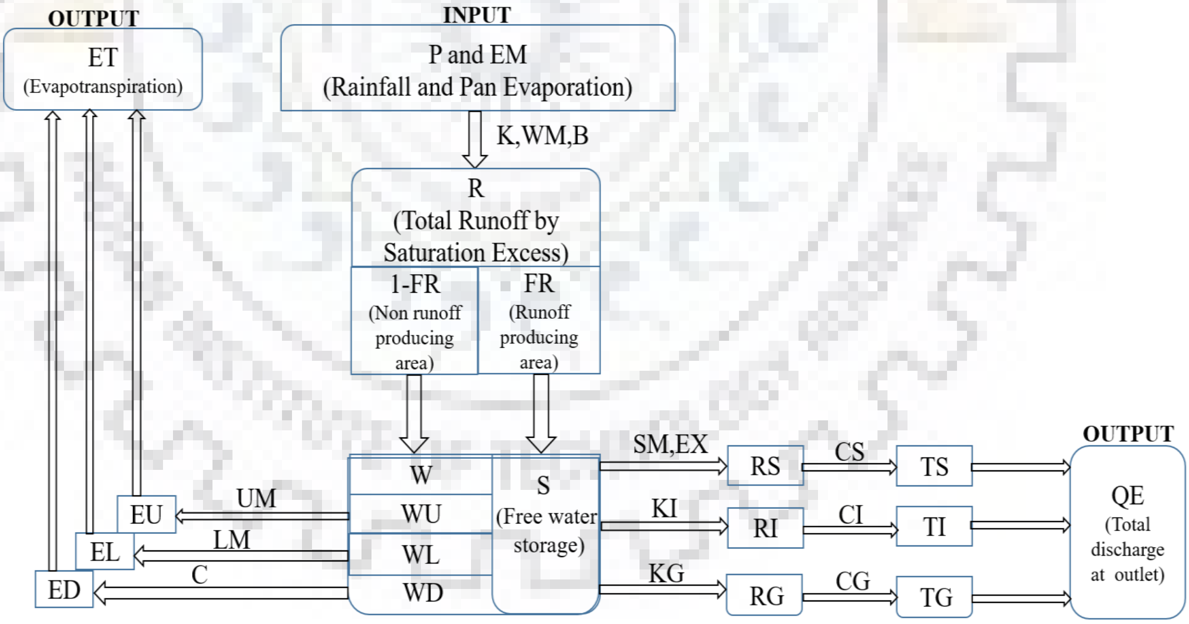


Figure 2.1. Structure of the Xinanjiang model

2.2.1 Sub-module, Variables and Parameters used in the Xinanjiang Model

The variables used in the Xinanjiang model are grouped into four categories i.e. input variables, output variables, state variables and internal variables. Similarly, the parameter used in the

Xinanjiang model are grouped in to four categories i.e. parameters used in the evapotranspiration sub-module, runoff generation sub-module, runoff separation sub-module and runoff concentration sub-module. The detail description of variables and parameters used in the Xinanjiang model are given in Table 1 and Table 2 respectively.

2.2.1.1 Evapotranspiration in the Xinanjiang model

The evapotranspiration in the Xinanjiang model is interconnected to potential evapotranspiration through a three-layer soil moisture arrangement, which depends on four parameters K, UM, LM, and C. Until the soil moisture storage of upper soil layer (WU) is exhausted or emptied, evaporation occurs at the potential rate, which is equal to the coefficient K times of the pan evaporation. When the soil moisture capacity of upper layer exhausted, the evapotranspiration starts from lower layer at potential rate but at a rate proportionate to the soil moisture capacity of lower layer. Later the evapotranspiration reduces to a certain rate and occur up to the end of soil moisture capacity of deeper layer with the help of a parameter C. For estimating the evapotranspiration in the Xinanjiang model the following empirical equations are used:

$$EU = K \bullet EM \tag{2.1}$$

$$EL = (K \bullet EM - EU) \bullet WL/LM \tag{2.2}$$

$$ED = C \bullet (K \bullet EM - EU) - EL \tag{2.3}$$

where, EU, EL, ED are the evapotranspiration from upper, lower and deeper layer respectively. EM is the pan evaporation, WL is the soil moisture of lower layer and LM is capacity of lower layer i.e. the value of WL can be reach up to LM.

2.2.1.2 Runoff production in the Xinanjiang model

When rainfall rate is above the evapotranspiration rate, the runoff is produced at a point on repletion of the tension water storage at that point. A tension water storage capacity curve is used in the Xinanjiang model for representing non-uniform distribution of tension water storage capacity throughout the catchments. Fig. 2.2 shows a typical distribution of tension water storage capacity curve used in the Xinanjiang model represented by Eq. 2.4.

$$\frac{f}{F} = 1 - \left(1 - \frac{W'M}{MM}\right)^{B} \tag{2.4}$$

Table 2.1 Description of Variables used in the Xinanjiang Model

VARIABLES	MEANING AND DESCRIPTIONN	REMARK
P	Rainfall	Input Variable
EM	Pan evaporation	Input Variable
QE	Estimated discharge at outlet	Output Variabale
ET	Total Evapotranspiration	Output Variabale
EU	Evapotranspiration from upper soil moisture layer	Output Variabale
EL	Evapotranspiration from lower soil moisture layer	Output Variabale
ED	Evapotranspiration from lower soil moisture layer	Output Variabale
W'	Point tension water storage	State Variabale
W	Areal mean tension water storage	State Variabale
WU	Areal mean tension water storage of upper layer	State Variabale
WL	Areal mean tension water storage of lower layer	State Variabale
WD	Areal mean tension water storage of deeper layer	State Variabale
S'	Point free water storage	State Variabale
S	Areal mean free water storage	State Variabale
R	Total runoff	Internal Variable
RS	Surface Runoff	Internal Variable
RI	Contribution to Interflow	Internal Variable
RG	Contribution to Groundwater	Internal Variable
TS	Discharge from single linear reservoir of surface runoff	Internal Variable
TI	Discharge from single linear reservoir of interflow runoff	Internal Variable
TG	Discharge from single linear reservoir of groundwater flow runoff	Internal Variable

Table 2.2 Description of Parameters used in the Xinanjiang Model

PARAMETERS	MEANING AND DESCRIPTIONN	REMARK
K	Coefficient of pan evaporation for calculating potential evapotranspiration	Evapotranspiration sub-module
X	Coefficient for calculating upper soil moisture layer capacity (UM)	Evapotranspiration sub-module
Y	Coefficient for calculating lower soil moisture layer capacity (LM)	Evapotranspiration sub-module
C	Coefficient for deep evaporation	Evapotranspiration sub-module
WM	Areal mean tension water storage capacity	Runoff generation sub-module
B	A parameter used in generating tension water storage capacity curve which also responsible for showing the heterogeneity of the soil surface of the watershed.	Runoff generation sub-module
W'M	The point soil tension water capacity	Runoff generation sub-module
MM	Maximum of point soil tension water capacity	Runoff generation sub-module
S'M	Capacity of point soil free water storage	Runoff separation sub-module
MS	Maximum of point soil free water storage capacity	Runoff separation sub-module
SM	Areal mean free water storage capacity	Runoff separation sub-module
EX	A parameter in exponent of the tension free water storage capacity curve it is similar to parameter B	Runoff separation sub-module
KG	Coefficient for Ground water generation	Runoff separation sub-module
KI	Coefficient for Inter flow generation	Runoff separation sub-module
CG	Coefficient for Ground water concentration	Runoff concentratioin sub-module
CI	Coefficient for Inter flow concentraion	Runoff concentratioin sub-module
CS	Coefficient for Surface flow concentration	Runoff concentratioin sub-module

Where, f/F represents the proportion of the pervious area of the watershed whose tension water capacity is less than or equal to W'M, B is a parameter to change the shape of the curve and also it represents the heterogeneity of the soil.

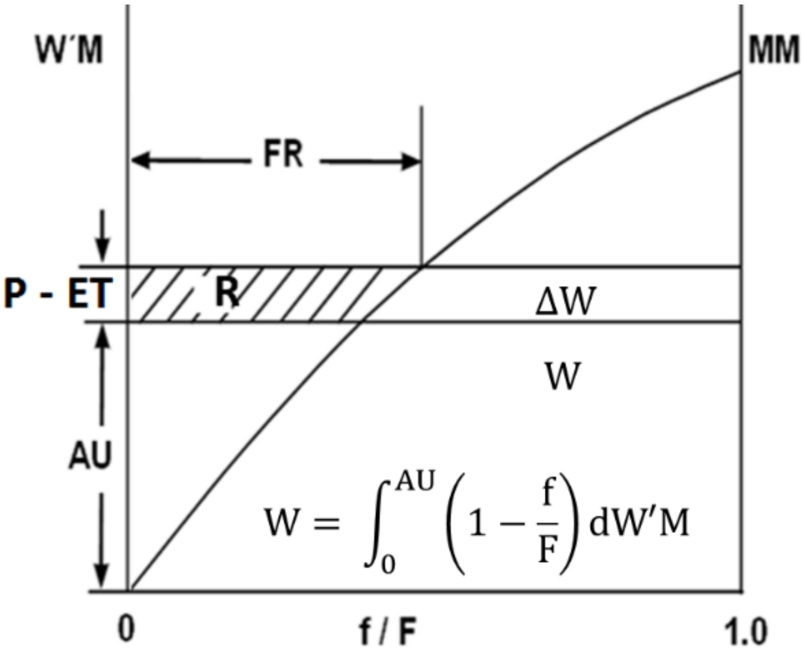


Figure 2.2. Distribution of tension water storage capacity curve in the Xinanjiang model

In the Fig. 2.2, AU represents the current state of the areal mean tension water storage (W). The area under the curve represents the areal mean tension water storage capacity (WM). The value of parameter MM which is the maximum of point soil tension water capacity, is calculated as follows:

$$MM = WM\,(B + 1) \tag{2.5}$$

Runoff generation: In the Xinanjiang model, first the total runoff is estimated and thereafter it is separated in to different runoff components. The formulation for saturation excess runoff generation mechanism in the Xinanjiang model is given as follows:

If (P – ET + AU) < MM, then

$$R = \int_{AU}^{AU+P-ET} \frac{f}{F} dW'M$$

$$R = P - ET - (WM - W) + WM\left(1 - \frac{P - ET + AU}{MM}\right)^{B+1} \tag{2.6}$$

Otherwise,

$$R = P - ET - (WM - W) \tag{2.7}$$

where, R is the total runoff and P is the rainfall.

2.2.1.3 Runoff Separation in the Xinanjiang model

After generating the saturation excess, total runoff (R) is separated into its three components as surface runoff (RS), ground water runoff (RG) and interflow (RI). For separation of generated runoff, the concept of free water storage S´ and free water storage capacity S´M is used. The value of S´M varies from zero to a parameter MS over runoff producing area FR. FR is the current runoff producing area which occurs when runoff (R) is produced. Which is given by:

$$\mathrm{FR} = \frac{\mathrm{R}}{\mathrm{P} - \mathrm{ET}} \tag{2.8}$$

For a non-uniform distribution of free water storage capacity throughout the catchments, a free water storage capacity curve is used in the Xinanjiang model, which is similar to tension water storage capacity curve and the total runoff R generated is expressed as the depth P – ET over the runoff producing area FR of the watershed.

$$\frac{\mathrm{f}}{\mathrm{FR}} = 1 - \left(1 - \frac{\mathrm{S´M}}{\mathrm{MS}}\right)^{\mathrm{EX}} \tag{2.9}$$

Where, f is that portion of the watershed area for which the free water storage capacity is less than or equal to S´M.

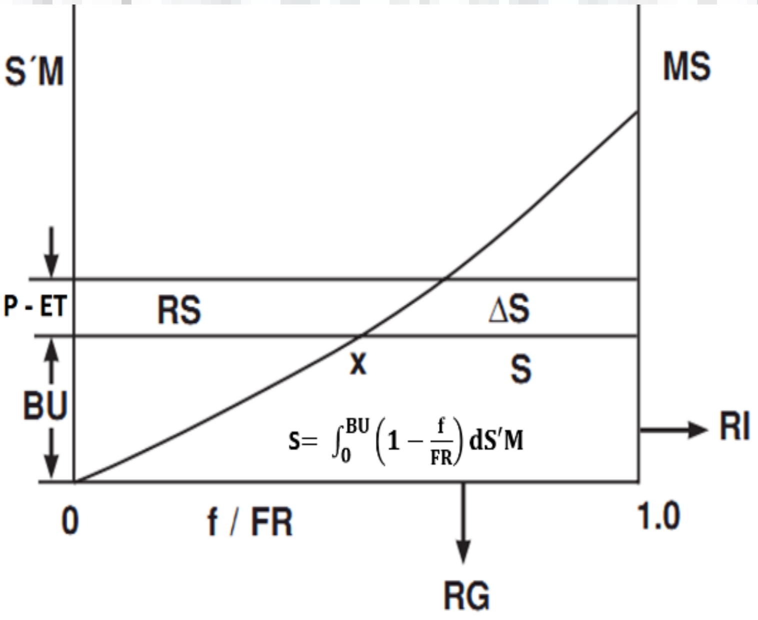


Figure 2.3 The distribution of free water storage capacity for separation of runoff components

In the Fig. 2.3, BU represents the current state of the areal mean free water storage (S). The area under the curve represents the areal mean free water storage capacity (SM). The value of parameter MS is calculated as follows:

$$MS = SM\,(EX + 1) \tag{2.10}$$

Surface Runoff: Finally, the surface runoff (RS) is separated as follows:

If (P – ET + BU) < MS, then

$$RS = \int_{BU}^{BU+P-ET} \frac{f}{FR}\,dS'M$$

$$RS = \left[P - ET - (SM - S) + SM\left(1 - \frac{P - ET + BU}{MS}\right)^{EX+1}\right] \times FR \tag{2.11}$$

Otherwise,

$$RS = [P - ET - (SM - S)] \times FR \tag{2.12}$$

Interflow: The interflow (RI) is separated as follows:

$$RI = S \times KI \times FR \tag{2.13}$$

Ground water flow: The ground water flow (RG) is separated as follow:

$$RG = S \times KG \times FR \tag{2.14}$$

2.2.1.4 Runoff Concentration and water balance

All three components of runoff i.e. RS, RI and RG are further routed through single linear reservoir. TS, TI and TG represents the surface, interflow and ground water outflow discharge from these single linear reservoirs respectively.

$$TS_{(t)} = TS_{(t-1)} \bullet CS + RS_{(t)} \bullet (1 - CS) \tag{2.15}$$

$$TI_{(t)} = TI_{(t-1)} \bullet CI + RI_{(t)} \bullet (1 - CI) \tag{2.16}$$

$$TG_{(t)} = TG_{(t-1)} \bullet CG + RG_{(t)} \bullet (1 - CG) \tag{2.17}$$

Where, t represents the time.

Total discharge at outlet: Finally, the total discharge at outlet (QE) of the watershed is obtained by adding outflows from these single linear reservoirs.

$$QE = TS + TI + TG \tag{2.18}$$

Water Balance: For continuous simulation of runoff generation from the model, the soil moisture budgeting is essential, that can be obtained in the Xinanjiang model as:

$$W_{(t)} = W_{(t-1)} + P_{(t-1)} - ET_{(t-1)} \tag{2.19}$$

$$S_{(t)} = S_{(t-1)} + R_{(t-1)} - (RS_{(t-1)} + RI_{(t-1)} + RG_{(t-1)}) \tag{2.20}$$

$$AU_{(t)} = MM\left(1 - \left(1 - \frac{W_{(t)}}{WM}\right)^{\frac{1}{B+1}}\right) \tag{2.21}$$

$$BU_{(t)} = MS\left(1 - \left(1 - \frac{S_{(t)}}{SM}\right)^{\frac{1}{EX+1}}\right) \tag{2.22}$$

The water balance in the Xinanjiang model can be obtained as:

$$\text{Change in Storage} = \text{Inflow} - \text{Outflow} = P - (QE + ET) \tag{2.23}$$

The left side of the equation (2.23) i.e. the change in storage is obtained as the sum of all the changing storages in computational time interval. These stores represent change in storage from areal mean tension water storage ΔW, change in storage from areal mean free water storage ΔS, storages from single linear reservoirs used in the model during runoff concentration i.e. change in storage from single linear reservoir due to surface runoff (ΔRS), change in storage from interflow linear reservoir ΔRI and change in storage from ground water single linear reservoir ΔRG. Mathematically it can be given as:

$$\text{Change in Storage} = \Delta W + \Delta S + \Delta RS + \Delta RI + \Delta RG \tag{2.24}$$

Finally, the water balance in the Xinanjiang model is given as

$$\Delta W + \Delta S + \Delta RS + \Delta RI + \Delta RG = P - (QE + ET) \tag{2.25}$$

2.3 APPLICATIONS OF THE XINANJIANG MODEL

The Xinanjiang rainfall-runoff model is a popular model applied extensively in the humid/ sub-humid regions of the world for forecasting of flood, climate change studies and water resources assessment, planning and management and also in drought assessment. So, its applications are very vast, therefore, here some of the applications of the model have been reviewed which are directly relevant to the present investigation. For the present review purpose, these applications of the model have been discussed under three climatic conditions depending upon the average runoff coefficient as wet, average and dry conditions. The catchments having a runoff coefficient more than 0.65 has been classified as a wet catchment. The catchments having a runoff coefficient between 0.36 and 0.65 has been classified as average catchment. The catchments having a runoff coefficient less than or equal to 0.35 has been classified as a dry catchment (Gan et al. 1997, Durbude et al., 2011; Jain et al., 2012).

2.3.1 Wet catchments

Khan (1993) applied the Xinanjiang model in Bird creek catchment of USA for simulation of river flow, this catchment belongs to humid catchment category. He studied the behaviour of Xinanjiang model in different aspects i.e. how the Xinanjiang model works and which parameters are most responsible for runoff generation process. He found that only three of the five parameters are most responsible for runoff generation process. Also in his study he found that the evapotranspiration by three layers in the Xinanjiang model is not that much important instead only two layers can perform well in estimation of evapotranspiration in this catchment. Finally, it was concluded that simulation of discharge is satisfactory for Bird creek catchment by Xinanjiang model.

Hapuarachchi et al. (2003) applied the Xinanjiang model in Kalu river basin of Sri lanka which falls under the wet zone of the country. In their study, they used the Xinanjiang model as a conceptual watershed model, the SWAT model (Arnold et al, 1998) as a distributed watershed model and two types of ANN based modelling approaches named multi-layer perceptron (MLP) network and radial basis function (RBF) for predicting daily stream flow of the Kalu River. They concluded that the performance of the distributed model depends upon quality of input data while the performance of the conceptual model depends upon calibration of the model.

Hayakawa and Lu (2003) made an attempt to find out the more effective way to use gauged and radar- measured rainfall data for hydrological forecasting in the humid catchment of Uono River basin of Japan. They applied a distributed hydrological modelling approach by using the Xinanjiang model for runoff generation. The study basin was distributed into small grid cells and generated runoff from individual discretized cells have been routed to the basin outlet through a channel network delineated from a geographical information system. They also developed an online calibration algorithm for estimation of radar constants essential for estimation of rainfall from radar. Comparing with hydrographs calculated from gauged rainfall, the hydrographs obtained from calibrated radar rainfall showed significant improvement.

Jayawardena et al. (2006) investigated the suitability of a conceptual technique along with a data-driven technique, to model the rainfall-runoff process in southern China. The conceptual technique utilized in this study depends on the Xinanjiang model combined with geographic information system (GIS) for runoff routing and the information driven model depended on genetic programming (GP). They concluded that the conceptual model outperformed the data driven model and gave a superior representation of the rainfall-runoff transformation process, specifically the peak discharge.

Nghi et al., (2008) compared the performance of Xinanjiang model with NAM model in the Nong Son humid catchment, in the Central Vietnam and concluded that the Xinanjiang model performs relatively better in runoff production.

Liu et al. (2009) coupled the Xinanjiang model with the physically based kinematic wave method to simulate runoff and overland flow routing. They tested the developed model by dividing catchment into several hillslopes in the form of a raster grid of flow vectors representing the water flow directions. In each grid cell, the runoff yield was estimated by the Xinanjiang model, then the kinematic wave approach was applied to a ranked raster network for flow routing. The model was applied to simulate the discharge from the catchment of Huaihe River, China. A relation for estimation of Manning’s roughness with the help of a linear flood depth relationship was suggested in their study for improving flood forecasting. The results from calibration and validation process showed that the developed model worked well in estimation of stream flow discharge.

Jinkang et al. (2016) developed a new framework to assess the functions of reservoirs areas and their influence on daily peak flow attenuation for an expansive Ganjiang river basin of China. They utilized the Xinanjiang model to obtain the inflows to the reservoirs from different sub-basins of the river and outflows from the reservoirs were evaluated using reservoir operation rules. The results showed that the reservoirs reduced the peak discharge more effectively for the floods with single peak as well as for multi peak hydrographs. The proposed framework of evaluating functions of multiple reservoirs storage capacities and locations on peak attenuation was found to be valuable for flood control planning and supervision at basin scale.

2.3.2 Average catchments

Chau and Zhang (1995) applied the Xinanjiang model in semi humid Changtan watershed of northern China. They used the Xinanjiang model as a rainfall-runoff model and the Muskingum method was used for the channel routing, with the help of an expert system of flow routing. They concluded that the expert framework can be utilized as an instrument for supporting civil engineers to manage the challenges of flow routing on a river network and for instructors as an instructing material to display the models and their application.

Yun et al. (2012) investigated the impacts of climate variability and vegetation change on stream flow by using modified Xinanjiang-ET and SIMHYD-ET models in the Crawford River catchment, a tributary of the Glenelg River, Australia. The results show that the plantation reduces streamflow by 20.5 mm/acre and variability of climate reduces the stream flow by 11.9 mm/acre. It is suggested that the increase in plantation can reduce stream flow more than that of the climate change.

Duan and Mei (2014) presented a comparative study of hydrological, meteorological and agricultural drought due to climate change using data from different General Circulation Models (GCMs), under different emission scenarios. They used three hydrological models as Xinanjiang model (Zhao 1992), SIMHYD model (Chiew et al. 2002) and HBV model (Seibert 1997) to investigate drought variations from 1961–2000 and 2061–2100 in Huai River basin in China. Drought frequency and duration projected with Xinanjiang model were found to be more from meteorological to hydrological and agricultural drought. Their results reveal that under the same climatic conditions, the selection of hydrological models can propel the major differences in drought simulations. Also while recognizing frequency of extreme drought and maximum drought duration, the role of hydrological model uncertainty may become dominating among the other uncertainty sources.

Hongxia et al. (2009) used the polar-orbiting terra satellite-leaf area index (MODIS-LAI) data into Xinanjiang rainfall–runoff model and evaluated the performance of the model using data from 210 catchments in south-east Australia located predominantly in semi- humid and semi-arid climatic conditions with runoff coefficient ranging from 0.1 to 0.7. The outcomes demonstrate that the incorporation of LAI information enhances both the model calibration results as well as runoff prediction in ungauged catchments.

Bai et al. (2016) comprehensively evaluated two versions of the Xinanjiang model (one with 14 parameter set and another with only 7 parameter sets) for streamflow prediction in ungauged basins based on their efficiency, parameter identifiability, and independence. They tested performance of these models using data from twenty-six mountainous catchments having limited anthropogenic influences as test catchments. These test catchments are located in the Poyang Lake basin which is the largest freshwater lake in China. They showed that the Xinanjiang model with 14 parameters was more flexible than the simple Xinanjiang model with only 7 parameters in calibration process. However, these two versions of the model showed similar performance in validation and regionalization process. They concluded that the lack of parameter identifiability and the presence of parameter interdependence most likely explain why the complex Xinanjiang model with 14 parameters could not consistently outperform the Xinanjiang model with only 7 parameters in different modes. Therefore, the simple Xinanjiang model with 7 parameters is a better choice than the Xinanjiang model with 14 parameters for streamflow prediction in ungauged basins.

2.3.3 Dry Catchments

Gan et al. (1997) evaluated performance of Xinanjiang model alongside SMAR model (O'Connell et al., 1970; Kachroo, 1992), Sacramento model (Burnash et al., 1973, Gosain A. K. et al., 1980), Pitman model (Pitman, 1976) and NAM model (DHI, 1982) in three medium sized dry catchments situated in Africa and USA. They showed that the Xinanjiang model performed consistently better in the studied catchments as compared to other studied models, because Xinanjiang model is the only model that considers the non-uniform distribution of runoff producing areas for runoff generation process, which is very important for dry catchments. In modelling dry catchments, they recommended that users should be careful in selecting the models, calibration data and the objective function to be applied to their catchments.

He et al. (2010) presented a case study utilizing the TIGGE (THORPEX Interactive Grand Global Ensemble) database for flood warning in the Upper Huai catchment, China. They adopted the Xinanjiang model as a rainfall runoff model to estimate the discharge for flood events. They showed that by coupling the atmospheric data as TIGGE database and hydrologic model as Xinanjiang model is a promising tool for producing forecasts of discharge comparable with the observed discharge and can possible to deliver a fairly reliable warning as early as 10 days in advance. The TIGGE archive, found to be more effective to hold the great benefit for flood management and preparedness.

Bao et al. (2011) also presented a case study by coupling the TIGGE database with the Xinanjiang model. They used the Xinanjiang model as a Grid – Xinanjiang hydrological model and applied on the Xixian catchment having dry to semi-humid climatic conditions which is situated in Henan area of China. Based on this study, they provided a probabilistic discharge estimate as the end product for flood forecasting. Results showed that the association of the TIGGE database and the Grid-Xinanjiang model gives a promising tool for an early warning of flood events several days ahead. Also they concluded that the TIGGE offers a new opportunity for flood forecast.

Qin and Huang (1998) applied the Xinanjiang model in Lake Qinghai, a large inland lake on the northeast Qinghai-Tibet Plateau in China for climate change studies. They coupled the Xinanjiang model with two other models, one was lake thermodynamic model which was used to simulate the lake surface temperature and estimation of the evapotranspiration and the second was the lake water balance model to predict the lake water level change. They concluded that the coupled model is capable for the assessment of climatic change impacts on inland lakes in arid mountainous regions.

Yuan et al. (2008) developed the a physically based two-source potential evapotranspiration model to calculate the spatiotemporal variation of potential evapotranspiration over the Hanzhong catchment in China. They combined the calculated potential evapotranspiration with the Xinanjiang model to estimate the discharge at the basin outlet. An equation similar to the Penman–Monteith equation was used in the potential evapotranspiration model to calculate different components constituting potential evapotranspiration as potential canopy transpiration, potential soil evaporation and interception evaporation. A land data assimilation system was developed for deriving the related vegetation parameters using 1 km global land cover data. Based on single grid cell test they found significant effect of land cover on the potential evapotranspiration, temporal variation and associated components. The simulated daily discharge by the Xinanjiang model using the estimated potential evapotranspiration matches well with the observed daily discharge at the catchment outlet.

Yang et al. (2011) developed a new model, named EcoHAT model, for the Songtao catchment of Hainan, based on the Xinanjiang model and SWAT model for surface runoff and pollutants transport simulation. Based on the input data concerning the agricultural practice, soil properties, land use and hydrological parameters for the Songtao catchment, the developed EcoHAT model was used to simulate the sediments, nutrients and surface runoff. They found that rainfall runoff method based on the Xinanjiang model was appropriate for the runoff volume prediction. The EcoHAT model was found to be capable for predicting the runoff volume within the range of acceptable accuracy.

Lu et al. (2013) estimate streamflow in the Luo River in a southern region of China using the Xinanjiang rainfall-runoff model. Using the PSO algorithm, the sensitivity of the model parameters, correlation between the state variables and the model computed streamflow has been determined. The Xinanjiang rainfall-runoff model was coupled with intelligent optimization algorithms for reducing the uncertainity of parameter, model structure errors and stream flow data errors. Simulation result has been analyzed for three cases (the Xinanjiang model coupled with the parameter assimilation or the state variable assimilation, or the dual data assimilation). The dual data assimilation results were superior to those for the other cases. The parameter only assimilation was found superior than the state variable only assimilation results. They found model parameters more vital than the state variable assimilation.

Kneis et al. (2014) evaluated the quality of tropical rainfall measuring mission data for the lower Mahanadi River basin, India. They used an ensemble of models such as the analytical solution by Todini (1996) for direct runoff, LARSIM (Ludwig and Bremicker, 2006) for interflow and groundwater recharge and the Xinanjiang model for estimation of runoff from saturated areas for hydrological simulation. They concluded that a true valuation would require the execution of a framework for stream flow assimilation by the hydrological model and the assessment of a long array of hindcasts. They further suggested that even if the hydrological model is perfectly initialized through continuous updating, a significant forecast error must be expected.

2.4 MODIFICATIONS TO THE XINANJIANG MODEL

Nirupama et al. (1995)

Nirupama et al. (1995) modified the evapotranspiration sub-module of the Xinanjiang model, by incorporating an energy balance method (Kondo (1994) and Brutsaert (1982)) in place of pan evaporation data. This modification to the Xinanjiang model was made due to the unavailability of the pan evaporation data, therefore a comparative analysis between original and the modified Xinanjiang model has not been shown. They applied the modified Xinanjiang model in Yodo river catchment (Area = 924.9 km^2) of Japan, having humid climatic condition. They found that the Xinanjiang model performs well in that catchment for daily runoff estimation while for hourly runoff estimation the performance of the model was found to be poorer.

Nirupama et al. (1996)

Nirupama et al. (1996) further modified the Xinanjiang model by adding a parameter ‘m’ in the equation of tension water capacity curve of the original Xinanjiang model to incorporate greater control over the tension water distribution. Fig. 2.4 shows the modified tension water distribution capacity curve given by Nirupama et al. (1996). Also in their modification, they correlated the value of parameter WM with the Gamma function. The modified Xinanjiang model given by Nirupama et al. (1996) is given by:

$$\frac{W'M}{MM} = \left[1 - \left(1 - \frac{f}{F}\right)^{\frac{1}{B}}\right]^{m-1} \tag{2.26}$$

Where all the notations are same as in the original Xinanjiang model. After correlating the parameter WM with Gamma function, the value of parameter MM was modified as:

$$\mathrm{MM} = \mathrm{WM}\frac{\Gamma(\mathrm{m}+\mathrm{B})}{\Gamma(\mathrm{m})\Gamma(\mathrm{B}+1)} \tag{2.27}$$

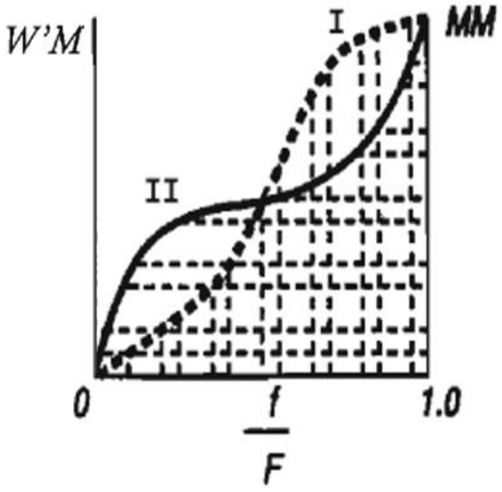


Figure 2.4 Distribution of tension water distribution capacity curve by Nirupama et al. (1996)

They used data from two humid catchments located in different regions (Kizu River in Japan and Ping River in Thailand) to test the performance of the modified Xinanjiang model. The performance of the modified Xinanjiang model was compared with four other water balance model namely, VIC model as model 1 and model 2 and two other models with different concept of runoff generation process as confined (model 3) and unconfined (model 4). However, they did not compare the performance of the modified Xinanjiang model with the original Xinanjiang model. In their results, they found that the modified Xinanjiang model is much more flexible and provide improved simulations as compare to other four models.

Jayawardena and Zhou (2000)

Jayawardena and Zhou (2000) modified the Xinanjiang model by introducing the double parabolic tension water distribution curve in place of single parabolic curve in the Xinanjiang model. In their modification, the tension water distribution curve have been divided in two parts in which the upper part of the curve represents dryness while the lower part of the curve represents wetness in the soil moisture. They further argued that the modified double parabolic curve of the Xinanjiang model could account for heterogeneity of the soil moisture variation in a more realistic manner. Under this modification, they introduced a parameter ‘c’ to represent the relative weight between the lower and the upper branches of the tension water storage capacity curve. They applied the model in Shanqiao catchment area of 131 km^2 of Pearl river, China having humid climatic conditions. They showed that the single curve (curve from original Xinanjiang model) and double curve (curve from modified Xinanjiang model) perform similarly when used in wet seasons while the double curve improves the simulation when used in dry season. Fig. 2.5 shows the modified tension water distribution curve as double parabolic curve used in the Xinanjiang model. The double parabolic curve for the modified Xinanjiang model given by them is:

$$\frac{f}{F} = (0.5-c)^{1-B}\left(\frac{W'M}{MM}\right)^{B} \quad ; \text{when} \quad 0 \le \frac{W'M}{MM} \le 0.5-c \tag{2.28}$$

$$\frac{f}{F} = 1-(0.5+c)^{1-B}\left(1-\frac{W'M}{MM}\right)^{B} \quad ; \text{when} \quad 0.5-c < \frac{W'M}{MM} \le 1 \tag{2.29}$$

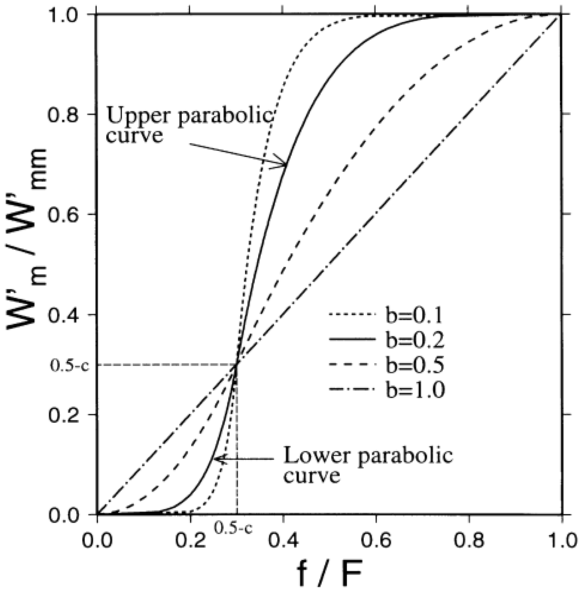


Figure 2.5 Double parabolic curve of the Xinanjiang model proposed by Jayawardena and Zhou (2000)

Li et al. (2009)

Li et al. (2009) modified the evapotranspiration sub-module of the Xinanjiang model by coupling the MODIS-LAI to the Xinanjiang model. As in the original Xinanjiang model, evapotranspiration is calculated by inbuilt three-layer soil moisture arrangement with empirical equations while in this modified version of the Xinanjiang model, evapotranspiration is calculated as single layer arrangement using Penman–Monteith equation. To assess the performance of the modified Xinanjiang model, they applied it on 210 catchments of southeast Australia. Most of catchments were in semi-arid and semi-humid regions, with runoff coefficient ranging from 0.1 to 0.7. Their result showed that inclusion of LAI for computation of evapotranspiration in to the Xinanjiang model improved the performance of the model in both calibration and validation processes for ungauged catchments.

Yang et al. (2011)

Yang et al. (2011) coupled the Xinanjiang model with SWAT model by using Eco hydrological analysis tools (EcoHAT). EcoHAT is an ecohydrological model, which is based on the concept of the ecohydrological processes in the soil-plant atmosphere continuum. It mainly contains four practices i.e. nutrient cycles, sedimentary processes, hydrological cycle and plant growth in ecosystems. In this modified Xinanjiang model, the evaporation obtained by Prestiely and Taylor was used as an input, instead of pan evaporation. They applied the modified Xinanjiang model in Songtao reservoir watershed in Hainan Island, China, falls under humid climatic condtions. In their results, they showed that the modified Xinanjiang model predicts the runoff volume in the range of acceptable accuracy. The NSE value for monthly discharge, was 0.885 in calibration process and 0.834 in validation.

Lin et al. (2014)

In another modification to the Xinanjiang model, Lin et al., (2014) considered spatial soil moisture capacity (WM) as the function of maximum soil moisture retention potential (S_I) of SCS-CN method. To effect this, they used a coefficient α for determining the spatial soil moisture capacity. The main purpose of combining the SCS-CN method to the Xinanjiang model was to assess the change in environmental flow, by considering change in curve number of the catchments with respect to time. To assess the performance of the modified model, they applied it in three catchments of the Dongjiang River basin of China, having subtropical climatic conditions with average annual temperature ranging from 20 - 22 ºC. They showed that the modified Xinanjiang model simulated the runoff within an acceptable accuracy. The NSE value was found more than 0.70 for all studied catchments in both calibration and validation processes. The relationship suggested by them is:

$$WM = \alpha.S_I \tag{2.30}$$

Where, α is the coefficient. The value of S_I could be obtained by generating the curve number grid of the watershed.

2.5 HYBRID CONCEPTUAL HYDROLOGICAL MODELS

Considering the complex nature of runoff generation process, numerous hydrological models are being developed in order to explain such a complex phenomenon. The concept of hybrid hydrological modelling may resolve the problems associated with uneven pattern of rainfall, heterogeneity of watersheds in terms of soil and runoff generation processes. The hybridization of hydrological models may include the combination of two hydrological models, combination of two techniques like the Artificial Neural Network (ANN) and the Adaptive Neural-Fuzzy Inference System (ANFIS), or combination of two runoff generation mechanisms in a single model (Chetan and Sudheer, 2006, Nayak et al. 2007, Mukerji et al., 2009). Aral and Gunduz (2003) presented the possibility of a "hybrid modeling concept" in order to resolve some issues related with the completely physics-based representation of all sub-system procedures of a watershed while Wensheng et al. (1992) built up a conceptual hybrid model in light of both the significant runoff generation mechanisms. This model was first published in Chinese language in ‘Journal of Soil and Water Conservation’ which was published later by Hu et al. (2005) in English language. Jingwen et al. (2012) also developed a hybrid rainfall-runoff model, but in this model, they combined two models in a single model, named as XXT model. The similarity in these two models is the use of the Xinanjiang model. Hu et al. (2005) modified the Xinanjiang model by incorporating the infiltration excess runoff mechanism while Jingwen et al. (2012) combined the TOPMODEL with the Xinanjiang model. There are some other models based on both the runoff generation mechanisms but not related to the Xinanjiang model, like, THALES (Moore and Grayson, 1991) and LASCAM (Sivapalan et al. 1996a, b) may be considered as the hybrid rainfall runoff models but in literature these models are knows as rainfall runoff models not as hybrid rainfall runoff models.

Hybrid model by Wensheng et al. (1992) or Hu et al. (2005)

Hu et al. (2005) modified the Xinanjiang model to consider both the runoff generation mechanisms i.e. saturation excess runoff and infiltration excess runoff generation mechanism simultaneously. To effect this, they used another distribution function for time interval infiltration capacity. Therefore, in this modified Xinanjiang model, the generation of runoff occurs using two distribution functions simultaneously. The first distribution function is the tension water storage capacity curve (α) and second is distribution curve of the infiltration capacity (β) for time interval Δt.

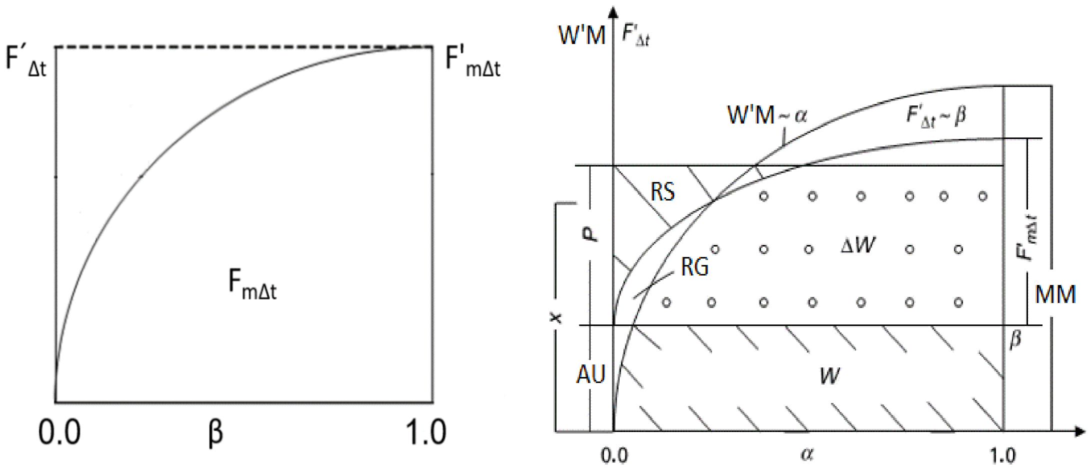
$$\alpha = \frac{\mathrm{f}}{\mathrm{F}} = 1 - \left(1 - \frac{\mathrm{W'M}}{\mathrm{MM}}\right)^{\mathrm{B}} \tag{2.31}$$

For a time interval Δt, the distribution curve of the infiltration capacity has been expressed as:

$$\beta = 1 - \left(1 - \frac{F'_{\Delta t}}{F'_{m\Delta t}}\right)^{cb} \tag{2.32}$$

Where, cm is the parameter similar to parameter B, $F'_{\Delta t}$, is the point soil infiltration capacity, $F'_{m\Delta t}$ is the maximum point soil infiltration capacity and β is the area fraction in which the soil infiltration capacity is less than or equal to $F'_{\Delta t}$. $F'_{\Delta t}$ varies from zero to maximum $F'_{m\Delta t}$. In this model, the areal mean time interval infiltration capacity $F_{m\Delta t}$ is used in the runoff generation process. The time interval infiltration capacity of the watershed $F_{m\Delta t}$ is similar to areal mean tension water storage capacity but it changes with each time interval therefore, it is calculated in each time interval for continuous storm period until the intensity of the rainfall is above f_c, where f_c is the final constant infiltration rate used in Horton's infiltration equation. The modified model is given in detail in Hu et al. (2005). The combined form of the distribution of tension water capacity and infiltration capacity curve of the Hu et al. (2005) is given in Fig. 2.6.

To evaluate the performance of the modified Xinanjiang model, Hu et al. (2005) used hourly rainfall runoff data from three catchments with semi-humid and semi-arid climatic conditions in China and compared the results with two other models (VIC and TOPMODEL) along with original Xinanjiang model. Based on their analysis they concluded that the modified Xinanjiang model perform better in semi-arid catchments as compared to original Xinanjiang model. This study emphasized on need for inclusion of infiltration excess runoff generation mechanism into rainfall– runoff models for use in arid and semi-arid areas. However, Ren et al. (2009) applied modified Xinanjiang model of Hu et al. (2005) in semi-arid catchments of northeast China and showed that the modified Xinanjiang model performed poorer as compared to spatially varying storage capacity (VSC) model, which was developed by them.



(a) (b)

Figure 2.6 The distribution of infiltration capacity curve (a) and the combined form of the distribution of tension water capacity and infiltration capacity curve (b) by Hu et al. (2005)

In above Fig. 2.6, x denotes the intersecting point of the two curves i.e. tension water distribution capacity curve which is denoted here as W´M~α and infiltration capacity curve which is denoted here as $F'_{\Delta t}$~β.

Runoff generation in Hu et al. (2005) model

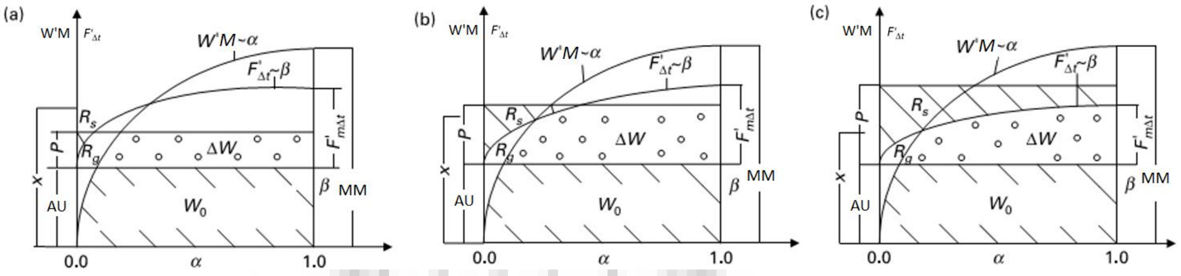
In the hybrid model proposed by Hu et al., (2005), runoff is generated based on two conditions of distribution capacity curve.

Condition 1. When both the curves i.e. the tension water storage capacity curve (α) and infiltration capacity curve (β) intersect at a point x then runoff generates using further three conditions as shown in Fig. 2.7. From Fig. 2.7 it is seen that in all three conditions the value of maximum infiltration capacity ($F'_{m\Delta t}$) is always lower than the maximum point soil tension water capacity (MM), therefore, the condition of intersection of both the curve is forming.

Condition 2. When both the curves i.e. α and β do not intersect at a point x then runoff generates using further three conditions as shown in Fig. 2.8. From fig. 2.8 it is seen that in all three conditions the value of maximum infiltration capacity ($F'_{m\Delta t}$) is always greater than the maximum point soil tension water capacity (MM), therefore, both the curve is not intersecting each other.

2.6 CONCLUDING REMARKS

A brief description of the Xinanjiang model and its modified versions along with the applications of the model have been discussed in this chapter. The Xinanjiang model was originally developed for modelling runoff from humid and semi-humid catchments, and over a period of time have become useful in flood forecasting and climatic change studies.

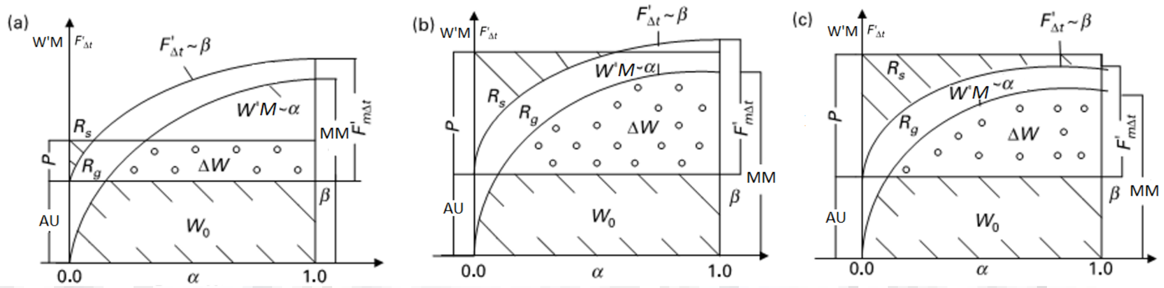


$P + AU \leq X$; $X \leq AU + P \leq F'_{m\Delta t}$; $AU + P \geq W_o + F'_{m\Delta t}$

$$R_S = \int_0^P \beta dF'_{\Delta t} \quad ; \quad R_S = \int_0^P \beta dF'_{\Delta t} \quad ; \quad R_S = P - \int_0^{F'm\Delta t} (1-\beta) dF'_{\Delta t}$$

$$R_g = \int_0^{AU+P} \alpha dW'M - \int_0^P \beta dF'_{\Delta t} \ ; \quad R_g = \int_{AU}^{X} \alpha dW'M - \int_0^{X-AU} \beta dF'_{\Delta t} \ ; \quad R_g = \int_{AU}^{X} \alpha dW'M - \int_0^{X-AU} \beta dF'_{\Delta t}$$

Figure 2.7 Runoff generation when W´M~α and F´$_{\Delta t}$~β curves intersect at point x



$P + AU \leq MM$; $MM \leq AU + P \leq AU + F'_{m\Delta t}$; $AU + P \geq AU + F'_{m\Delta t}$

$$R_S = \int_0^P \beta dF'_{\Delta t} \quad ; \quad R_S = \int_0^P \beta dF'_{\Delta t} \quad ; \quad R_S = P - \int_0^{F'm\Delta t} (1-\beta) dF'_{\Delta t}$$

$$R_g = \int_{AU}^{AU+P} \alpha dW'M - \int_0^P \beta dF'_{\Delta t} \ ; \quad R_g = \int_0^P (1-\beta) dF'_{\Delta t} - (WM - W_O) \ ; \quad R_g = \int_0^{F'\Delta t} (1-\beta) dF'_{\Delta t}$$

Figure 2.8 Runoff generation when there is no intersection point of W´M~α and F´$_{\Delta t}$~β curves

The Xinanjiang model had undergone several modifications either by coupling with some other hydrological models or by inclusion of different input database like TIGGE database, LAI, and also by modifying its evapotranspiration module. Few attempts have also been made to modify runoff generation process. In some studies, the modification in the Xinanjiang model was found poorer for dry catchments. However, review of literature reveals that the application of the Xinanjiang model have not been studied extensively in the catchments of India having different climatic conditions. Therefore, there exists a need to check the performance of the Xinanjiang model and its variants in the catchments from India which having different climatic condition.

Review of literature reveals that due to absence of infiltration excess mechanism of runoff generation, the performance of Xinanjiang model is poorer in arid and semi-arid conditions and there exists a need to introduce hybrid model which can take care of both infiltration excess and saturation excess runoff generation mechanism with parsimonious parameters.

3

DEVELOPMENT OF HYBRID CONCEPTUAL MODELS

3.1 GENERAL

In the previous chapter, the Xinanjiang rainfall - runoff model and some of its variants were discussed along with application details of these models in different parts of the world. In some studies, the Xinanjiang model shows comparatively poor performance in rainfall runoff modelling. Therefore, many researchers attempted to improve its performance (Nirupama, 1996; Jayawardena and Zhou, 2000; Hu et al. 2005). Nirupama (1996) reasoned that the Xinanjiang model uses spatial distribution of soil water storage capacity which is inflexible in its form and, therefore, it could be made flexible in distributing soil moisture to ultimately enhance the runoff simulation process. Hu et al. (2005) opined that though the Xinanjiang model has been widely applied in different regions of the world for rainfall-runoff simulation, but its performance in arid and semi-arid regions of northern China is usually not so good as in the humid regions. Therefore, they proposed a new hybrid model, but applied it in a sub-humid catchment only. On the other hand, Ren et al., (2009) criticized the model developed by Hu et al. (2005) and they developed an alternate model which is better than the hybrid-runoff model of Hu et al. (2005) in simulating the daily runoff processes. Lin et al., (2014) stated that the Xinanjiang model performs better in humid and semi-humid catchments and, therefore, they made an attempt to further refine the Xinanjiang model so as to assess land use impact for humid and semi-humid areas of China. So it could be said that the Xinanjiang model was basically developed for applying in humid and semi-humid climatic condition of catchments, which is the main limitation of this model. Therefore, different researchers have modified the model to remove its limitations and apply it for in all catchments subjected to different types of climatic conditions. Some of the modified versions of the Xinanjiang model have been presented in this study and have been checked for their applicability under different climatic conditions. However, no researcher has studied the different versions of the modified Xinanjiang models for their applicability in catchments subjected to dry climatic conditions.

Therefore, in this study, two modified forms of the Xinanjiang model have been proposed and they are applied in catchments of different climatic conditions and compared with other forms of the Xinanjiang model. In this Chapter details on the proposed hybrid conceptual models based on the Xinanjiang model are presented. The proposed models have been applied for runoff generation in some the Indian catchments and the simulation performance of these models are studied in comparison with the simulation results of the other existing variants of the Xinanjiang model.

3.2 PROPOSED HYBRID CONCEPTUAL MODEL XIN-CN

Review of literature presented in the previous Chapter indicate that the Xinanjiang model performs better for catchments subjected to humid climatic conditions where saturation excess mechanism of runoff generation is predominant. Whereas, the performance of the Xinanjiang model is relatively poorer for catchments under arid and semi-arid climate conditions which are predominantly dominated by infiltration excess runoff generation mechanism. This could be attributed to the fact that the runoff generation in the Xinanjiang model is primarily due to saturation excess runoff generation mechanism, and non-representation of dominant runoff generation mechanism existing in most of arid and semi-arid catchments which could be considered as the primary cause for the relatively poorer performance of the Xinanjiang model in catchments subjected to arid and semi – arid climate conditions. Therefore, in this study it is proposed to amalgamate both the runoff generation processes to take care of the runoff generation mechanisms of the catchments subjected to dry climate conditions.

In the proposed formulation, the spatial soil moisture capacity (WM) is considered as the function of the maximum retention potential (parameter S in SCS-CN method) as used by Lin et al., (2014). With this proposition, WM could be evaluated from average curve number of the watershed. It is further proposed to consider that the parameter S as the current soil water retention capacity which is updated on daily basis as the difference of WM and W (which is nothing but the current soil moisture deficit of the soil). When the value of W becomes zero then S is equal to WM. Also when W reaches WM (state of saturation in soil water store zone) S is equal to zero or SCS-CN equal to 100. In this way, the value of S is updated at each computational time step using the soil moisture updating procedure of the Xinanjiang model. In the proposed XIN-CN model, it is hypothesized to generate the surface runoff first by the SCS-CN method, and then the remaining rainfall is allowed to infiltrate and become part of the soil moisture, and the other components of total runoff are generated in the same way as in the original Xinanjiang model.

3.2.1 Structure of the XIN-CN model

Fig. 3.1 shows the structure of the proposed XIN-CN model. As it can be seen from Fig. 3.1 that in the proposed XIN-CN model all other components of the Xinanjiang model are retained and one more component obtained as infiltration excess runoff (RCN) using the SCS-CN method is contributing to surface runoff. The updating procedure of the maximum retention potential (S) in the proposed XIN-CN model is also depicted in Fig. 3.1.

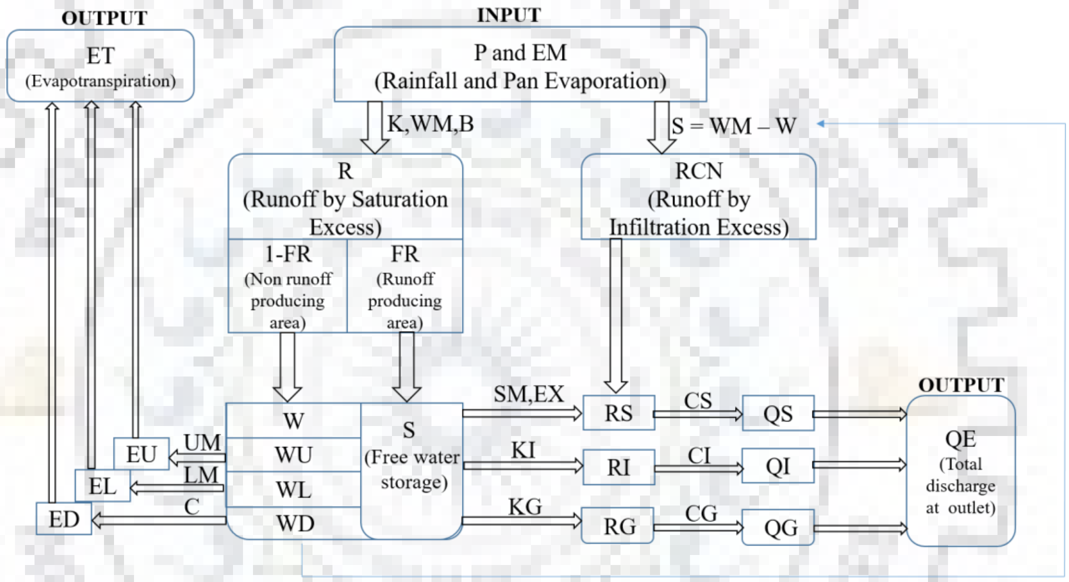


Figure 3.1 The Structure of the proposed XIN-CN model

3.2.2 Runoff generation process in the XIN-CN model

In the proposed XIN-CN model, the production of runoff takes place by both the major runoff generation mechanisms simultaneously, i.e., by the saturation as well as the infiltration excess runoff generation mechanisms, but in a systematic arrangement: first the direct runoff is produced by the SCS-CN method using the total rainfall as input and thereafter the rainfall is deducted by direct runoff and the remaining rainfall is used as input for the generation of saturation excess runoff in exactly similar way as has been adopted in the original Xinanjiang model. Thus, the direct runoff produced by the XIN-CN model is the sum of surface runoff produced by both the infiltration excess and the saturation excess runoff generation mechanisms.

Direct runoff estimated by the SCS-CN method

The SCS-CN method is based on water balance equation and two other proportionality hypotheses expressed as follows:

$$P = Ia + F + Q \tag{30}$$

$$\frac{Q}{P - Ia} = \frac{F}{S} \tag{31}$$

$$Ia = \lambda S \tag{32}$$

where, P is the total precipitation, Ia is the initial abstraction, F is cumulative infiltration, Q is the direct runoff, S is potential maximum retention of soil moisture and λ is a coefficient of initial abstraction that varies from 0 to ∞, but in general practice it is taken as 0.2 (Mishra and Singh 1999, 2003, Jain et al, 2012). For estimating direct runoff, the popular form of the SCS-CN method is obtained by combining the equations (30 – 32) as follows:

$$Q = \frac{(P - Ia)^2}{(P - Ia + S)} \quad \text{for } P \geq Ia \quad \text{and } Q = 0, \text{ otherwise} \tag{33}$$

or

$$Q = \frac{(Pe)^2}{(Pe + S)} \tag{34}$$

$$S = \frac{25400}{CN} - 254 \tag{35}$$

where, Pe is effective rainfall after subtracting the initial abstraction i.e. Pe = (P – Ia), and CN is the Curve Number that varies between 0 and 100. For CN = 100, the value of S becomes zero, which shows that there is no more capacity of soil to retain the moisture, i.e. the direct runoff is equal to Pe and for CN = 0, the value of S becomes ∞, which indicate that the soil has infinite potential to absorb the water which results the direct runoff equals to zero. The equations (33) or (34) are valid only if Pe > 0.0 otherwise, Q = 0.0.

In this study, the modified form of the SCS-CN method (Mishra and Singh, 1999, 2003) has been used to compute the direct runoff or infiltration excess runoff. The direct runoff by the modified SCS-CN method is obtained as follows:

If Pe > 0.0, then

$$\mathrm{RCN} = \frac{\mathrm{Pe}^2}{\mathrm{a.Pe} + \mathrm{S}} \qquad (36)$$

Otherwise,

$$\mathrm{RCN} = 0$$

where, RCN is direct runoff and ‘a’ is a parameter obtained through optimization.

The value of S linked to the tension water storage deficit, as explained earlier, is expressed as

$$\mathrm{S} = \mathrm{WM} - \mathrm{W} \qquad (37)$$

Derivation for modified SCS-CN method as a generalized form of the Mockus method

Mockus (1949) used the concept of Sherman (1949) of plotting the direct runoff with rainfall and then proposed a rainfall-runoff relationship expressed as:

$$\mathrm{Q} = \mathrm{Pe}\left(1 - 10^{-\mathrm{bPe}}\right) \qquad (38)$$

where, b is the parameter related to rainfall storm and watershed characteristics as:

$$\mathrm{b} = \frac{0.0374(10)^{0.229\mathrm{P5}}(\mathrm{LU})^{1.061}}{\kappa^{1.990}\mathrm{T_s}^{1.333}(10)^{2.271(\mathrm{K_h}/\mathrm{T_s})}} \qquad (39)$$

where, P5 = antecedent rainfall of five days, LU = land use cover practice, κ = seasonal parameter in terms of time and temperature, T_s = storm duration and K_h = soil index parameter. Equation (38) can also be expressed in exponential form as

$$\mathrm{Q} = \mathrm{Pe}\left(1 - \mathrm{e}^{-\mathrm{BPe}}\right) \qquad (40)$$

$$\frac{\mathrm{Q}}{\mathrm{Pe}} = 1 - \mathrm{e}^{-\mathrm{BPe}} \tag{41}$$

where, B = b ln(10)

Equation (40) can be expand as

$$\frac{\mathrm{Q}}{\mathrm{Pe}} = 1 - \left[1 - \mathrm{BPe} + \frac{(\mathrm{BPe})^2}{2!} - \frac{(\mathrm{BPe})^3}{3!} \ldots\ldots\ldots + (-1)^{\mathrm{N}}\frac{(\mathrm{BPe})^{\mathrm{N}}}{\mathrm{N}!}\right] \tag{42}$$

where, N is an integer.

For BPe < 1, the equation (42) can be approximated as (Mishra and Singh, 2003)

$$\frac{\mathrm{Q}}{\mathrm{Pe}} = 1 - [1 - \mathrm{BPe} + (\mathrm{BPe})^2 - (\mathrm{BPe})^3 \ldots\ldots\ldots + (-1)^{\mathrm{N}}(\mathrm{BPe})^{\mathrm{N}}] \tag{43}$$

$$\frac{\mathrm{Q}}{\mathrm{Pe}} = \mathrm{BPe}[1 - \mathrm{BPe} + (\mathrm{BPe})^2 - (\mathrm{BPe})^3 \ldots\ldots\ldots + (-1)^{\mathrm{N}}(\mathrm{BPe})^{\mathrm{N-1}}] \tag{44}$$

Alternatively, Equation (44) can be written as (Mishra and Singh; 2003)

$$\frac{\mathrm{Q}}{\mathrm{Pe}} = \frac{\mathrm{BPe}}{1 + \mathrm{BPe}} \tag{45}$$

which is also valid for the value of BPe < 1.

For B = 1/S, Equation (45) leads to Equation (34), which is the popular form of the SCS-CN method.

The value, B = 1/S can be derived from the derivation of Mockus method, which is given as follows:

The Horton infiltration model is expressed as

$$\mathrm{f} = \mathrm{f_c} + (\mathrm{f_o} - \mathrm{f_c})\mathrm{e}^{-\mathrm{kt}} \tag{46}$$

where, f = rate of infiltration, f_c = final constant infiltration rate, f_o = initial infiltration rate, the value of f, f_c and f_o are in LT^{-1} at time t, while f_o at time t = 0, f = fo. Integration of equation (46) with respect t gives the cumulative infiltration F as

$$F = \frac{f_o - f_c}{k}\left(1 - e^{-kt}\right) \tag{47}$$

If t tends to ∞ then F tends to $\frac{f_o - f_c}{k}$. From equation (31) if Q tends to (P – Ia) then F tends to S which is valid when t tends to ∞, therefore,

$$S = \frac{f_o - f_c}{k} \tag{48}$$

In a general infiltration test, $f_o = i_o$ (Mishra et al, 2003) where, i_o is the uniform rainfall intensity at time t = 0, therefore,

$$S = \frac{i_o - f_c}{k} \tag{49}$$

$$i_o - f_c = i_e = S\,k \tag{50}$$

where, i_e is the effective rainfall intensity, from equation (47) and (48)

$$\frac{F}{S} = 1 - e^{-kt} \tag{51}$$

Coupling Equation (51) with Equation (31) when Ia = 0

$$\frac{Q}{P} = 1 - e^{-kt} \tag{52}$$

An assumption of rainfall P growing linearly with time t leads to,

$$P = i_e t \tag{53}$$

when P excludes the static infiltration. Equation (53) implies the general notion P grows boundless (Ponce and Hawkins, 1996) and therefore, from equation (50) and (53), P = S k t

$$\frac{P}{S} = kt \tag{54}$$

therefore, substituting equation (54) into equation (52)

$$\frac{Q}{P} = 1 - e^{-P/S} \tag{55}$$

which is equivalent to equation (41) for B = 1/S and Ia = 0. Now replacing P by Pe, equation (55) yield the Mockus equation (41).

Finally, the implication of the generalized form of the Mockus method for SCS-CN method can be obtained as:

Neglecting the third and higher order terms in equation (42) gives

$$\frac{Q}{Pe} = 1 - \left[1 - BPe + \frac{(BPe)^2}{2!}\right]$$

$$= 1 - 1 + BPe - \frac{(BPe)^2}{2!}$$

$$= BPe(1 - 0.5Pe) \times \frac{1 + 0.5BPe}{1 + 0.5BPe}$$

$$= \frac{BPe - 0.25(BPe)^3}{1 + 0.5BPe}$$

$$= \frac{BPe}{1 + 0.5BPe} - \frac{0.25(BPe)^3}{1 + 0.5BPe}$$

$$= \frac{BPe}{1 + 0.5BPe}$$; after neglecting the terms of third order

$$= \frac{Pe}{1/B + 0.5Pe}$$

$$= \frac{\mathrm{Pe}}{\mathrm{S} + 0.5\mathrm{Pe}} \qquad ; \text{for } S = 1/B$$

$$\mathrm{Q} = \frac{\mathrm{Pe}^2}{\mathrm{S} + 0.5\mathrm{Pe}} \tag{56}$$

Therefore, in general form, equation (56) can be written as

$$\mathrm{Q} = \frac{\mathrm{Pe}^2}{\mathrm{S} + \mathrm{a.Pe}} \tag{57}$$

or

$$\mathrm{RCN} = \frac{\mathrm{Pe}^2}{\mathrm{S} + \mathrm{a.Pe}} \tag{58}$$

where, RCN is the runoff generated from SCS-CN method as shown in structure of the XIN-CN model (Fig. 3.1) and ‘a’ is the parameter obtained through optimization.

In the proposed XIN-CN model, input to the saturation excess runoff generation process in the proposed model (XIN-CN) is computed as.

PK = P – RCN (59)

where, PK is the rainfall after subtracting direct runoff from P.

Saturation excess runoff (R)

The formulation for saturation excess runoff generation mechanism in the modified Xinanjiang model is similar to the original Xinanjiang model, only the value of P is replaced by PK which is given as follows:

The ET is computed in a similar way as in the original Xinanjiang model, as

If (PK – ET + AU) < MM, then

$$\mathrm{R} = \int_{\mathrm{AU}}^{\mathrm{AU+PK-ET}} \frac{\mathrm{f}}{\mathrm{F}} \mathrm{dW'M}$$

$$R = PK - ET - (WM - W) + WM\left(1 - \frac{PK - ET + AU}{MM}\right)^{B+1} \quad (60)$$

Otherwise,

$$R = PK - ET - (WM - W) \quad (61)$$

$$FR = \frac{R}{PK - ET} \quad (62)$$

$$MS = SM\,(EX + 1) \quad (63)$$

Surface Runoff

If (PK – ET + BU) < MS then

$$RS = \int_{BU}^{BU+PK-ET} \frac{f}{FR} dS'M$$

$$RS = \left[PK - ET - (SM - S) + SM\left(1 - \frac{PK - ET + BU}{MS}\right)^{EX+1}\right] \times FR \quad (64)$$

Otherwise,

$$RS = [PK - ET - (SM - S)] \times FR \quad (65)$$

Combined Surface Runoff

Finally, the Combined surface runoff (RSB) is obtained as follows:

$$RSB = RS + RCN \quad (66)$$

Interflow

The interflow (RI) is separated as follows:

$$RI = SF \times KI \times FR \quad (67)$$

where, SF is free water storage

Ground water flow

The ground water flow (RG) is separated as follow:

$$RG = SF \times KG \times FR \quad (68)$$

where, SF is the free water storage.

Runoff Concentration and water balance in the proposed hybrid XIN-CN model

In the proposed hybrid XIN-CN model, all three components of runoff, i.e., RSB, RI and RG are routed through single linear reservoir. TS, TI and TG represents the surface, interflow and ground water outflow discharge from these single linear reservoirs respectively.

$$TS_{(t)} = TS_{(t-1)} \bullet CS + RSB_{(t)} \bullet (1 - CS) \tag{69}$$

$$TI_{(t)} = TI_{(t-1)} \bullet CI + RI_{(t)} \bullet (1 - CI) \tag{70}$$

$$TG_{(t)} = TG_{(t-1)} \bullet CG + RG_{(t)} \bullet (1 - CG) \tag{71}$$

Where, t represents the time.

Total discharge at outlet

Finally, the total discharge at the outlet (QE) of the watershed is obtained by adding outflows from these single linear reservoirs.

$$QE = TS + TI + TG \tag{72}$$

Water Balance

For continuous simulation of runoff generation from the model, the soil moisture budgeting is essential, that can be obtained in the proposed XIN-CN model as:

$$W_{(t)} = W_{(t-1)} + PK_{(t-1)} - R_{(t-1)} - ET_{(t-1)} \tag{73}$$

$$SF_{(t)} = SF_{(t-1)} + R_{(t-1)} - (RS_{(t-1)} + RI_{(t-1)} + RG_{(t-1)}) \tag{74}$$

$$AU_{(t)} = MM\left(1 - \left(1 - \frac{W_{(t)}}{WM}\right)^{\frac{1}{B+1}}\right) \tag{75}$$

$$BU_{(t)} = MS\left(1 - \left(1 - \frac{S_{(t)}}{SM}\right)^{\frac{1}{EX+1}}\right) \tag{76}$$

$$S_{(t)} = WM - W_{(t)} \tag{77}$$

The water balance in the proposed XIN-CN model can be expressed as:

$$\text{Change in Storage} = \text{Inflow} - \text{Outflow} = P - (QE + ET) \tag{78}$$

Change in Storage = $\Delta W + \Delta SF + \Delta RSB + \Delta RI + \Delta RG$ (79)

Finally, the water balance in the proposed XIN-CN is computed as

$$\Delta W + \Delta SF + \Delta RSB + \Delta RI + \Delta RG = P - (QE + ET) \quad (80)$$

3.3 THE PROPOSED DYNAMIC VARIABLE INFILTRATION CAPACITY (DVIC) MODEL

The proposed DVIC model is the modified form of the Hu et al. (2005) model which is less complex in its runoff generation process as compared to the model developed by Hu et al. (2005). Hu et al. (2005) considered both the runoff generation mechanisms, i.e., saturation excess and infiltration excess runoff generation mechanisms simultaneously using both the distribution curves, i.e., the distribution curve of the tension water capacity and the distribution curve of the infiltration capacity while the proposed DVIC model considers only infiltration capacity curve in its runoff generation process. The Hu et al. (2005) model is very complex in its runoff generation process due to a number of steps involved in the runoff generation process, i.e., the model uses six steps for generating surface runoff as well as the ground water runoff components. However, the proposed DVIC model uses only the distribution of infiltration capacity curve for surface runoff generation, which involves only two steps for surface runoff generation in comparison with Hu et al. (2005) model which involves six computational steps for the surface runoff as well as the ground water runoff production. The ground water runoff in the proposed DVIC model is obtained when soil moisture exceeds the field capacity of the soil moisture. As $F_{m\Delta t}$ is the function of point soil infiltration capacity ($F'_{\Delta t}$) and the value of $F'_{\Delta t}$ varies from 0 to $F'_{m\Delta t}$ and, therefore, the proposed DVIC model shows its variability in terms of infiltration capacity distribution curve. The average time interval infiltration capacity $F_{m\Delta t}$, which corresponds to the Horton's infiltration rate, changes at each time interval of computation process (in this study the time interval is one day) enables the proposed DVIC model to be more dynamic in the computational process. Therefore, the model named as Dynamic Variable Infiltration Capacity (DVIC) model.

3.3.1 Structure of the Dynamic Variable Infiltration Capacity (DVIC) model

The DVIC model is simple in its structure as shown in Fig. 3.2 along with different components used in different computational processes.

3.3.2 The Runoff production in the proposed DVIC model

In the proposed DVIC model, runoff is produced at a point when rainfall exceeds the point soil infiltration capacity $F'_{\Delta t}$, after satisfying the point soil infiltration capacity. For representing non-uniform distribution of point soil infiltration capacity throughout the catchments, a point soil infiltration capacity curve given by eq. 80 is used in the DVIC model.

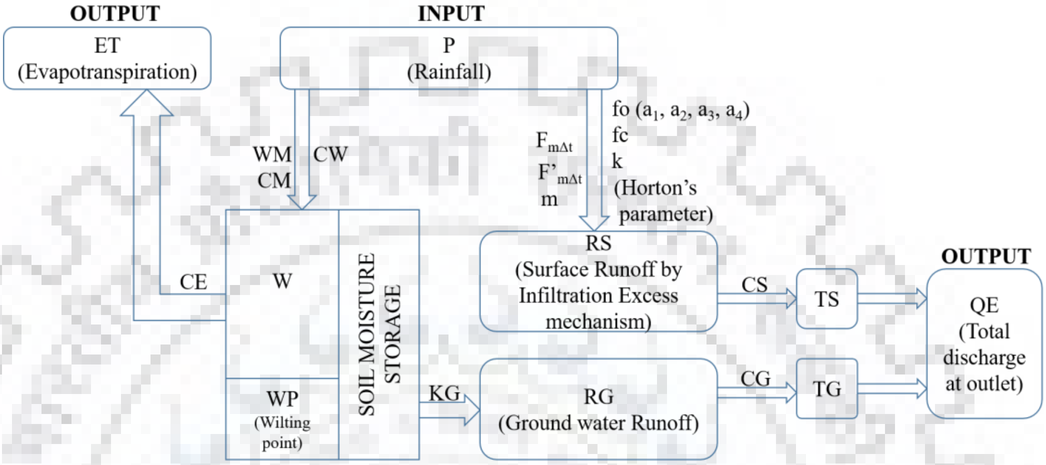


Figure 3.2 The Structure of the DVIC model

$$\beta = 1 - \left(1 - \frac{F'_{\Delta t}}{F'_{m\Delta t}}\right)^{cb} \tag{81}$$

where, cb is the parameter similar to parameter B, $F'_{\Delta t}$, is the point soil infiltration capacity, $F'_{m\Delta t}$ is the maximum point soil infiltration capacity and β is the area fraction in which the soil infiltration capacity is less than or equal to $F'_{\Delta t}$. The value of $F'_{\Delta t}$ varies from zero to $F'_{m\Delta t}$. The characteristics of the parameter $F'_{m\Delta t}$ is similar to that of the parameter MM used in the original Xinanjiang model by Zhao (1992). Where MM represents the maximum point soil tension water capacity for W'M in the original Xinanjiang model.

For computing the spatially average time interval soil infiltration capacity, the Horton's infiltration equation has been adopted as the spatially averaged point soil infiltration capacity function in DVIC model. The Horton's infiltration equation can be written as,

$$f = f_c + (f_o - f_c)\, e^{-kt} \tag{82}$$

Where, in this study, f is taken as rate of infiltration in mm/day, f_c (obtained through optimization) is the final constant infiltration rate in mm/day, f_0 is the initial infiltration capacity of the soil in mm/day and k is the decay coefficient for a continuous storm period of time t. The range for optimizing the value of f_c has been used as suggested by Akan (1993). Now the average time interval infiltration capacity $F_{m\Delta t}$ can be computed by integrating the Eq. (82) for a time interval as:

$$F_{m\Delta t} = \int_{t}^{t+\Delta t} f dt = f_c \Delta t + \frac{1}{k}(f_0 - f_c)e^{-kt}\left(1 - e^{-k\Delta t}\right) \tag{83}$$

where, $F_{m\Delta t}$ is the average time interval infiltration capacity. The value of $F_{m\Delta t}$ changes with time interval and, therefore, it is calculated for each time interval for continuous storm period until the intensity of the rainfall is above f_c. Fig. 3.3 depicts the concept of denoting average time interval infiltration capacity $F_{m\Delta t}$ on the infiltration capacity curve f. Fig. 3.4 shows the manner in which the value of $F_{m\Delta t}$ is distributed throughout the catchment. The alternative parameter $F'_{m\Delta t}$ that is similar to parameter MM as in the Xinanjiang model can be computed as:

$$F'_{m\Delta t} = (cm+1)\, F_{m\Delta t} \tag{84}$$

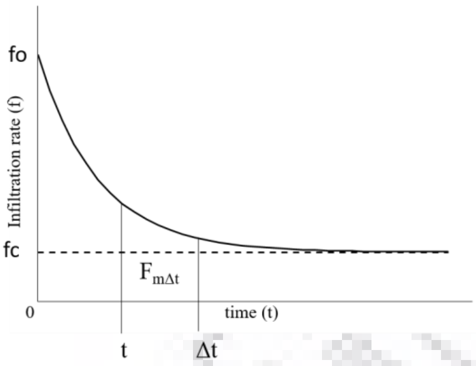


Figure 3.3 Watershed infiltration rate curve

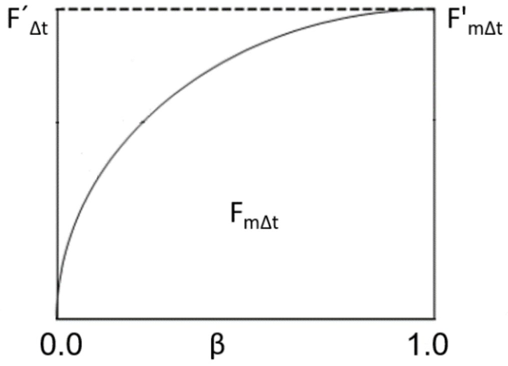


Figure 3.4 Distribution of infiltration capacity

3.3.2.1 Surface Runoff

The surface runoff occurs when rainfall P exceeds the point soil infiltration capacity. The surface runoff is generated in DVIC model using two conditions.

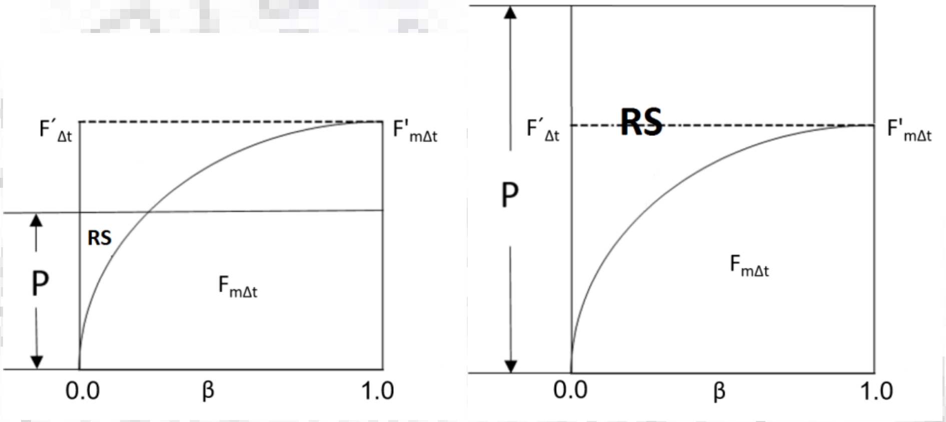
From Fig. 3.5 (a) and (b),

If $P \leq F'_{m\Delta t}$, then

$$RS = \int_0^P \beta \, dF'_{\Delta t} = P - F_{m\Delta t}\left[1 - \left(1 - \frac{P}{F'_{m\Delta t}}\right)^{cb+1}\right] \tag{85}$$

Otherwise,

$$RS = \int_0^{F'_{m\Delta t}} (1-\beta) dF'_{\Delta t} = P - F_{m\Delta t} \tag{86}$$



(a) (b)

Figure 3.5 Surface runoff generation in proposed DVIC model

3.3.2.2 Groundwater runoff

The groundwater runoff is produced when soil moisture (W) reaches the field capacity of soil. At field capacity any rainfall that infiltrate into the soil generates the groundwater runoff. It is expressed as:

If W > FC then,

$$RG = KG \cdot (W - FC) \tag{87}$$

Otherwise,

$RG = 0$

Where, RG is groundwater runoff, KG is the ground water runoff generation coefficient and FC is the field capacity. The parameter KG and FC are obtained through optimization.

3.3.2.3 Total Runoff

The total runoff is calculated as sum of surface runoff and ground water runoff as,

$$R = RS + RG \tag{88}$$

3.3.3 Evapotranspiration in DVIC model

The evapotranspiration (ET) in the DVIC model is calculated as a coefficient times the available moisture between field capacity and the wilting point (WP). Therefore, for calculating the evapotranspiration, wilting point of the soil has to be determined first. In this study, the wilting point is determined by using the relationship between wilting point and field capacity used by Zotarelli et al. (2010), Dobbs et al. (2013) and Migliaccio et al. (2015). Zotarelli et al. (2010) explained the relationship between wilting point and field capacity with the help of a diagram while Dobbs et al. (2013) and Migliaccio et al. (2015) converted it into table form. In this study the table has been converted into the form of an equation i.e. the wilting point is the fraction of field capacity, which can be expressed as:

Table 3.1. Relationship between wilting point and field capacity

SOIL TYPE	WP (cm/cm)	FC (cm/cm)	WP in fraction of FC (CW = WP/FC)
Sand	0.02	0.08	0.25
Sandy loam	0.06	0.16	0.38
Loam	0.08	0.26	0.31
Silt loam	0.10	0.31	0.32
Clay loam	0.14	0.34	0.41
Clay	0.16	0.37	0.43

$$WP = CW \cdot FC \tag{89}$$

where, CW is the coefficient, obtained through optimization. The value of CW varies from 0.25 to 0.43 according to Table 3.1. (Dobbs et al., 2013 and Migliaccio et al., 2015).

Finally, the value of evapotranspiration is calculated as

If W > WP then,

$$ET = CE \bullet (W - WP) \tag{90}$$

Otherwise,

$$ET = 0$$

where, CE is a parameter obtained through optimization.

Runoff Concentration and Discharge at the Outlet

For computation of runoff concentration, same formulation as used in the original Xinanjiang model has been adopted here as well,

$$\mathrm{TS}_{(t)} = \mathrm{TS}_{(t-1)}.\mathrm{CS} + \mathrm{RS}_{(t)}.(1 - \mathrm{CS}) \tag{91}$$

$$\mathrm{TG}_{(t)} = \mathrm{TG}_{(t-1)}.\mathrm{CG} + \mathrm{RG}_{(t)}.(1 - \mathrm{CG}) \tag{92}$$

Where, TS and TG are outflows from single linear reservoir for surface and groundwater runoff respectively, CS and CG are the runoff concentration parameters. Finally, the discharge at the outlet (QE) is estimated as follows:

$$QE = TS + TG \tag{93}$$

Water Balance

For continuous simulation of runoff generation from the model, the soil moisture budgeting is essential. In proposed DVIC model, soil moisture budget is expressed as

$$\mathrm{W}_{(t)} = \mathrm{W}_{(t-1)} + \mathrm{P}_{(t-1)} - \mathrm{R}_{(t-1)} - \mathrm{ET}_{(t-1)} \tag{94}$$

Updating the components of Horton's equation

In the proposed DVIC model, the initial infiltration rate (fo) of the Horton's equation need to be update with the updating of soil moisture. The initial infiltration rate on each time interval is updated according to Wensheng et al. (1992) model, based on the available soil moisture (W) storage. Using an empirical equation given as (Wensheng et al., 1992)

$$\mathrm{fo}_{(t)} = a_1 - a_2 . W_{(t)} + a_3 . W_{(t)}^2 - a_4 . W_{(t)}^3 \tag{95}$$

Where, a_1, a_2, a_3, and a_4 are parameters.

The water balance in the proposed DVIC model is computed in a way similar to that of the original Xinanjiang as:

$$\text{Change in Storage} = \text{Inflow} - \text{Outflow} = P - (QE + ET) \tag{96}$$

$$\text{Change in Storage} = \Delta W + \Delta RS + \Delta RG \tag{97}$$

Finally, the water balance in the proposed DVIC model is computed as,

$$\Delta W + \Delta RS + \Delta RG = P - (QE + ET) \tag{98}$$

3.4 PERFORMANCE EVALUATION CRITERIA

The hydrological models are powerful tools for the simulation of the effect of hydrological processes and management of soil-water resources. Computer based hydrological models are widely used to save time and money because these models have the ability to perform long-term simulation of the hydrological processes and different management activities for water quantity, water quality, and quality of soil (Moriasi et al. 2007). Therefore, quantitative evaluation of results obtained from the developed hydrological models is required based on certain indices for their performance evaluation. A number of performance evaluation criteria are available in the literature like the Coefficient of determination R^2, the Nash-Sutcliffe efficiency NSE, the index of agreement d, relative efficiency criterion E_{rel}, relative error (RE) etc. (Krause et al., 2005; Moriasi et al., 2007; Willmott et al., 2012). In this study, the performance evaluation of the model has been assessed based on the two categories of statistical indices. First is the model efficiency, and second is the error criteria.

3.4.1 Model efficiency

In this study, the two well-known and universally accepted statistical indices namely the Nash-Sutcliffe efficiency (NSE) (Nash and Sutcliffe, 1970) (Sevat and Dezetter, 1991; ASCE 1993; Refsguard and Knudsen, 1996; Legates and McCabe 1999; El Sadek et al., 2001; Fentie et al., 2002; Jain and Singh, 2005; Michel et al., 2005) and R^2 (Coefficient of determination) have been used for the evaluation of performance of the model. The NSE is a normalized statistical tool that determines the relative magnitude of the residual variance, compared to the observed data variance (Nash and Sutcliffe, 1970). The value of NSE varies from −∞ to 1.0, with NSE = 1, indicating the perfect matching of the simulated results with the observed data. The NSE values estimated from 0.5 to 1.0 are generally considered as acceptable levels of performance, whereas, the values less than 0.0 indicates that the mean of the observed value is a better predictor than the simulated value, which indicates unacceptable performance (Moriasi et al. 2007). Coefficient of determination (R^2) describe the degree of collinearity between the simulated and observed data. R^2 describes the proportion of the variance in observed data explained by the model. R^2 ranges from 0 to 1, with higher values of R^2 indicating less error variance, and generally the values greater than 0.5 are considered acceptable (Santhi et al., 2001, Van Liew et al., 2003, Moriasi et al. 2007). The NSE and R^2 are expressed, as

$$\mathrm{NSE} = 1 - \frac{\sum_{i=1}^{N}\left(Q_{o,i} - Q_{e,i}\right)^2}{\sum_{i=1}^{N}\left(Q_{o,i} - \overline{Q}_o\right)^2} \tag{99}$$

$$R^2 = \left(\frac{\sum_{i=1}^{N}\left(Q_{e,i} - \overline{Q}_e\right)\left(Q_{o,i} - \overline{Q}_o\right)}{\sqrt{\sum_{i=1}^{N}\left(Q_{e,i} - \overline{Q}_e\right)^2}\sqrt{\sum_{i=1}^{N}\left(Q_{o,i} - \overline{Q}_o\right)^2}}\right)^2 \tag{100}$$

where, $Q_{o,i}$ is the observed discharge (mm), $Q_{e,i}$ is the model simulated discharge (mm), $\overline{Q}_o$ is the mean observed discharge (mm), $\overline{Q}_e$ is the mean simulated discharge (mm), N is the total number of simulated data of the specific time interval.

3.4.2 Error Criteria

Several statistical error indices are commonly used for the evaluation of performance of a hydrological model. These include mean square error (MSE), mean absolute error (MAE), root mean square error (RMSE), Standard Error of estimate (SE) (McCuen, 2003), percentage Relative Error (RE) etc. The root mean square error (RMSE) is a very widely used statistical index for evaluating the performance of the hydrological models (McLeod et al., 1987; Sudheer et al., 2002; Nayak et al., 2004; Coulibaly and Baldwin, 2005; Chetan and Sudheer, 2006; Dawson et al., 2007; Chen et al., 2015). The RMSE estimate is valuable in respect of model evaluation because it indicates error in the units (or squared units) of the component of interest, which aids in analysis of the results (Moriasi et. al., 2007). The root returns the metric to actual units, this metric that emphasises larger errors, and, therefore, tends to attention on high flow events in the time series (Hauduc et al., 2011). The RMSE value varies between zero and positive infinity. A smaller RMSE indicates a better simulation performance, and the best RMSE value is zero (Zhang et al., 2016) which indicates a perfect match between the observed and the predicted values and with increasing RMSE values indicating an increasingly poor match (Golmohammadi et. al., 2014). Willmott and Matsuura (2005) found that the RMSE varies with the variability of the error magnitudes and the sample size. The percentage relative error (RE) is also helpful in evaluation of model performance that may have a negative and positive values. Values with negative sign indicates the under estimation and with positive values indicates the overestimation by the model and %RE with zero value indicates a perfect match, i.e., no over or under estimation. (Moriasi et al. 2007, Jain et al. 2012, Lin et al. 2014). In this study, these two statistical error indices of RMSE and RE have been used to evaluate the performance of the developed models. The RMSE and RE are expressed respectively, as:

$$\mathrm{RMSE} = \sqrt{\frac{1}{\mathrm{N}}\sum_{\mathrm{i}=1}^{\mathrm{N}}(\mathrm{Q_o} - \mathrm{Q_e})^2} \tag{101}$$

$$\mathrm{RE}\ (\%) = \frac{\sum_{\mathrm{i}=1}^{\mathrm{N}}(\mathrm{Q_o} - \mathrm{Q_e})}{\sum_{\mathrm{i}=1}^{\mathrm{N}}\mathrm{Q_o}} \times 100 \tag{102}$$

3.5 SUMMARY

In this chapter, the development formulation of two proposed modified form of the Xinanjiang model have been presented. Under the formulation of the proposed models, the theoretical background, mathematical development processes, figures and graphs showing the runoff generation process of the proposed hybrid Xinanjiang model (XIN-CN) and proposed Dynamic Variable Infiltration Capacity (DVIC) model have been presented. Since these hydrological models are conceptual in nature and, therefore, they need to be tested before applying them to the actual data set collected from the field. For the evaluation of the hydrological models, some well-known evaluation criteria based on statistical analysis are used. In this chapter, the model performance evaluation criteria, i.e., the statistical indices like NSE, R^2, RMSE and %RE have been discussed along with their utility and relevance in hydrological modelling.

4

STUDY AREA AND DATA AVAILABILITY

4.1 GENERAL

To test the performance of existing and proposed hybrid conceptual models, 20 catchments from different climatic conditions from rivers flowing towards western direction in Western Ghats, coastal areas of India and few sub-catchment of major rivers basins of India namely Narmada river basin, Krishna river basin and Cauvery river basin have been selected. This Chapter presents the salient details of the study catchments, including their main physical characteristics, climatic conditions, land use land cover, soil type present in these catchments. The rainfall and pan evaporation data for study catchments have been obtained from India Meteorological Department, Water Resources Development Organization, Bangalore, Karnataka and India-WRIS website.

4.2 CATCHMENTS FROM NARMADA RIVER BASIN

The Narmada River basin rises in the Plateau of Maikal range of Amarkantak in the Shahdol district of Madhya Pradesh state at an elevation of 1057 m amsl at latitude of 22° 40' N and longitude of 81° 45' E. The river Narmada traverse a distance of 1,312 km before falling into Gulf of Cambay (Khambat) of Arabian Sea near the Bharuch district in Gujarat state. With many short tributaries flowing into it from north and south, Narmada is the largest west flowing river of the peninsular India, which forms a very important topographic feature to the country. In this study, 10 sub-catchments (Dindori, Chidgaon, Gadarwara, Belkheri, Manot, Bamni Banjar, Patan, Kogaon, Mohegaon and Hridaynagar) from Narmada river basin have been selected. Selected catchments are located at different geographical locations of the Narmada River. The drainage and soil taxonomy maps of these catchments with their location in the Narmada River basin are shown in the Figure 4.1 and Figure 4.2 respectively. Brief description of these catchments is presented in the following text.

4.2.1 Dindori catchment

The Dindori catchment lies in the Dindori district of the Madhya Pradesh state of India. It is situated in the upper most region of Narmada basin between 22º26’24” N and 23º04’45” N Latitudes and 81º03’07” E and 81º46’22” E longitudes. The geographical area of catchment is 2292 km^2 area with elevation ranging from 1139 m amsl to 657 m amsl. The climate of Dindori catchment is characterized by hot summer with general dryness except during southwest monsoon season. The climate of the catchment can be classified as tropical semi humid with average annual rainfall of 1220 mm and average temperature of 24.4ºC. About 80 – 90% of the annual rainfall is received during monsoon season (June to October). The pan evaporation in this catchment varies from 2 mm/day in winter to 10.5 mm/day in summer. The catchment area falls under the plateau and hills region which is covered with cultivated land, forest and permanent pastures. The soils of the area are dominated by loamy soils.

4.2.2 Chidgaon Catchment

The Chidgaon catchment belongs to the Ganjal tributary of the Narmada River basin that covers three districts namely Harda, Betul and Hosangabad of Madhya Pradesh state of India. It is situated in the middle region of Narmada River basin between 21º58’10” N and 22º24’44” N Latitudes and 71º17’36” E and 77º45’18” E longitudes. The catchment covers 1729 km^2 area with the elevation range in between 289 – 827 m amsl. The climate of Chidgaon catchment is characterized by a hot summer and normal dryness throughout the year except during the southwest monsoon season. It receives an average annual rainfall of 1109 mm. The maximum temperature of 42.1ºC occurs during the month of May and minimum of 11.7ºC during the month of January. The pan evaporation varies from 3 mm/day in winter to 14 mm/day in summer. The area falls under the plateau and hills region which is covered with cultivated land, forest and permanent pastures. Soils of the Chidgaon catchment are characterized by black grey with red and yellow colours, which is mixed with ferruginous red gravel or lateritic and red and black alluvium soils. Generally, such type of soil group is commonly known as black soils.

4.2.3 Gadarwara Catchment

The Gadarwara catchment belongs to the Sakkar tributary of the Narmada River basin that covers districts of Chindwara and Narshingpur of Madhya Pradesh state. The Gadarwara catchment is is situated in between upper and middle region of the Narmada River basin spanning from 22º21’30” N and 22º55’44” N Latitudes and 78º46’43” E and 79º16’54” E longitudes. The elevations of this catchment varies between 322 – 1149 m amsl and drains an area of 2270 km^2. This catchment falls under the category of semi-humid climatic conditions with average annual rainfall depth as 1179 mm. The pan evaporation varies from 3 mm/day in winter to 11 mm/day in summer. The normal maximum temperature observed during the month of May is 42.5ºC and minimum during the month of January is 8.2ºC. The soils are mostly clayey to loamy in their texture and have the presence of calcareous concretions invariability. In summer season, the soil becomes sticky and develops deep cracks due to shrinkage.

4.2.4 Belkheri Catchment

The Belkheri catchment is situated in the upper region of the Narmada River basin just adjacent to the Gadarwara catchment. It is drained by Sher tributary of the Narmada River. It covers two district Seoni and Narsinghpur of the Madhya Pradesh state. Geographically it is located between 22º28’10” N and 22º57’00” N Latitudes and 79º13’24” E and 79º44’09” E longitudes and drains an area of 1508 km^2. The elevations of the Belkheri catchment varies between 342 – 895 m amsl. The climatic conditions of this catchment is semi-humid with general dryness in summer season. The average annual rainfall of the Belkheri catchment is 1125 mm and the pan evaporation varies from 3 mm/day in winter to 11 mm/day in summer. The land profile of this catchment is mostly hilly and plateau with forest and agricultural land. The soil of this catchment is well drained and comprises mostly of loamy soil with fine clay textures with both deep and shallow soils depths.

4.2.5 Manot catchment

The Manot catchment is situated in the upper most region of the Narmada River basin, which is the extended part of the Dindori catchment. Geographically it is located between 22º26’40” N and 23º17’07” N Latitudes and 80º23’55” E and 81º46’30” E longitudes and drains an area of 4661 km^2. The elevations of the Manot catchment varies between 442 – 1139 m amsl. The catchment can be divided into forest and agricultural land and with hilly and plateau region. The climate of the Manot catchment is semi humid with average annual rainfall of 1269 mm and average temperature of 24.4ºC. The pan evaporation varies from 2 mm/day in winter to 11 mm/day in summer. In most the part of the catchment, soils are medium black, yellow and red with very shallow depths. However, in small parts of plain land, soils are moderately deep with dark and grayish clay loam.

4.2.6 Bamni Banjar catchment

The Bamni Banjar catchment is situated in the upper region of the Narmada River basin which covers four districts, Balaghat and Mandla from Madhya Pradesh state which covers most of

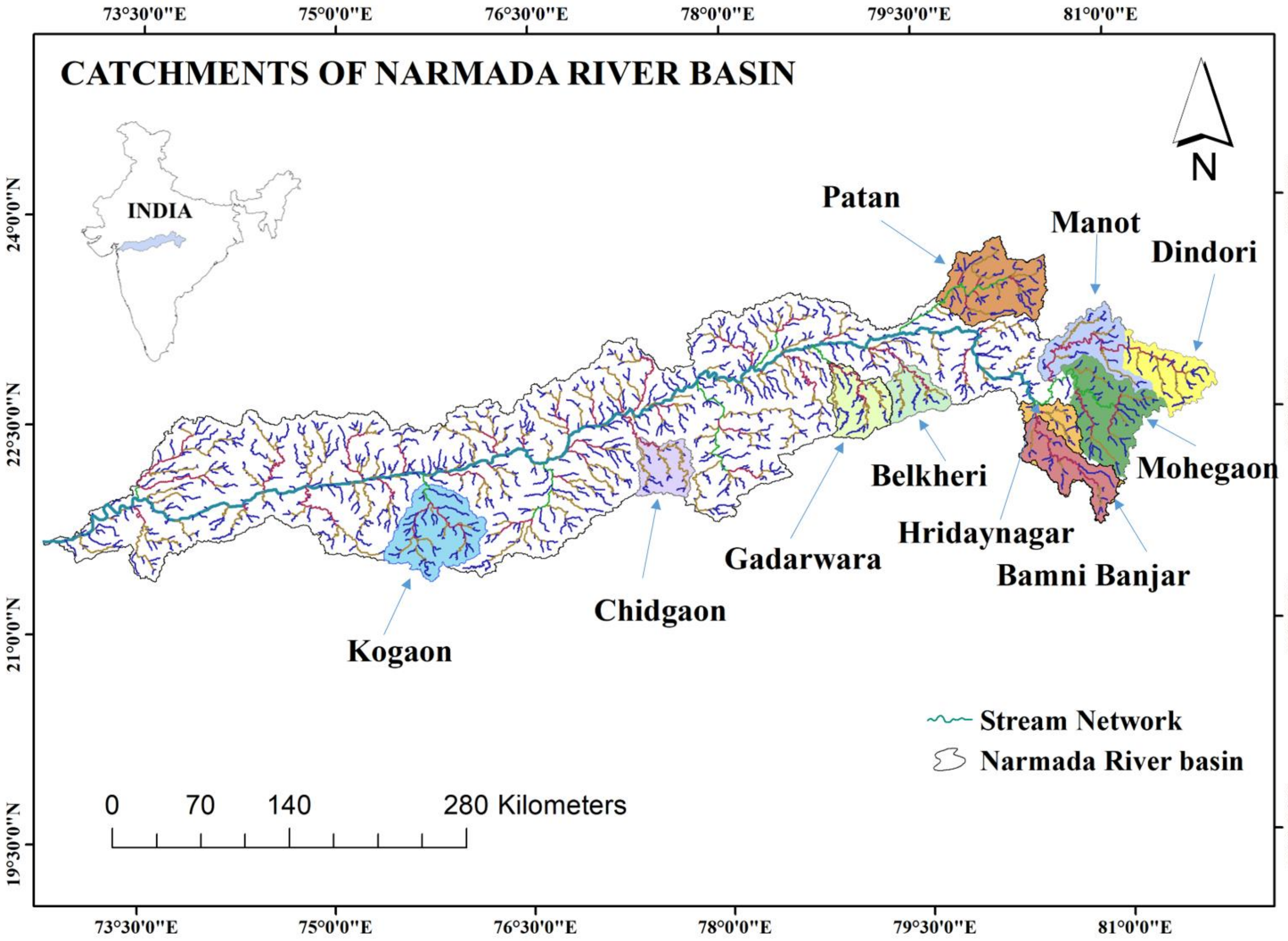


Figure 4.1 Location map of catchments under Narmada River basin

the catchment area and Kawardha and Raj Nandgaon districts from Chhattisgarh state. Geographically it is located between 21º42’27” N and 22º29’10” N Latitudes and 80º13’57” E and 80º59’33” E longitudes and drains an area of 1864 km^2. The elevations of the Bamni Banjar catchment vary between 342 – 895 m amsl. The climatic conditions of this catchment is semi humid with general dryness in summer season. The average annual rainfall of the Bamni Banjar catchment is 1292 mm and the pan evaporation varies from 3 mm/day in winter to 11 mm/day in summer. The temperature of this catchment varies from 12 ºC (in winter season) to 42 ºC in summer season. The catchment area comprises of both undulating and flat lands covered with permanent pastures, forest, timber, and cultivated land. Soils of the catchment vary from black soil to mixed red soils.

4.2.7 Patan Catchment

The Patan catchment is situated in the upper region of the Narmada River basin and drained by Heran tributary of the Narmada river basin. Geographically it is located between 23º08’21” N and 23º46’50” N Latitudes and 79º38’17” E and 80º30’15” E longitudes and drains 3950 km^2 area from three districts Jabalpur, Damoh and Katni of Madhya Pradesh state. The elevations of the Patan catchment vary between 345 – 736 m amsl. The climatic condition of this catchment is reported as semi humid climate with very hot in summer season but cold in winter season. The temperature of Patan catchment varies in between 9 ºC to 45 ºC. The average annual rainfall of this catchment is 1290 mm and the pan evaporation varies from 3 mm/day in winter to 11 mm/day in summer. The land profile of this catchment is Vindhyan Plateau, hills, valleys and flat lands cover with forest and agricultural lands. The soil of Patan catchment mainly consists of black cotton clay with few patches of loamy soil.

4.2.8 Kogaon Catchment

The Kogaon catchment is situated in between lower and middle region of the Narmada River basin and drained by Kundi tributary of the Narmada River. Geographically it is located between 21º23’39” N and 22º06’22” N Latitudes and 75º21’51” E and 76º09’40” E longitudes and drains 3919 km^2 area from Khargon (West Nimar) and Barwani districts of Madhya Pradesh state. The elevations of the Kogaon catchment vary between 153 – 980 m amsl. The climatic of this catchment is characterized by dry climate with very hot summer with temperature reaching upto 45 ºC and 15 ºC in winter season. The average annual rainfall of this catchment is 749 mm, indicating prevalence of dry condition in the catchment. The pan evaporation varies from 2 mm/day in winter to 15 mm/day in summer. The black cotton clay soil dominants most of catchment area and some part of the catchment is covered with loamy soils. The land profile of the catchment is Deccan plateaus and hills valley.

4.2.9 Mohegaon Catchment

The Mohegaon catchment is drained by the Burhner tributary of the Narmada River basin in the upper most region of the Narmada basin. Geographically it is located between 22º43’43” N and 22º55’10” N Latitudes and 80º34’34” E and 81º23’15” E longitudes draining an area of 5032 km^2 from three districts Mandla, Balaghat and Dindori of Madhya Pradesh state. A small upper part of this catchment covers the Kawardha district of Chhattisgarh state. The elevation ranges of this catchment vary between 450 – 1016 m amsl. This catchment is characterized by the dry climatic condition. Its average annual rainfall is 1223 mm and the temperature varies between 12 ºC to 42 ºC. The pan evaporation varies from 3 mm/day in winter to 11 mm/day in summer. The area falls under the plateau and hills region which is covered with cultivated land, forest and grasslands. Soils of the area characterized by well-drained clay and loamy soil groups.

4.2.10 Hridaynagar catchment

The Hridaynagar catchment is situated in the upper region of the Narmada River basin, which is the extended part of the Bamni Banjar catchment. Geographically it is located between 21º42’03” N and 22º36’40” N Latitudes and 80º13’51” E and 80º59’33” E longitudes and drains an area of 3370 km^2. The elevations of the Hridaynagar catchment varies between 438 – 905 m amsl. The catchment is covered with forest and agricultural land and comprises of hilly and plateau regions. This catchment receives an average annual rainfall 1428 mm, However, due to soil and geological conditions of the catchment, the runoff production is very less as the Runoff Coefficient for this catchments is 0.24, therefore the climate of this catchment falls under dry category (Gan et al., 1997; Durbude et al., 1997; Jain et al., 2012). The temperature of this catchment varies from 12 ºC (in winter season) to 45 ºC in summer season. The measured pan evaporation (extracted from evaporation maps of India, IMD) varies from 3 mm/day in winter to 11 mm/day in summer. The catchment area comprises of both undulating and flat lands covered with permanent pastures, timber, cultivated and forest land use. Soils vary from black soil to mixed red soils.

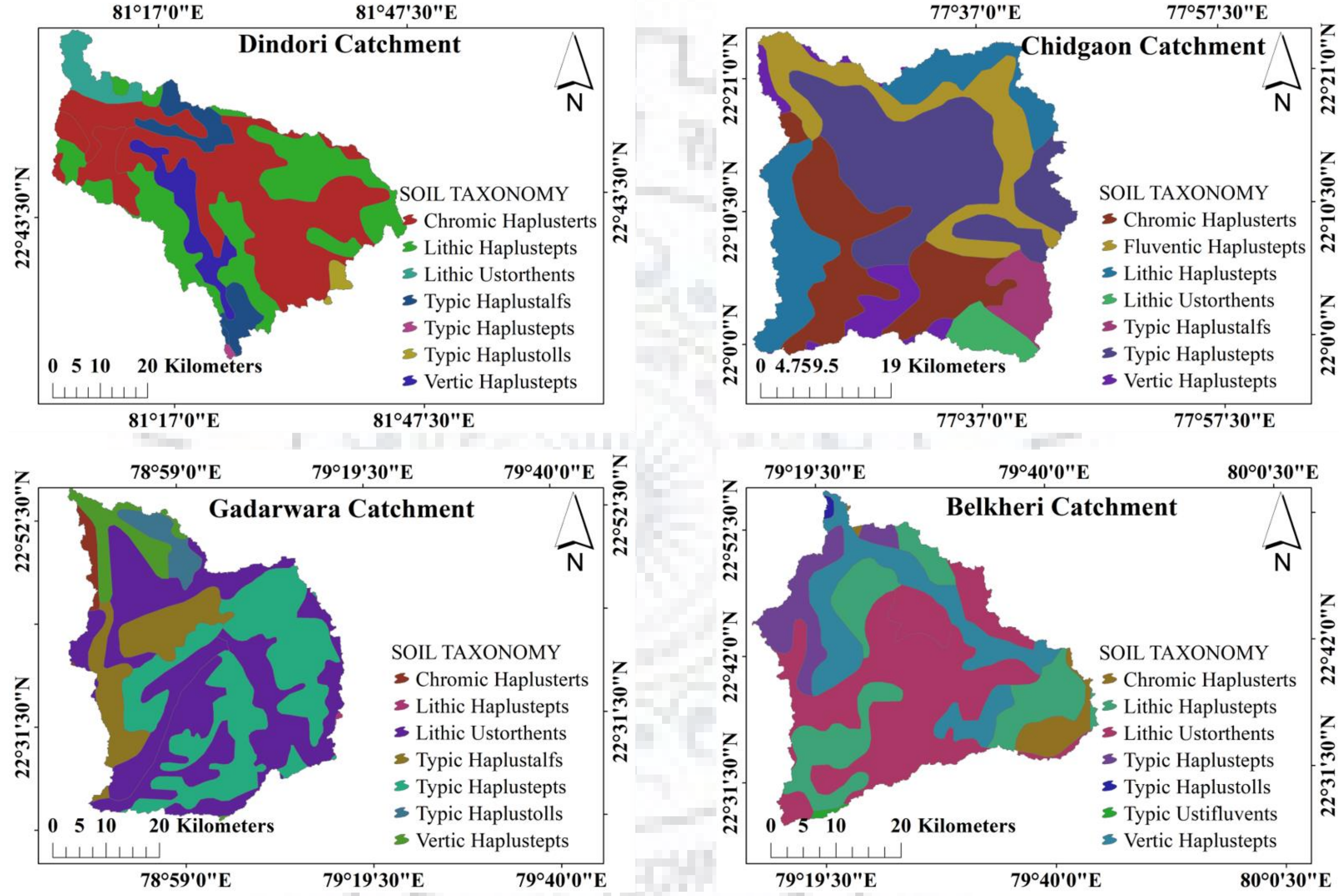
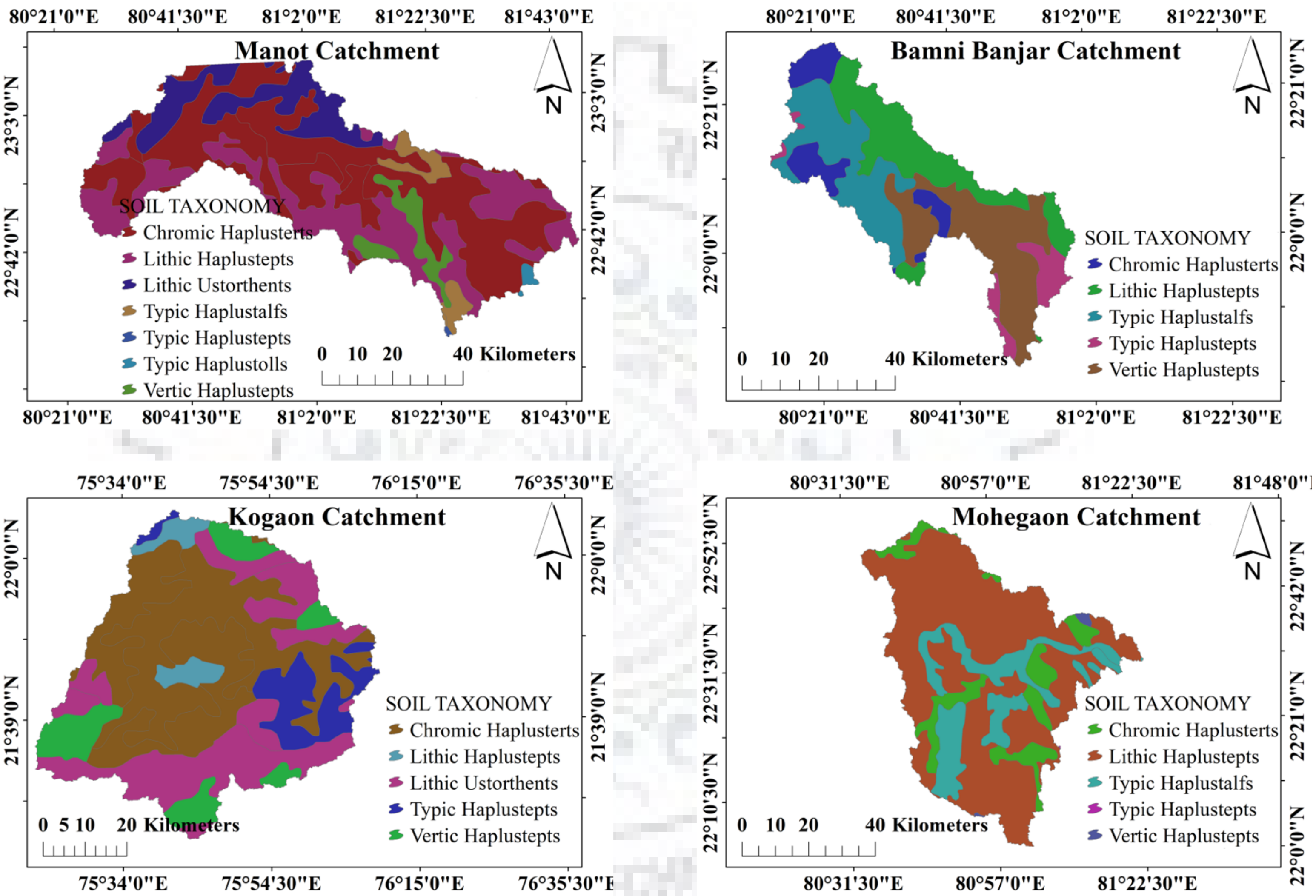


Figure 4.2 Taxonomy of soils for the catchments under Narmada river basin



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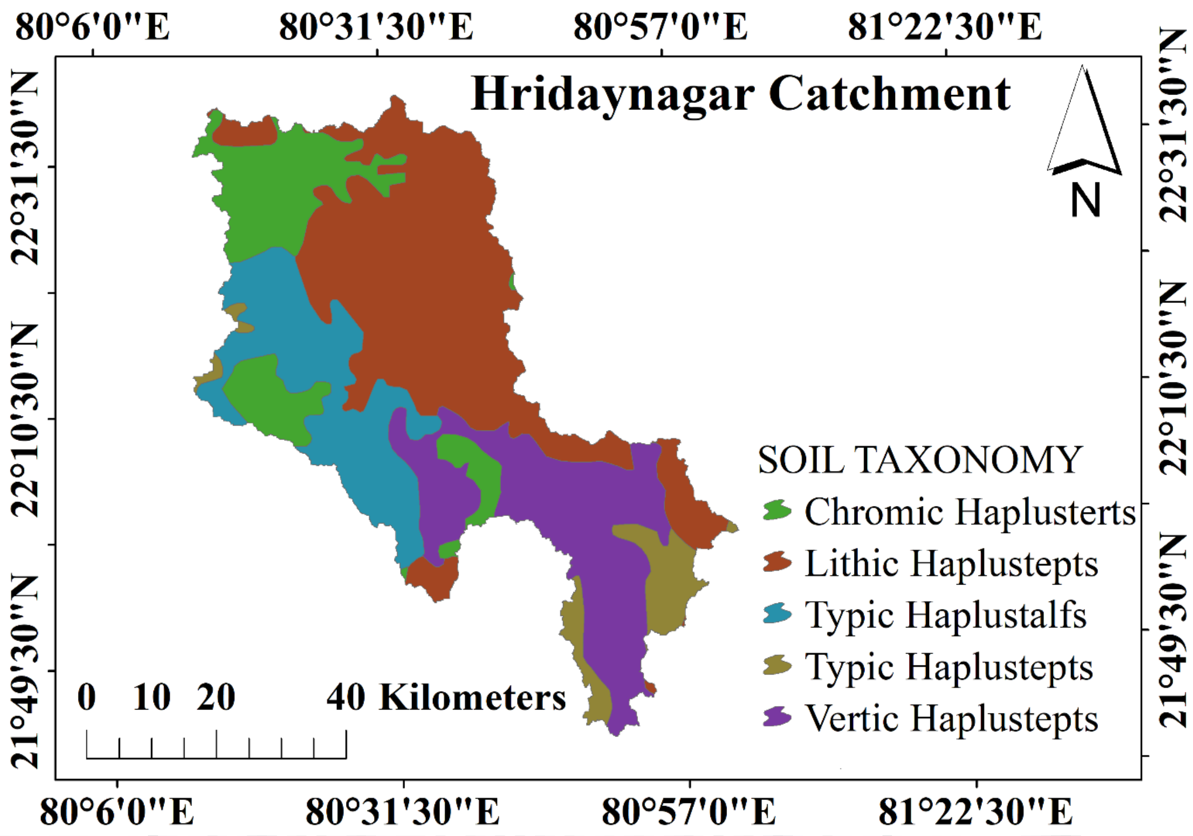


Figure 4.2 Continue…

4.3 CATCHMENTS UNDER KRISHNA RIVER BASIN

The Krishna River basin extends over the states of Maharashtra, Andhra Pradesh, and Karnataka and drains a total area of 258948 km^2, which is approximately 8% of the total geographical area of India. Geographically it lies between 73°17’ to 81°9’ E longitudes and 13°10’ to 19°22’ N latitudes with maximum length and width of about 701 km and 672 km respectively. It is bounded by the Balaghat range on the north, the Eastern Ghats on the south and by the Western Ghats on the west. The Krishna River rises from the Western Ghats near Jor village of Satara district of Maharashtra state at an altitude of 1,337 m just to the north of Mahabaleshwar. The total length of Krishna river from its origin to its outfall into the Bay of Bengal is about 1,400 km. Its major tributaries joining from left are Musi, Bhima and Munneru and those joining from right are Malprabha, Ghatprabha and Tungabhadra. The major part of the Krishna river basin is covered with agricultural land accounting to about 75% of the total basin area and about 4% of the basin area is covered by water bodies. In this study, Amachi catchment that belongs to Tungabhadra tributary and Khanpur catchment that belongs to the Malprabha tributary of Krishna river basin has been selected. The drainage and soil taxonomy maps of these catchments along with their location in the Krishna River basin are shown in Figure 4.3 and Figure 4.4 respectively.

4.3.1 Amachi Catchment

The Amachi catchment is located between 14º11’18” N and 14º16’43” N Latitudes and 75º02’57” E and 75º10’54” E longitudes and drains an area of 87 km^2 of the Shimoga district of Karnataka state. The Amachi catchment is characterized as dry because its runoff coefficient is low. The average annual rainfall of this catchment is 1817 mm and the pan evaporation varies from 3 mm/day in winter to 11 mm/day in summer. The temperature in this catchment varies from 13 ºC (in winter season) to 45 ºC in summer season. The land profile of Amachi catchment falls under plateau and hills region that is cover with forest, agricultural land and permanent pastures. The soils in this catchment consists mainly of laterite clayey soils and red gravelly loamy soils.

4.3.2 Khanpur catchment

Malaprabha River originating in the Sahyadri mountains at an altitude of 792.48 m amsl at Kanakumbi village, Khanapur taluka in Belgaum District of Karnataka. The Malaprabha river upto Khanapur gauging station is considered for the present study. Geographically the Khanpur catchment is, located between 15º30’03” N and 15º48’30” N Latitudes and 74º12’29” E and 74º32’18” E longitudes that covers 320 km^2 area of the Belgaum district of Karnataka state. Land elevation in the catchment vary between 646 – 1024 m amsl. The climate of the catchment is characterized by humid category with an average annual rainfall of 3419 mm. The temperature in the catchment varies between 15 ºC (in winter season) to 40 ºC in summer season and the pan evaporation varies from 3.5 mm/day in winter to 9 mm/day in summer. The land profile of this catchment fall under mostly hills region with valley bottom that is covered with forest and agricultural lands. The soils in this catchment consists mostly of red loamy and medium black soil.

4.4 CATCHMENTS UNDER CAUVERY RIVER BASIN

Cauvery is an easterly flowing river of the Peninsular India that runs across three southern Indian states i.e. Karnataka, Tamil Nadu, Kerala and a Union Territory of Pondicherry. It drains an area of 81,155 km^2, which is approximately 2.7% of the total geographical area of the country.

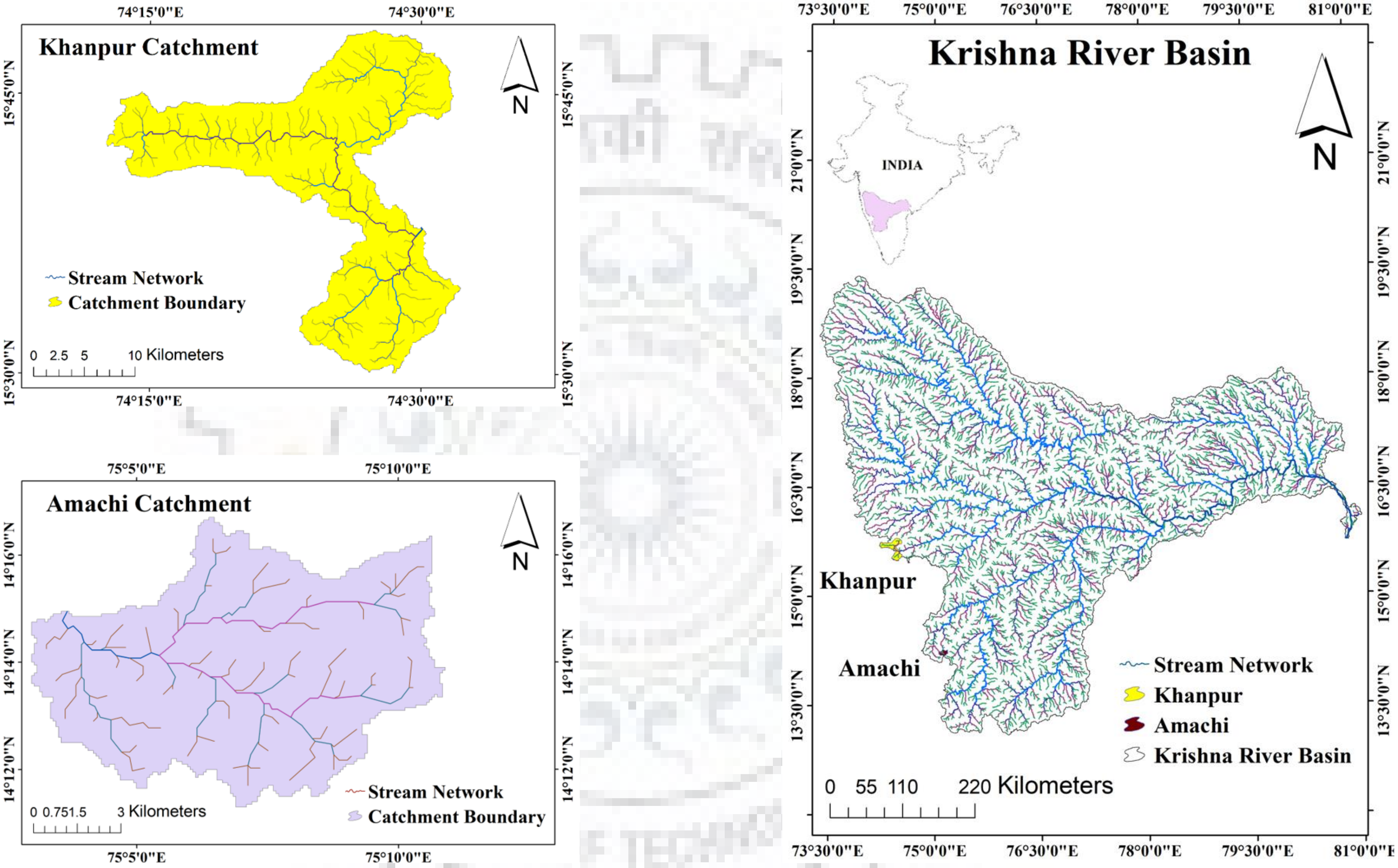


Figure 4.3 Location map of catchments under Krishna River basin

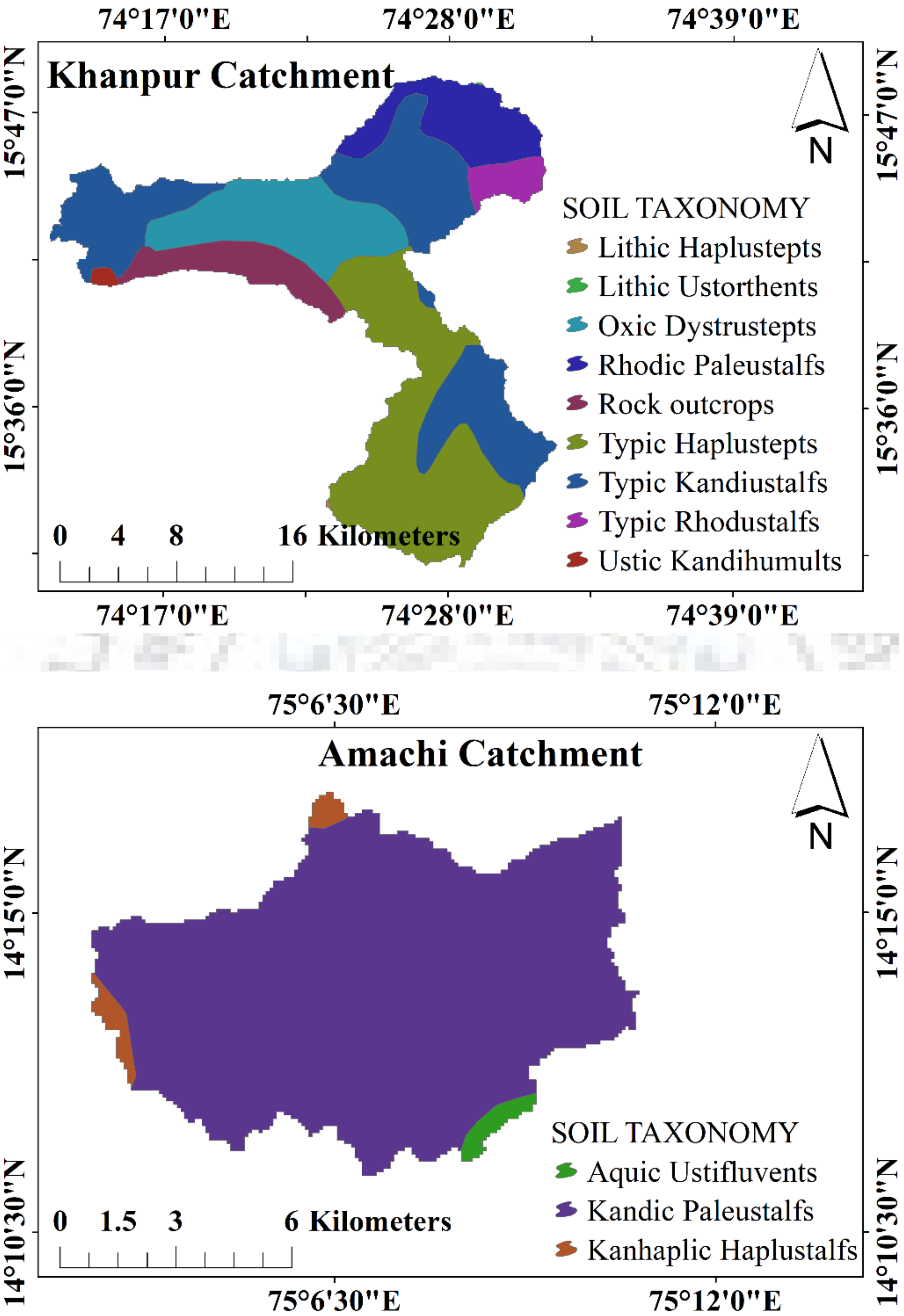


Figure 4.4 Taxonomy of soils for the catchments under Krishna river basin

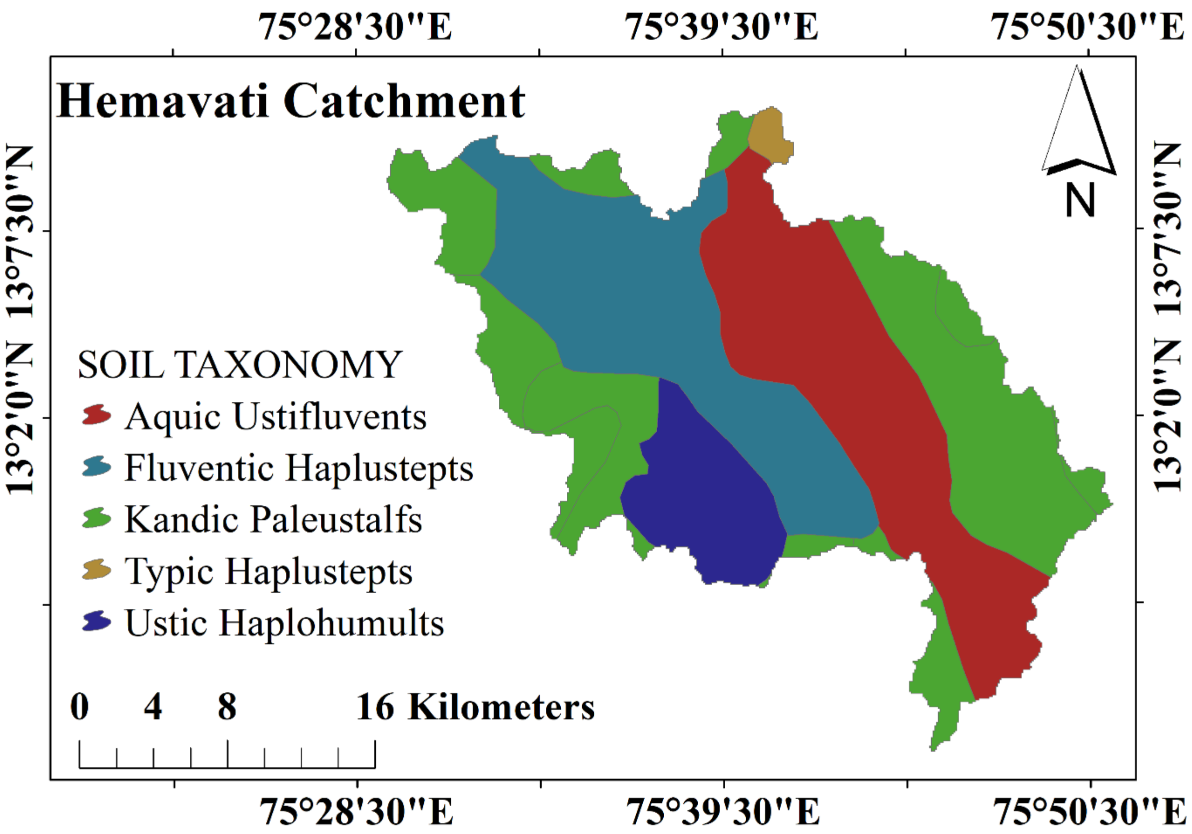


Figure 4.5 Taxonomy of soils for the catchment under Cauvery river basin

In its 800-km long journey starting from Western Ghats, it traverses through Mysore plateau and finally forms a delta on the eastern coastline of the subcontinent before falling into the Bay of Bengal. Its main tributaries joining from left are the Hemavati, Harangi, Shimsha and Arkavati, whereas the Amaravati, Kabbani, Lakshmantirtha, Suvarnavati, Bhavani, and Noyil joins from right. Most of the part of basin is covered with agricultural cultivable land covering about 66% area of the basin. In this study, the Hemavati tributary has been taken for the study from this basin. Figure 4.6 shows the location map with drainage network of catchment under Cauvery river basin and the soil taxonomy map is shown in Figure 4.5.

4.4.1 Hemavati Catchment

The Hemavati River is a tributary of the Cauvery river basin that originates in Ballaiarayanadurga in the Western Ghats of Chikmagalur district of Karnataka State. It traverses a total length of about 55.13 km up to gauging site at Sakleshpur. Geographically, the Hemavati catchment is located between 12º52’05” N and 13º11’09” N Latitudes and 75º29’24” E and 75º51’13” E longitudes and drains 600 km^2 area from Chikmagalur and Hassan districts of the Karnataka state. The elevation of the Hemavati catchment varies between 889 – 1419 m amsl. The climate of this catchment is characterized under humid category. The average annual rainfall of this catchment is 2869 mm and the pan evaporation varies from 0.5 mm/day in winter to 9.4 mm/day in summer. The temperature in this catchment varies from 15 ºC (in winter season) to 38 ºC in summer season. The land of this catchment comes under low land and semi hilly region that is covered with forest, plantation, coffee and agricultural lands. The soils of the catchment are characterized by red loamy and red sandy soils.

4.5 CATCHMENTS FROM WESTERN GHATS OF INDIA

The Western Ghats comprises of 1600 km long, unbroken chain of mountains along the west bank of Peninsular India. The 'Ghats' stretch out from the mouth of the stream Tapti to the tip of south India (around 8º N), with a hole in Palghat. Western Ghats are separated into three noteworthy domains (Pascal, 1988). The principal district, from Surat to Goa, is the most homogeneous embracing the western edge of the tremendous level shaped by the basaltic outpourings of the Deccan Trap. The edge of the level is cut by numerous waterways, which deplete the substantial monsoonal rains along profound inclines towards the ocean (e.g. Kali stream). The Maharashtra plateau towards east is cut by the Bhima, Krishna and Godavari waterways. The coastal area receives more than 3000 mm rainfall annually, which is reduced to less than 1200 mm above the Ghats region. In this study, seven catchments (Anthroli, Barchi, Halkal, Jadkal, Haladi, Dasanakatte and Kokkarne) from Western Ghats, flowing towards west direction have been taken. The drainage and soil taxonomy maps of these catchments along with their location in the Western Ghats region are shown in Figure 4.7 and Figure 4.8 respectively.

4.5.1 Anthroli catchment

Anthroli catchment is drained by the Kalinadi river of Western Ghats, Uttara Kannada district of northern Karnataka, India. The Kalinadi River originates in the Western Ghats at an altitude of 900 m amsl. With a total length of 184 km, it drains an area of 4837 km^2. Physiographically, the Kalinadi river basin is divided into three distinctive zones, as midland, narrow coast, and flatter elevated eastern zone. Midland region comprises of separation of high hills and ridges, valleys with thick forest cover and gorges. The flatter elevated eastern zone is surrounded by the Deccan plateau. The river basin is a biodiversity habitat for many plant species and organisms. Anashi and Dandeli national wildlife national park are located within the basin.

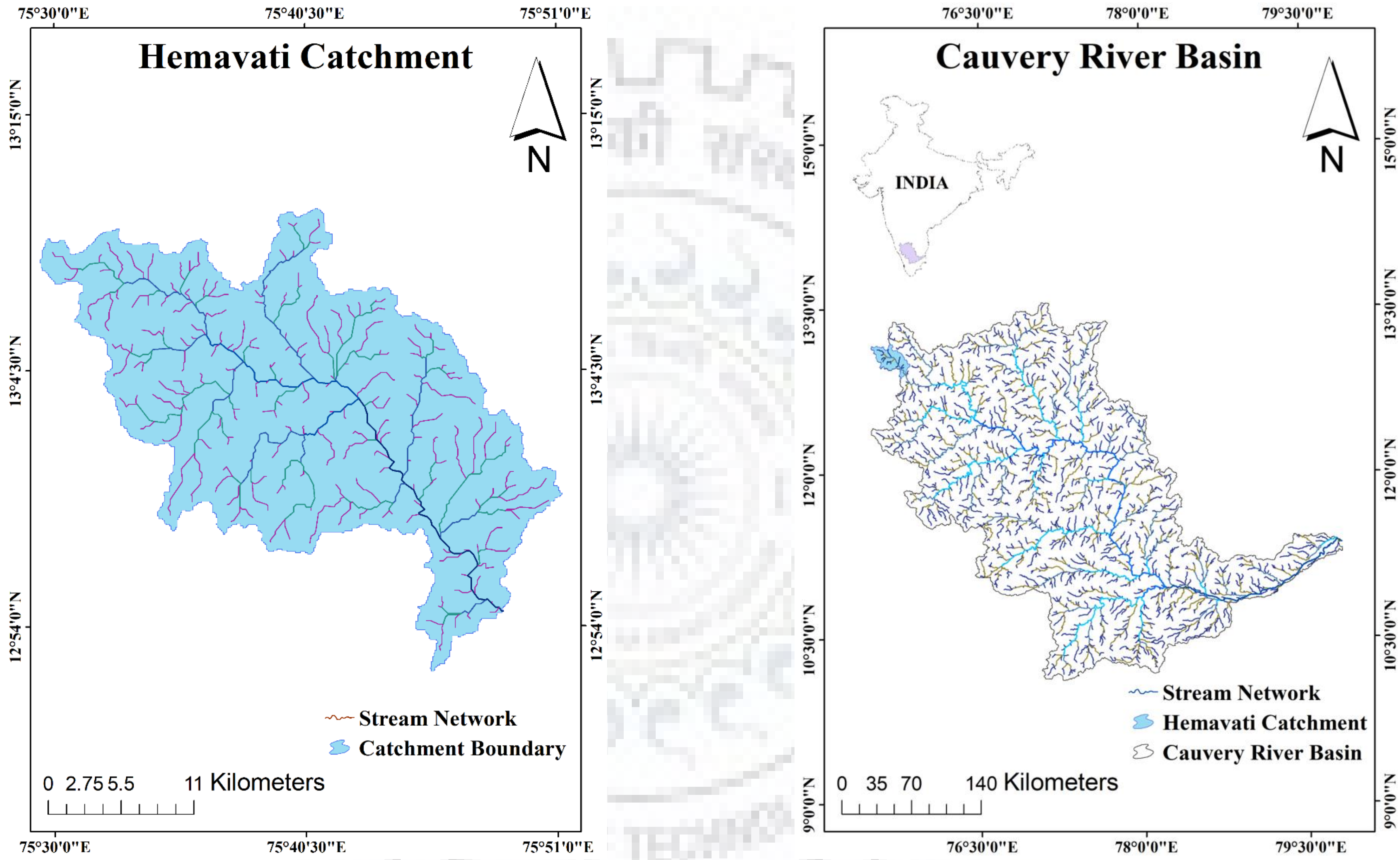


Figure 4.6 Location map of catchments under Cauvery River basin

The litho-units come across in the area are peninsular gneissic complex at the base superimposed by meta-volcano-sedimentary sequence of Dharwad Super-Group of rocks with younger intrusive of granites and dykes. The Anthroli catchment is locatd geographically between 15º21’58” N and 15º34’02” N Latitudes and 74º35’09” E and 74º55’46” E longitudes and drains 503 km^2 area from district Belgaum and Dharwad of the Karnataka state. The elevation of the Anthroli catchment varies between 536 – 846 m amsl. The Anthroli catchment experiences tropical monsoon climate with average annual precipitation of 939 mm. Pan evaporation in this catchment varies from 2 mm/day in winter to 11 mm/day in summer. The mean temperature in this catchment area varies from 16 ºC (in winter season) to 42 ºC in summer season. Red loamy group of soils dominants the catchment area.

4.5.2 Barchi Catchment

Barchi Catchment also belongs to the Kalinadi river of Western Ghats. Barchi catchment is located between 15º18’23” N and 15º23’31” N Latitudes and 74º36’19” E and 74º39’19” E longitudes and drains 14.5 km^2 area from Belgaum and Uttar Kannada districts of Karnataka state. The catchment area comprises of hilly zone of Karnataka which are covered with Forest and agricultural lands. The elevation of this catchment varies between 468 – 707 m amsl. The Barchi catchment is characterized by dry tropical monsoon climate with average annual rainfall of 1412 mm. Pan evaporation in this catchment varies from 2 mm/day in winter to 15 mm/day in summer. The temperature in this catchment varies from 17 ºC (in winter season) to 42 ºC in summer season. Brownish and fine-grained soil group characterizes the soil of this catchment.

4.5.3 Halkal Catchment

Halkal catchment is drained by the Kollur River in the Udupi district of Karnataka state. The coastal regions of Udupi district, Karnataka is characterized by sand estuaries, beaches, mudflats, creeks and mangrove patches. Udupi district receives average annual rainfall of 3000-4000 mm. Temperature is very low in the starting of January and gradually increases in the subsequent months. The coastal portions of this catchment record the highest temperature during the month of May and the average day temperature ranges from 16-38°C. The Halkal catchment is geographically located between 13º47’58” N and 13º54’52” N Latitudes and 74º42’46” E and 74º53’03” E longitudes and drains 108 km^2 area from Udupi district of Karnataka state.

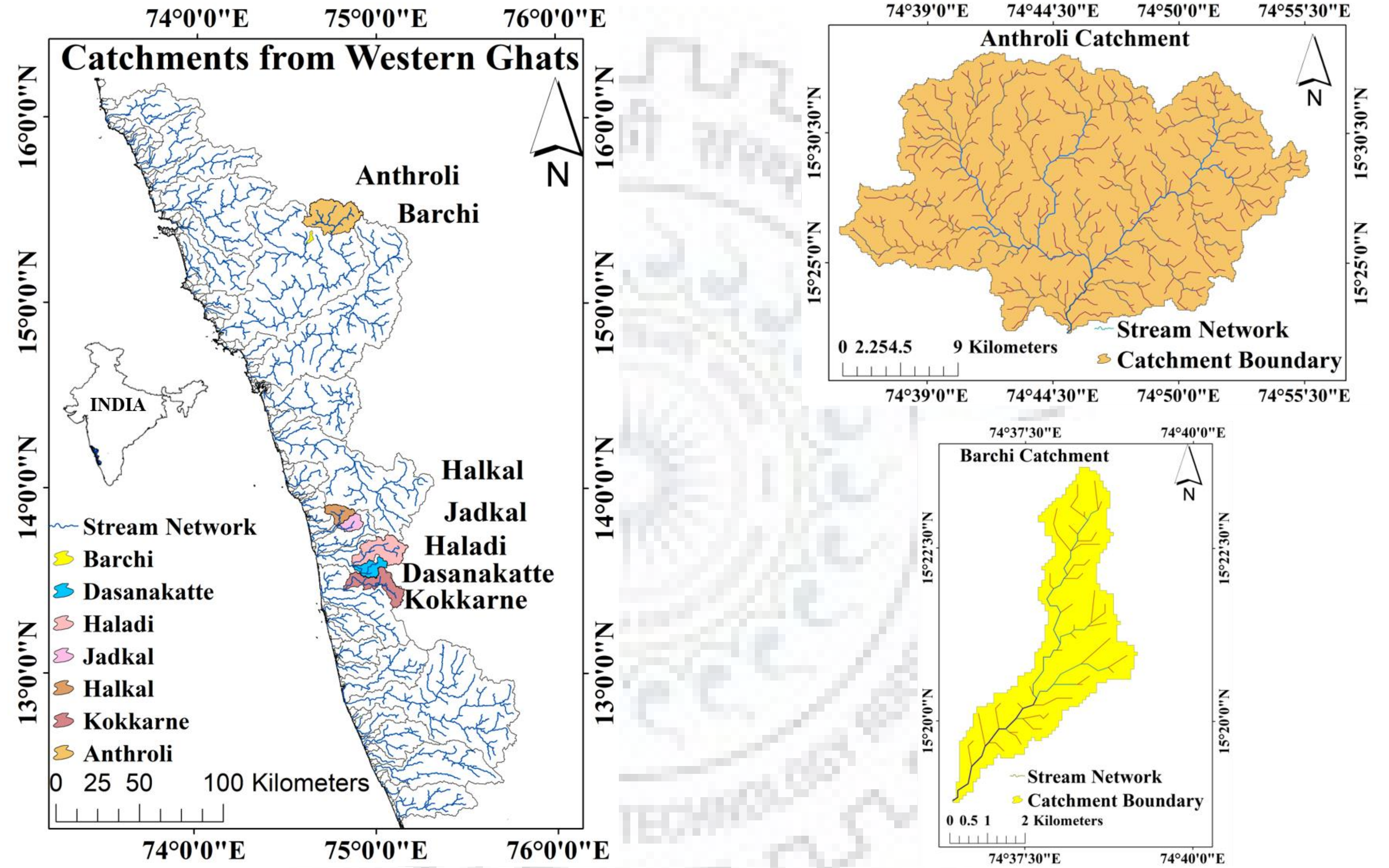
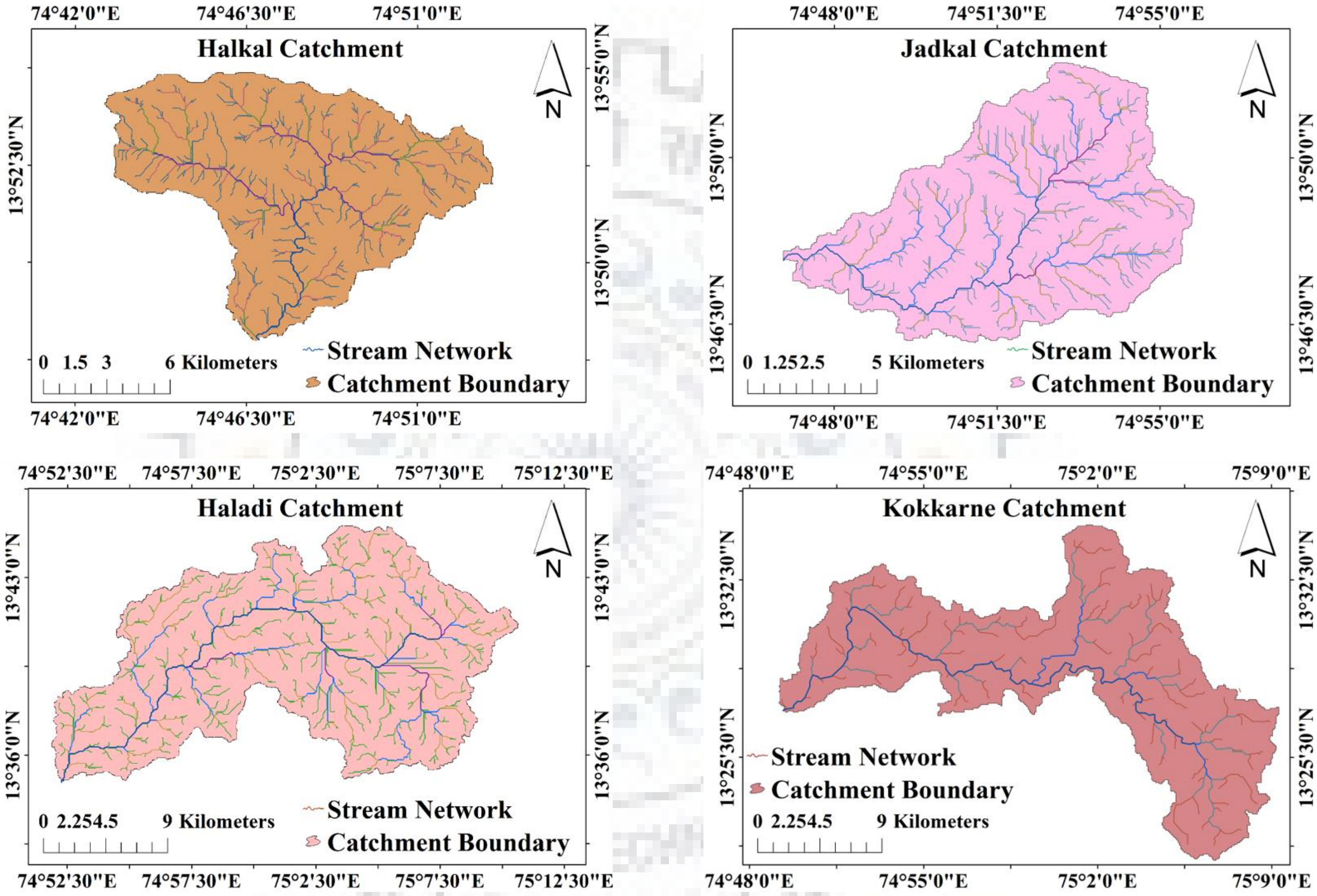


Figure 4.7 Location map of catchments from Western Ghats



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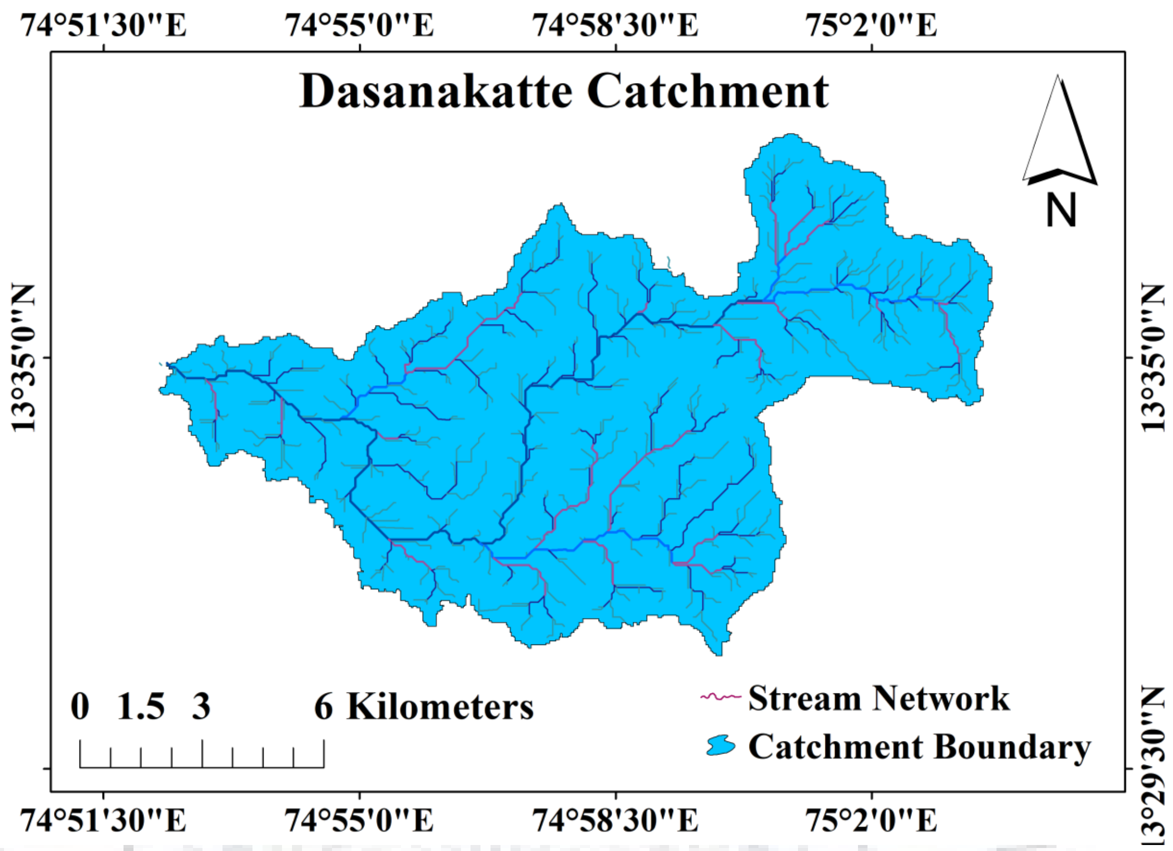


Figure 4.7 Continue…

The catchment area is characterized with hilly topography and covered with Megani valley reserved forest. The elevation of the Halkal catchment varies between 31 – 1333 m amsl. This catchment is characterized by humid climate with average annual rainfall of 5340 mm. Pan evaporation in this catchment varies from 2 mm/day in winter to 6 mm/day in summer. Laterite soil group characterizes the soil of this catchment.

4.5.4 Jadkal Catchment

Jadkal catchment also belongs to the Kollur river in Udupi district of Karnataka state that is adjacent to the Halkal catchment. Geographically, it is located between 13º46’07” N and 13º52’00” N Latitudes and 74º46’53” E and 74º55’46” E longitudes and drains 90 km^2 area from Udupi district of the Karnataka state. The catchment area is predominantly hilly and covered with reserved forest. The elevation of the Jadkal catchment varies between 33 – 1333 m amsl. The Jadkal catchment is characterized by humid climate with average annual rainfall of 5276 mm. The pan evaporation in this catchment varies from 2 mm/day in winter to 6 mm/day in summer. The temperature of this catchment varies from 16 ºC (in winter season) to 38 ºC in summer season. Laterite soil group characterizes the soil of this catchment.

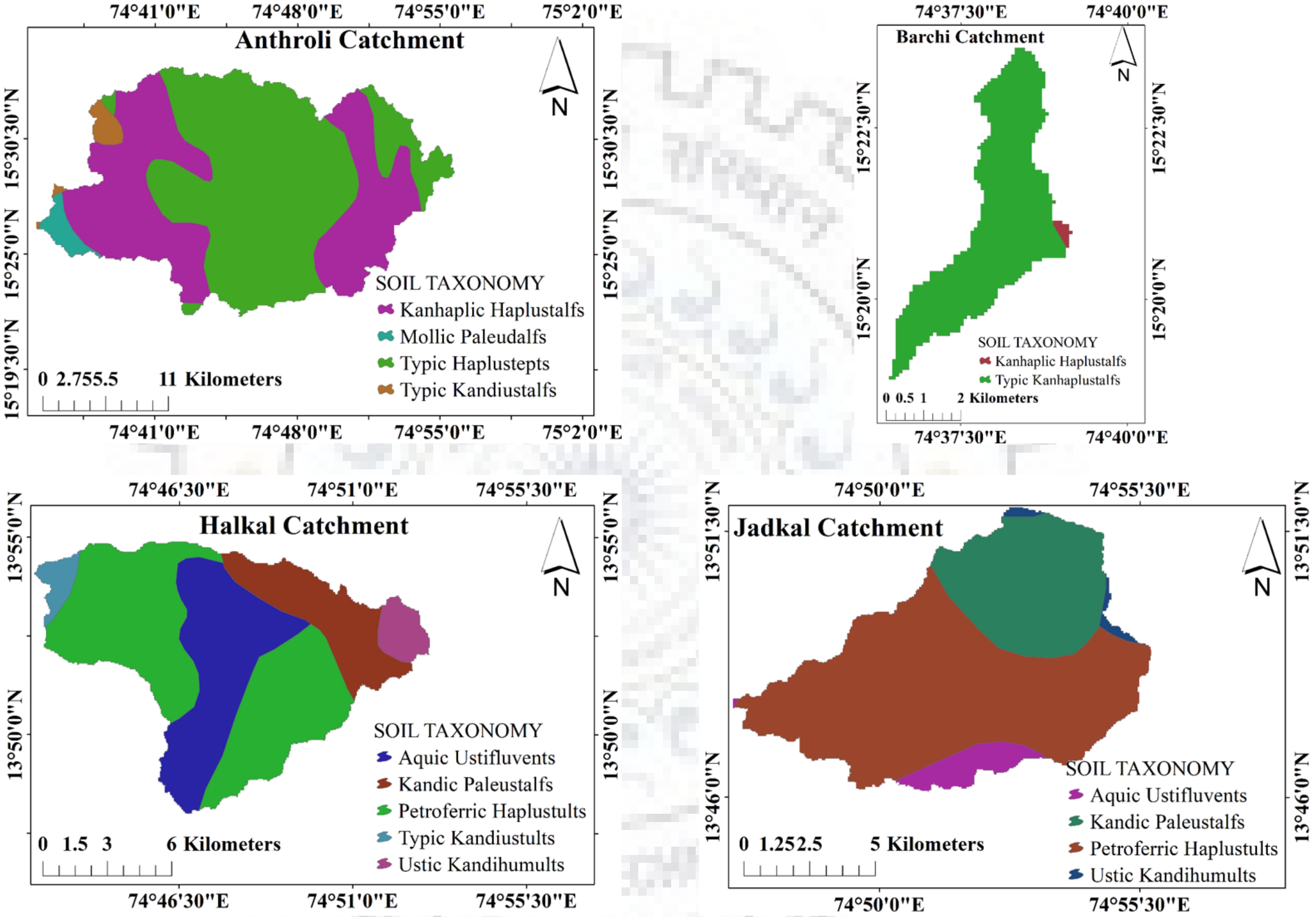
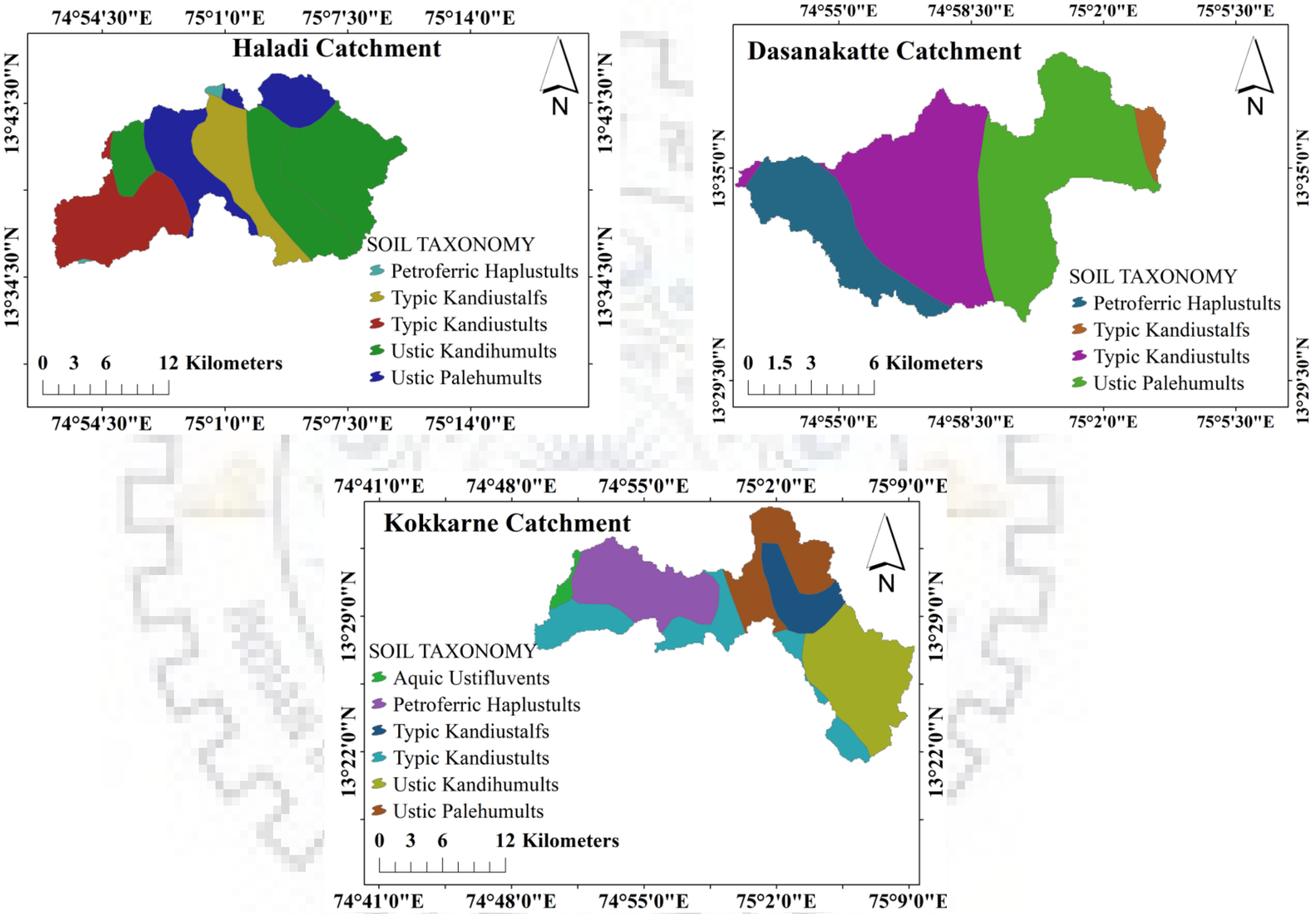


Figure 4.8 Taxonomy of soils of the catchments from Western Ghats



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4.5.5 Haladi Catchment

Haladi catchment belongs the Varahi river of Karnataka state. Varahi River is an important river in the state of Karnataka and is named after the Varaha, an embodiment of Hindu God Vishnu. The river has its origins in the Western Ghats (Shimoga district) and it terminates in the Arabian Sea. The source of Varahi River is at 730 m amsl at Hebbagilu village near a place named Agumbe, which is commonly referred to as Cherrapunji of the Karnataka state. The river runs a course of 25 km in its early stage and then goes down 455m fall to form the famous Kunchikal Falls. Geographically, the Haladi catchment is located between 13º35’02” N and 13º45’05” N Latitudes and 74º51’50” E and 75º10’40” E longitudes and drains 505 km^2 area from Udupi district of the Karnataka state. The catchment area is predominantly hilly and covered with reserved forest. The elevation of the Haladi catchment varies between 7 – 964 m amsl. The Haladi catchment is characterized by humid climate with average annual rainfall of 4556 mm. Pan evaporation in catchment area varies from 2 mm/day in winter to 6 mm/day in summer. The temperature of this catchment varies from 12 ºC (in winter season) to 38 ºC in summer season. Laterite soil group characterizes the soil of this catchment.

4.5.6 Dasanakatte Catchment

Dasanakatte catchment also belongs to the tributary of Varahi River, Karnataka. Geographically, the Dasanakatte catchment is located between 13º31’02” N and 13º38’02” N Latitudes and 74º52’14” E and 75º03’42” E longitudes that covers 135 km^2 area from Udupi district of the Karnataka state. The catchment is hilly and mostly covered with reserved forest. The elevation of the Haladi catchment varies between 7 – 874 m amsl. The Dasanakatte catchment is characterized by humid climate with average annual rainfall of 4679 mm. The temperature of this catchment varies from 16 ºC (in winter season) to 38 ºC in summer season. Laterite soil group characterizes the soil of this catchment.

4.5.7 Kokkarne Catchment

Kokkarne catchment belongs to the Sitanadi river basin of Karnataka state. Sitanadi river basin is located in the west coastal zone of India, Udupi district, Karnataka state. The catchment is located between 13º11’24” N and 13º34’43” N Latitudes and 74º49’08” E and 75º09’18” E longitudes that covers 343 km^2 area from Udupi district of the Karnataka state. The Kokkarne catchment is characterized by humid climate with an average annual rainfall of 5133 mm. The pan evaporation in this area varies from 3 mm/day in winter to 7 mm/day in summer. The temperature of this catchment varies from 16 ºC (in winter season) to 38 ºC in summer season.

The elevation of the Kokkarne catchment varies between 10 – 1147 m amsl. Physiographical divisions consist of midland, low land, and high land. The low land region is 2-8 km wide with sandy tract running parallel to the coast that extends up to a distance of 16 km along the river path. It has small lateritic ridges with cultivable low lands, in between small exposures of gneisses and laterite hillocks with light vegetation. The midland region comprises of laterite ridges and structural hills composed of gneisses with incised tapered valleys of younger cycle. High land hills contain mostly of etavolcanics, archaean gneisses and metasediments of Dharwad super group of Proterozoic age. The foremost lithological units of Sitanadi river basin are banded granitic gneisses, laterites and chlorite schist's covers some parts. Thin layer of coastline sediments is also found in the western portion of the basin.

4.6 HYDRO-METEOROLOGICAL DATA

For the present study, input data consisting of rainfall, pan evaporation and observed runoff data is required for calibration and validation of the model. In addition, soil map and land use/land cover maps are also needed as the input in one of the studied model. The soil map of the studied catchments have been obtained from National Bureau of Soil Survey and Land Use Planning (NBSSLUP), India. As the measured pan evaporation data is not readily available for these catchments, the same was extracted from the mean monthly evaporation maps of India which are available at Indian Meteorological Department (IMD) website (http://www.imdagrimet.gov.in/node/92). In these maps evaporation data from a dense network system of 176 observatories have been used to prepare the evaporation maps. These evaporation maps have been developed based on fairly long period averages i.e. a period of 12-26 years of evaporation data and thus gives a fairly good idea of spatial and temporal distribution of the evaporation which is a regional parameter. The available maps are based on the averages of the mean daily evaporation in mm for all the twelve months and average annual total evaporation in cm. These maps also show the geographical locations of different types of observatories which are included in preparations of these maps. At these meteorological stations, evaporation is recorded twice a day from wire mesh covered class A pan evaporimeter.

The daily rainfall and discharge data of the selected catchments have been collected from the India Meteorological Department (IMD), Water Resources Development Organization (WRDO), Bangalore, Karnataka (India) and IndiaWRIS website (http://www.india-wris.nrsc.gov.in/wris.html) for use in this study. The IndiaWRIS is a Web Enabled Water Resources Information System of India which has been setup by the Central Water Commission

(CWC) of India, in association with Indian Space Research Organization (ISRO). The IndiaWRIS Web-GIS aims as a Single Window platform where the authoritative, comprehensive and consistent data and information of India’s water resources system is available. It also stores related natural resources data in a standardized nationwide GIS framework (WGS-84 datum and LCC projection) with tools to visualize, search, access, understand and analyse the data for assessment, planning, monitoring, development and finally Integrated Water Resources Management (IWRM).

5

ANALYSIS AND DISCUSSION OF RESULTS

5.1 GENERAL

Hydrological models may vary in structure, representation of runoff generation process, type and complexity to represent dominant hydrological processes operating in a catchment. In order to determine their suitability and adequacy of representation of hydrological processes being modelled, these models needs to be assessed to test their ability in reproducing the observed catchment behaviour. This Chapter deals with this objective, by calibrating and validating the existing models and the proposed modified models by employing data from catchments operating under different climatic conditions using common performance evaluation criteria discussed in the previous Chapter.

5.2 CALIBRATION OF MODEL PARAMETERS

Mathematical rainfall-runoff models use a number of parameters for their operation and handling of different hydrological processes operating on them, depending on the conceptual framework, process representation, spatial representation and prediction capability of the hydrological model. For calibration of the parameters of models, observed stream flow time series data is used. In this study, the available observed hydrological data have been split into two groups, one group for aiding the calibration of parameters of the model, and the other group of data used to validate the performance of the calibrated models. In this study, the performance of Xinanjiang rainfall-runoff model (Zhao, 1992) and its three modified versions by Nirupama et al. (1996), Hu et al. (2005) and Lin et al. (2014) have been evaluated. In addition, two new modified versions of the Xinanjiang model termed hereafter as XIN-CN and DVIC have also been evaluated. The calibration of all these models have been performed using rainfall-runoff data observed at one-day time interval. The performances of the models in reproducing different features of the hydrological behaviour of the catchment have been assessed using the statistical indices like NSE, R^2, RMSE and %RE besides the visual comparison.

5.2.1 Parameter estimation of the studied models

The Xinanjiang model and its variants and the proposed hybrid model use a number of parameters, to represent different hydrological processes. For calibration of parameters of the models used in this study, the Shuffled Complex Evolution global optimization algorithm developed by the University of Arizona (SCE-UA) by Duan et al. (1992) is used in this study. The objective of the SCE-UA method is to combine the strength of the simplex procedure (Nelder and Mead, 1965) with the concepts of controlled random parameters search (Price, 1987), competitive evolution (Holland, 1975) and complex shuffling. SCE-UA method is capable to complete the searching of parameters even in one run (Gan and Biftu, 1996). Zhang et al. (2015) showed while applying SCE-UA method for optimizing the hydrological model parameters, the parameter estimates are not affected by the data length used and this indicates the robustness of the SCE-UA algorithm. Tables 5.1 to 5.6 show the initial, upper and lower bound of parameter values along with the optimized value of parameters obtained for all the studied models. The value of each parameter is usually bounded by certain range according to mathematical constraints and physical significance and information regarding the range of parameters value is deduced from catchment characteristics and modelling experiences (Wang et al., 2012). In this study, the range of different parameters have been selected based on the recommended range adopted from previous studies, for example, Jayawerdena, (2000), Dong et al., (2009), Zhijia et al., (2011) and Wang et al., (2012) and the physical catchment characteristics. In the models of Zhao (1992), Lin et al. (2014) and the proposed DVIC model, 13 parameters have been studied and calibrated, while in the model proposed by Nirupama (1996) and the XIN-CN model, 14 parameters have been calibrated, and in the model by Hu et al. (2005), 15 parameters have been calibrated. Though, the set of optimized values of parameters obtained by the SCE-UA could reproduce a good model in reproducing the observed outputs, but for some catchments, the peaks and recession segments of the observed hydrograph could not be reproduced well requiring a manual adjustment of few parameters for improving the match with respect to peaks and recession curves.

It is found in the literature that the Xinanjiang model was modified by adding some parameters in the runoff generation sub-module (Nirupama, 1996; Jayawardena, 2000; Hu et al. 2005) and in the evapotranspiration sub-module (Nirupama, 1995; Li et al. 2009). In this study, the evapotranspiration in the proposed DVIC model is related to the potential evapotranspiration through a single layer soil moisture (W) by considering a parameter CE. The value of parameter CE varies between 0 – 1, because the estimated evapotranspiration cannot be more than the available soil moisture (W). Since the soil moisture (W) is a larger value as compared to the pan evaporation and therefore, a small value of parameter CE is sufficient for the estimation of evapotranspiration Therefore, the parameter CE obtained is a very small value during the process of calibration, as seen from Table 5.6.

In the model proposed by Lin et al., (2014), WM is visualized as a function of S_I. Therefore, the curve number grid of different catchments have been generated using the spatial maps of soil type and landuse present in the catchments using standard SCS-CN tables from Mishra and Singh, 2003. In this study HEC-Geo HMS extension in ArcGIS have been used to generate curve number grids. Table 5.7 shows the values of S_I and Figure 5.1 shows the CNGRID map of the Hemavati catchment as illustrated and the CNGRID maps for rest of the catchments are shown in APPENDIX-VI.

5.2.2 Inter-comparison of the Studied Models

To compare the performance of the studied models, the catchments selected for this study have been grouped into three categories as wet, average and dry based on average value of runoff coefficient. Accordingly, the catchment having a runoff coefficient more than 0.65 has been classified as a wet catchment, the catchment having a runoff coefficient between 0.36 and 0.65, has been classified as average catchment and the catchment having a runoff coefficient less than or equal to 0.35, has been classified as a dry catchment (Gan et al., 1997, Durbude et al., 2011, Jain et al., 2012) representing humid, average and dry climatic conditions respectively. Accordingly, six out of twenty catchments, namely, Haladi, Jadkal, Dasanakatte, Halkal, Kokkarne and Hemavati fall into the wet category, nine catchments, namely, Khanpur, Dindori, Chidgaon, Gadarwara, Belkheri, Manot, Bamni Banjar, Patan and Anthroli into the average category, and the remaining five catchments, namely, Kogaon, Barchi, Mohegaon, Amachi and Hridaynagar fall under dry category. The calibration and validation of Patan catchment has not been carried out for Lin et al. (2014) model due to unavailability of soil map and land use data for this catchment.

Tables 5.8 to 5.11 show the performance evaluation values of statistical indices obtained during the calibration period for the existing and the proposed hybrid conceptual models, i.e., XIN-CN and DVIC for comparison purposes for all the three climatic categories of catchments. Tables 5.8 to 5.11 also shows the maximum and minimum values of the statistical indices value for each of the catchments (Numbers in bold font represent the maximum value while the underlined italic bold numbers represent the minimum values for the respective models for each the studied catchments).

Table 5.1 Details of Parameter values of the studied catchments for the Xinanjiang model of Zhao, (1992)

S. No.	1	2	3	4	5	6	7	8	9	10	11	12	13
Model Parameter	K	WM	X	Y	C	B	SM	EX	KG	KI	CG	CI	CS
Initial value	0.500	200.000	0.000	5.000	0.100	0.900	10.000	0.900	0.050	0.500	0.990	0.500	0.200
Lower bound	0.001	70.000	0.000	0.100	0.080	0.000	10.000	0.100	0.010	0.500	0.900	0.500	0.100
Upper bound	1.700	1500.000	1.000	50.000	0.150	2.000	200.000	7.000	0.200	0.800	0.999	0.990	0.999
CATCHMENT	**OPTIMIZED PARAMETER VALUES**												
Haladi	0.149	559.596	0.609	33.505	0.113	0.960	85.530	0.485	0.072	0.641	0.992	0.962	0.571
Jadkal	0.167	579.521	0.507	12.409	0.099	1.259	54.087	5.290	0.011	0.797	0.993	0.954	0.560
Dasanakatte	0.299	696.454	0.944	20.702	0.113	1.473	71.993	0.420	0.015	0.800	0.998	0.957	0.540
Halkal	0.477	684.980	0.803	38.631	0.116	0.985	52.130	1.124	0.011	0.800	0.992	0.960	0.594
Kokkarne	0.925	645.252	0.737	20.032	0.128	1.315	51.834	0.307	0.019	0.725	0.993	0.941	0.528
Hemavati	0.558	609.891	0.672	26.541	0.139	0.945	50.638	1.894	0.011	0.730	0.993	0.957	0.599
Khanpur	1.700	1473.091	0.012	44.402	0.089	1.491	299.499	0.247	0.200	0.594	0.999	0.908	0.370
Dindori	1.006	404.578	0.344	14.610	0.094	1.309	26.003	0.601	0.163	0.563	0.996	0.968	0.204
Chidgaon	0.805	291.170	0.321	22.109	0.103	0.597	55.632	1.063	0.144	0.645	0.992	0.831	0.100
Gadarwara	0.795	280.256	0.314	28.450	0.130	0.889	50.442	2.764	0.131	0.670	0.995	0.926	0.517
Belkheri	0.977	170.981	0.297	23.697	0.121	0.985	52.341	3.876	0.126	0.686	0.995	0.934	0.139
Manot	1.089	144.085	0.823	27.097	0.105	0.103	40.444	0.384	0.199	0.759	0.999	0.897	0.347
Bamni Banjar	1.473	266.357	0.005	37.034	0.145	0.156	102.438	1.458	0.191	0.628	0.998	0.874	0.344
Patan	1.174	416.562	0.889	22.741	0.104	0.110	122.627	0.163	0.200	0.502	0.999	0.753	0.598
Anthroli	1.572	102.266	0.045	30.449	0.110	1.212	43.104	4.754	0.193	0.751	0.999	0.966	0.530
Kogaon	0.629	257.583	0.075	33.065	0.137	0.896	26.666	0.313	0.131	0.604	0.994	0.932	0.109
Barchi	1.357	819.373	0.096	36.911	0.109	1.488	274.033	1.638	0.094	0.100	0.999	0.817	0.594
Mohegaon	0.996	110.972	0.796	12.561	0.122	0.125	33.823	0.186	0.200	0.800	0.999	0.892	0.100
Amachi	1.368	366.994	0.900	23.580	0.102	0.488	133.647	0.919	0.200	0.608	0.999	0.981	0.456
Hridaynagar	1.601	506.397	0.104	4.978	0.120	1.389	40.790	5.113	0.200	0.681	0.998	0.965	0.599

Table 5.2 Details of Parameter values of the studied catchments for the modified Xinanjiang model (Nirupama, 1996)

S. No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Model Parameter	K	WM	X	Y	C	B	SM	EX	KG	KI	CG	CI	CS	m
Initial value	0.500	200.000	0.000	5.000	0.100	0.900	10.000	0.900	0.050	0.500	0.990	0.500	0.200	2.000
Lower bound	0.001	70.000	0.000	0.100	0.080	0.000	10.000	0.100	0.010	0.500	0.900	0.500	0.100	1.001
Upper bound	1.700	1500.000	1.000	50.000	0.150	2.000	200.000	7.000	0.200	0.800	0.999	0.990	0.999	50.000
CATCHMENT	**OPTIMIZED PARAMETER VALUES**													
Haladi	0.098	500.594	0.875	12.700	0.113	0.608	85.806	0.492	0.060	0.653	0.994	0.964	0.568	16.643
Jadkal	0.200	610.840	0.857	10.517	0.119	0.483	53.896	5.857	0.011	0.796	0.990	0.953	0.558	38.133
Dasanakatte	0.298	644.479	0.609	31.132	0.110	0.533	71.784	0.424	0.023	0.796	0.994	0.957	0.544	14.841
Halkal	0.470	823.083	0.621	37.883	0.099	0.313	52.271	1.134	0.013	0.795	0.991	0.960	0.595	25.375
Kokkarne	0.956	597.257	0.783	32.447	0.128	0.402	53.237	0.259	0.016	0.679	0.992	0.941	0.526	30.680
Hemavati	0.575	650.892	0.585	37.381	0.088	0.972	53.886	3.608	0.025	0.793	0.991	0.952	0.599	16.421
Khanpur	1.687	637.288	0.038	20.078	0.088	1.299	289.296	0.252	0.148	0.518	0.999	0.923	0.509	35.468
Dindori	0.982	264.663	0.810	34.316	0.113	1.283	35.868	0.498	0.164	0.539	0.997	0.940	0.157	27.751
Chidgaon	0.740	262.709	0.388	24.986	0.112	0.238	54.271	0.916	0.190	0.747	0.995	0.852	0.100	23.936
Gadarwara	0.716	375.911	0.318	27.149	0.123	0.669	53.302	2.497	0.137	0.589	0.995	0.921	0.553	22.003
Belkheri	0.438	579.373	0.463	22.055	0.118	1.083	41.035	3.029	0.136	0.678	0.996	0.941	0.232	27.721
Manot	1.260	143.412	0.843	30.147	0.117	0.160	33.547	0.475	0.161	0.578	0.994	0.903	0.402	15.660
Bamni Banjar	1.613	246.253	0.023	32.495	0.142	0.173	99.169	1.510	0.185	0.579	0.993	0.845	0.375	9.084
Patan	1.350	524.320	0.583	33.417	0.109	0.111	119.142	0.190	0.200	0.533	0.998	0.764	0.599	8.512
Anthroli	0.941	194.933	0.209	32.599	0.084	1.315	34.406	3.909	0.197	0.785	0.999	0.980	0.589	31.916
Kogaon	0.617	254.570	0.092	34.058	0.146	0.479	27.478	0.383	0.094	0.774	0.992	0.932	0.100	34.733
Barchi	1.695	546.206	0.017	12.231	0.097	0.101	169.487	0.328	0.198	0.501	0.999	0.948	0.596	17.531
Mohegaon	0.977	269.155	0.326	42.316	0.086	0.115	33.896	0.188	0.200	0.796	0.999	0.895	0.100	1.265
Amachi	1.389	356.556	0.996	45.724	0.097	0.423	138.130	0.903	0.200	0.510	0.999	0.980	0.468	28.337
Hridaynagar	1.671	387.182	0.369	30.605	0.121	1.242	89.951	3.428	0.199	0.638	0.996	0.862	0.414	25.161

Table 5.3 Details of Parameter values of the studied catchments for the hybrid Xinanjiang model (Hu, 2005)

S. No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Model Parameter	K	WM	X	Y	C	B	CS	CG	FC	k	cm	a1	a2	a3	a4
Initial value	0.100	120.000	0.500	0.200	0.100	0.200	0.900	0.900	0.250	0.100	0.100	300.000	0.300	0.00000001	0.00000001
Lower bound	0.001	70.000	0.000	0.000	0.080	0.000	0.100	0.900	0.000	0.000	0.000	32.000	0.100	0.00000000	0.00000000
Upper bound	1.700	1500.000	1.000	50.000	0.150	2.000	0.999	0.999	31.200	1.000	5.000	3000.000	1.000	0.00090005	0.00000005
CATCHMENT	**OPTIMIZED PARAMETER VALUES**														
Haladi	0.246	699.491	0.915	40.037	0.081	1.992	0.801	0.979	13.114	0.000	0.263	346.985	0.459	0.00000003	0.00000004
Jadkal	0.484	531.930	0.994	11.127	0.118	0.136	0.800	0.900	10.512	0.603	1.742	531.705	0.983	0.00002366	0.00000004
Dasanakatte	0.379	508.425	0.777	19.354	0.127	0.356	0.800	0.957	26.743	0.292	0.280	251.060	0.435	0.00000002	0.00000003
Halkal	0.604	578.811	0.890	23.023	0.107	0.480	0.800	0.971	3.978	0.033	1.850	173.264	0.296	0.00000003	0.00000003
Kokkarne	0.899	664.326	0.933	33.438	0.116	0.092	0.800	0.907	11.027	0.137	0.985	279.331	0.432	0.00000002	0.00000001
Hemavati	0.548	383.991	0.912	13.973	0.110	0.010	0.800	0.961	14.848	0.904	0.006	197.079	0.497	0.00000001	0.00000002
Khanpur	1.678	529.105	0.766	34.204	0.116	0.156	0.822	0.975	30.746	0.198	1.865	176.817	0.466	0.00000003	0.00000003
Dindori	1.622	644.481	0.321	22.607	0.140	0.292	0.800	0.968	10.800	0.221	1.663	221.366	0.483	0.00000003	0.00000004
Chidgaon	0.638	354.161	0.453	36.831	0.140	0.007	0.800	0.900	9.191	0.876	1.843	231.153	0.466	0.00000003	0.00000001
Gadarwara	1.512	1014.914	0.439	21.395	0.144	0.731	0.800	0.918	6.570	0.225	1.294	259.496	0.469	0.00000003	0.00000004
Belkheri	0.764	1125.824	0.106	17.770	0.149	0.012	0.800	0.984	8.935	0.202	1.380	350.708	0.283	0.00000003	0.00000003
Manot	1.573	98.549	0.839	14.806	0.107	0.064	0.800	0.902	7.817	0.985	1.830	314.153	0.262	0.00000003	0.00000002
Bamni Banjar	1.347	517.790	0.244	22.163	0.140	0.224	0.801	0.940	11.399	0.003	0.855	258.236	0.571	0.00000003	0.00000001
Patan	1.582	428.660	0.567	20.039	0.132	0.087	0.800	0.900	16.815	0.880	1.095	679.635	0.333	0.00002328	0.00000003
Anthroli	1.503	1495.125	0.324	26.390	0.080	0.289	0.800	0.972	12.330	0.993	0.804	200.853	0.398	0.00034736	0.00000000
Kogaon	1.188	885.826	0.385	25.052	0.115	0.484	0.800	0.982	6.535	0.893	0.062	221.995	0.397	0.00001159	0.00000004
Barchi	1.694	371.783	0.864	36.833	0.089	0.012	0.800	0.999	0.083	0.037	1.918	204.082	0.391	0.00002908	0.00000002
Mohegaon	1.164	249.004	0.203	14.288	0.112	0.013	0.800	0.901	8.904	0.969	1.938	266.541	0.365	0.00022459	0.00000003
Amachi	1.699	697.970	0.589	29.967	0.080	0.351	0.800	0.982	1.896	0.104	1.675	684.962	0.404	0.00000002	0.00000002
Hridaynagar	1.681	360.905	0.447	19.379	0.143	0.242	0.800	0.901	13.169	0.951	1.134	681.068	0.373	0.00000003	0.00000003

Table 5.4 Details of Parameter values of the studied catchments for the modified hybrid Xinanjiang model (Lin, 2014)

S. No.	1	2	3	4	5	6	7	8	9	10	11	12	13
Model Parameter	K	α	X	Y	C	B	SM	EX	KG	KI	CG	CI	CS
Initial value	0.500	1.500	0.000	5.000	0.100	0.900	10.000	0.900	0.050	0.500	0.990	0.500	0.200
Lower bound	0.001	1.000	0.000	0.100	0.080	0.000	10.000	0.100	0.010	0.500	0.900	0.500	0.100
Upper bound	1.700	2.000	1.000	50.000	0.150	2.000	200.000	7.000	0.200	0.800	0.999	0.990	0.999
CATCHMENT	**OPTIMIZED PARAMETER VALUES**												
Haladi	0.098	1.248	0.680	23.393	0.113	0.760	87.387	0.463	0.093	0.646	0.992	0.962	0.575
Jadkal	0.154	1.309	0.844	21.804	0.110	1.110	54.220	5.369	0.010	0.796	0.992	0.956	0.565
Dasanakatte	0.285	1.995	0.995	14.608	0.105	1.250	72.099	0.410	0.025	0.796	0.996	0.958	0.546
Halkal	0.890	2.000	0.995	11.739	0.114	1.492	59.958	6.528	0.016	0.799	0.991	0.959	0.597
Kokkarne	1.217	1.999	0.996	14.907	0.140	1.208	68.266	0.913	0.010	0.792	0.990	0.946	0.487
Hemavati	0.656	1.978	0.995	15.046	0.131	1.283	54.285	3.678	0.011	0.799	0.992	0.954	0.599
Khanpur	1.699	1.003	0.118	15.197	0.111	0.015	175.441	0.377	0.200	0.748	0.999	0.948	0.598
Dindori	0.986	1.066	0.903	34.564	0.132	1.148	26.681	0.480	0.180	0.503	0.998	0.964	0.173
Chidgaon	0.893	1.673	0.505	19.393	0.137	0.020	55.017	0.954	0.154	0.564	0.993	0.803	0.100
Gadarwara	0.793	1.645	0.373	21.116	0.130	1.064	49.830	2.632	0.154	0.706	0.997	0.927	0.509
Belkheri	0.885	1.358	0.331	24.142	0.131	0.617	50.833	4.467	0.167	0.748	0.993	0.939	0.141
Manot	1.157	1.042	0.575	28.781	0.083	0.365	40.102	0.379	0.194	0.704	0.998	0.888	0.348
Bamni Banjar	1.551	1.884	0.021	35.844	0.148	0.507	100.202	0.977	0.186	0.520	0.995	0.849	0.371
Patan	1.311	1.778	0.694	22.732	0.140	0.182	125.254	0.152	0.200	0.707	0.998	0.747	0.599
Anthroli	1.220	1.376	0.039	46.998	0.081	0.682	50.601	3.829	0.196	0.536	0.999	0.969	0.523
Kogaon	0.626	1.945	0.086	21.473	0.133	1.373	26.052	0.413	0.198	0.780	0.992	0.922	0.102
Barchi	1.499	1.003	0.690	24.824	0.097	0.769	164.657	0.426	0.200	0.502	0.999	0.944	0.577
Mohegaon	1.133	1.214	0.318	25.124	0.092	0.066	40.014	0.186	0.113	0.502	0.995	0.873	0.100
Amachi	1.375	1.781	0.956	14.208	0.091	0.444	133.104	0.976	0.200	0.619	0.999	0.981	0.476
Hridaynagar	1.559	1.978	0.334	49.180	0.142	1.400	36.975	4.865	0.199	0.799	0.999	0.968	0.598

Table 5.5 Details of Parameter values of the studied catchments for the proposed modified hybrid Xinanjiang model (XIN-CN)

S. No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Model Parameter	K	WM	X	Y	C	B	SM	EX	KG	KI	CG	CI	CS	a
Initial value	0.500	200.000	0.000	5.000	0.100	0.900	10.000	0.900	0.050	0.500	0.990	0.500	0.200	1.100
Lower bound	0.001	70.000	0.000	0.100	0.080	0.000	10.000	0.100	0.010	0.500	0.900	0.500	0.100	1.000
Upper bound	1.700	1500.000	1.000	50.000	0.150	2.000	200.000	7.000	0.200	0.800	0.999	0.990	0.999	10.000
CATCHMENT	**OPTIMIZED PARAMETER VALUES**													
Haladi	0.150	505.864	0.689	26.093	0.130	1.396	96.701	0.571	0.096	0.664	0.992	0.964	0.501	3.694
Jadkal	0.200	697.147	0.673	8.733	0.121	1.995	113.853	3.044	0.011	0.793	0.990	0.965	0.500	1.393
Dasanakatte	0.295	582.960	0.841	29.988	0.095	1.591	87.810	3.764	0.042	0.800	0.993	0.959	0.516	4.410
Halkal	0.480	617.552	0.923	37.861	0.120	1.329	140.272	3.726	0.087	0.800	0.990	0.966	0.494	1.463
Kokkarne	0.899	526.185	0.837	2.074	0.120	0.716	63.483	1.401	0.016	0.734	0.990	0.946	0.464	3.649
Hemavati	0.570	492.192	0.717	21.447	0.109	0.864	50.025	4.903	0.012	0.772	0.991	0.964	0.641	3.572
Khanpur	1.245	360.264	0.858	18.944	0.128	0.929	298.950	3.392	0.200	0.798	0.999	0.970	0.436	2.726
Dindori	1.023	187.623	0.883	7.693	0.120	1.279	42.736	0.327	0.188	0.759	0.996	0.978	0.000	2.444
Chidgaon	0.764	252.745	0.691	32.051	0.135	0.270	52.201	0.545	0.162	0.604	0.994	0.811	0.000	6.625
Gadarwara	0.580	355.478	0.296	41.586	0.150	1.711	98.023	5.148	0.186	0.694	0.999	0.962	0.502	1.685
Belkheri	0.928	186.034	0.444	40.686	0.119	0.152	90.572	5.882	0.106	0.506	0.998	0.926	0.001	1.987
Manot	1.200	141.924	0.873	41.363	0.126	0.068	53.326	6.221	0.185	0.503	0.997	0.913	0.324	3.110
Bamni Banjar	1.164	255.819	0.231	11.067	0.123	0.430	82.442	0.526	0.130	0.504	0.999	0.969	0.484	3.131
Patan	1.506	492.294	0.606	18.880	0.147	0.356	87.500	0.641	0.200	0.633	0.997	0.782	0.703	3.904
Anthroli	1.096	160.345	0.177	34.305	0.135	0.167	82.014	5.352	0.178	0.592	0.999	0.988	0.449	2.405
Kogaon	0.514	285.147	0.084	20.969	0.105	0.860	26.044	5.197	0.164	0.709	0.994	0.962	0.200	5.696
Barchi	1.519	915.964	0.090	31.061	0.081	0.095	135.686	3.415	0.199	0.500	0.999	0.970	0.384	3.215
Mohegaon	1.187	143.302	0.415	18.750	0.096	0.161	37.669	0.283	0.065	0.501	0.994	0.920	0.200	6.036
Amachi	1.295	386.869	0.938	15.317	0.091	0.187	130.526	4.957	0.200	0.519	0.999	0.986	0.506	7.347
Hridaynagar	1.620	328.320	0.345	26.018	0.128	0.429	66.162	3.641	0.132	0.585	0.995	0.971	0.482	3.234

Table 5.6 Details of Parameter values of the studied catchments for the proposed modified hybrid Xinanjiang model (DVIC)

S. No.	1	2	3	4	5	6	7	8	9	10	11	12	13
Model Parameter	CE	CW	fc	cb	CS	KG	CG	a1	a2	a3	a4	k	WM
Initial value	0.18000000	0.25000000	7.000	0.200	0.100	0.200	0.900	300.000	0.010	0.00000001	0.00000001	0.100	100.000
Lower bound	0.00000000	0.25000000	0.000	0.000	0.100	0.001	0.800	32.000	0.000	0.00000000	0.00000000	0.000	70.000
Upper bound	1.00000000	0.43243243	31.200	5.000	0.950	0.900	0.999	3000.000	1.000	0.00000005	0.00000005	1.000	900.000
CATCHMENT	**OPTIMIZED PARAMETER VALUES**												
Haladi	0.00051330	0.27591512	18.792	1.995	0.544	0.018	0.802	247.535	0.280	0.00000000	0.00000003	0.001	152.300
Jadkal	0.00012302	0.32735197	8.475	4.941	0.472	0.014	0.800	465.524	0.499	0.00000001	0.00000000	0.135	260.221
Dasanakatte	0.00144693	0.29267776	18.851	4.932	0.482	0.021	0.800	522.472	0.403	0.00000000	0.00000001	0.036	632.625
Halkal	0.00227220	0.25046304	16.188	4.997	0.562	0.016	0.850	607.001	0.500	0.00000005	0.00000000	0.054	651.963
Kokkarne	0.00478595	0.25184025	9.819	4.814	0.488	0.016	0.800	327.198	0.369	0.00000004	0.00000004	0.003	299.660
Hemavati	0.00491486	0.25046334	14.078	3.874	0.599	0.026	0.913	221.727	0.301	0.00000001	0.00000003	0.080	392.697
Khanpur	0.00520312	0.43215111	31.184	4.971	0.820	0.005	0.845	573.496	0.497	0.00000004	0.00000000	0.034	698.715
Dindori	0.01227372	0.43105912	20.909	1.996	0.087	0.012	0.800	179.578	0.355	0.00000001	0.00000004	0.002	259.988
Chidgaon	0.00655448	0.36702019	12.980	0.655	0.080	0.894	0.895	400.361	0.499	0.00000002	0.00000002	0.210	669.636
Gadarwara	0.01292916	0.35253781	0.330	1.999	0.346	0.059	0.802	274.277	0.434	0.00000005	0.00000001	0.133	256.694
Belkheri	0.02229105	0.37936101	31.191	0.932	0.157	0.140	0.912	175.021	0.499	0.00000003	0.00000001	0.000	265.289
Manot	0.03067488	0.43211320	14.559	0.906	0.391	0.064	0.897	253.867	0.800	0.00000003	0.00000001	0.084	223.273
Bamni Banjar	0.01964278	0.43221690	0.262	1.604	0.482	0.895	0.962	525.982	1.000	0.00000003	0.00000000	0.024	438.875
Patan	0.02774263	0.25060386	8.846	1.975	0.723	0.897	0.956	456.917	1.000	0.00000003	0.00000000	0.000	399.895
Anthroli	0.02788504	0.42974089	14.661	1.970	0.483	0.015	0.801	234.420	0.300	0.00000002	0.00000000	0.633	70.402
Kogaon	0.02749769	0.25023276	21.327	0.374	0.080	0.376	0.844	91.119	0.891	0.00000004	0.00000001	0.008	169.881
Barchi	0.00814829	0.43216526	19.684	1.950	0.658	0.003	0.801	483.114	0.817	0.00000003	0.00000000	0.001	152.379
Mohegaon	0.02957974	0.39336061	12.701	0.397	0.080	0.889	0.916	285.815	0.999	0.00000002	0.00000000	0.150	242.611
Amachi	0.99198920	0.40801307	30.650	1.995	0.950	0.333	0.968	59.356	0.301	0.00000004	0.00000003	0.045	73.285
Hridaynagar	0.01843925	0.25010058	2.102	0.995	0.650	0.899	0.982	431.627	0.900	0.00000002	0.00000002	0.131	399.069

Table 5.7 Average Values of CN and S_I

	Average	Average	
Watershed	**CN_{II}**	**CN_I**	**S_I (mm)**
Haladi	82	66	131
Jadkal	82	66	131
Dasanakatte	83	67	125
Halkal	76	58	184
Kokkarne	84	68	120
Hemavati	78	60	169
Khanpur	76	58	184
Dindori	77	59	177
Chidgaon	83	67	125
Gadarwara	81	64	143
Belkheri	82	66	131
Manot	76	58	184
Bamni Banjar	82	66	131
Anthroli	82	66	131
Kogaon	83	67	125
Barchi	77	59	177
Mohegaon	78	60	169
Amachi	75	57	192
Hridaynagar	81	64	143

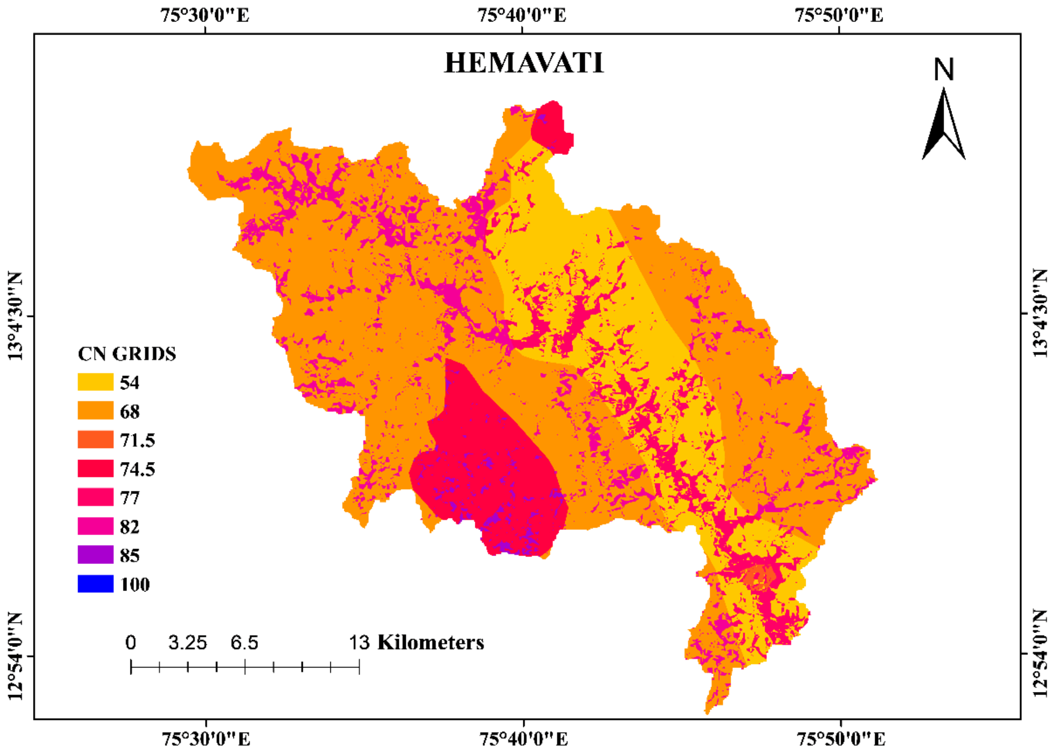


Figure 5.1 CNGRID map of the Hemavati catchment

5.2.2.1 For Wet Climatic Condition

Table 5.8 shows the NSE values estimated during calibration period. It is seen from this table that during the calibration period, the maximum NSE values have been estimated for the DVIC model, while the minimum NSE values have been estimated by Hu et al. (2005) model for all the catchments under wet category. It can be seen from Table 5.8 that the estimated NSE values for both the proposed models varies from 0.85 to 0.93 during calibration for all the high yielding catchments, indicating a very good model response (Motovilov et al., 1999; EI-Sadek et al., 2001; Fentie et al., 2002: Jain et al., 2012). The NSE values for the existing versions of the Xinanjiang model during calibration varies from 0.78 to 0.90 and that the minimum NSE value have been estimated for the Hu et al. (2005) model. It can also be seen from Table 5.8 that the performance of existing Xinanjiang model (Zhao, 1992) and its modified version proposed by Nirupama (1996) are similar and slightly better than that of the model proposed by Lin et al. (2014). However, the proposed XIN-CN model performed slightly better for one catchment, and for other catchments, its performance was similar to that of original Xinanjiang model, but the proposed DVIC model outperformed all other models in terms of better NSE compared to all other models in wet catchments.

It can be seen from the Tables 5.8 and 5.9 that for the studied wet catchments, the mean NSE and R^2 values estimated for the calibration period varies from 0.83 to 0.89, with a mean value of 0.87 and 0.89 for XIN-CN and DVIC models, respectively, indicating that the proposed models obtained higher NSE estimates as compared to all other versions of the Xinanjiang model for these catchments indicating a better stream flow generation features by the proposed models.

Comparative performance evaluation of the models have been further assessed using additional evaluation measures such as RMSE and RE (in %). Table 5.10 shows the values of RMSE obtained in calibration process. It can be seen from Table 5.10 that the values of RMSE varies between 1.39 to 10.14, which shows that all the studied models perform well in terms of RMSE (Golmohammadi et. al., 2014). The mean value of RMSE for wet catchments have been found to be lowest (= 5.93) for the proposed DVIC model and the next lowest being that of the proposed hybrid XIN-CN model with the mean value of RMSE is lower (= 6.49) as compared to other existing variants of the model except that of the Hu et al. (2005) model. It indicates that both the proposed modified Xinanjiang model are better in terms of RMSE for the runoff simulation in wet catchments as compared to the existing variants of the Xinanjiang model.

Table 5.8 NSE estimates obtained during calibration process for all the studied catchments by the proposed hybrid and existing versions of the Xinanjiang model

Climatic Condition	**Name of Catchment**	**Runoff Coefficient**	**EXISTING**				**PROPOSED**	
			Zhao (1992)	**Nirupama (1996)**	**HU (2005)**	**Lin (2014)**	**XIN-CN**	**DVIC**
W E T	Haladi	0.93	0.84	0.84	***0.83***	***0.83***	0.85	**0.89**
	Jadkal	0.92	0.85	0.85	***0.81***	0.84	0.85	**0.89**
	Dasanakatte	0.90	0.83	0.83	***0.78***	0.82	0.83	**0.86**
	Halkal	0.89	0.90	0.90	***0.88***	0.90	0.91	**0.93**
	Kokkarne	0.79	0.89	0.89	***0.84***	0.89	**0.90**	**0.90**
	Hemavati	0.78	0.86	0.86	***0.84***	0.86	0.87	**0.88**
	MEAN		0.86	0.86	***0.83***	0.86	0.87	**0.89**
A V E R A G E	Khanpur	0.60	***0.66***	0.67	0.72	***0.66***	**0.81**	0.75
	Dindori	0.51	0.75	0.77	***0.49***	0.74	**0.81**	**0.81**
	Chidgaon	0.50	0.75	0.75	***0.37***	0.75	**0.78**	0.71
	Gadarwara	0.49	**0.55**	0.54	***0.50***	**0.55**	**0.55**	**0.55**
	Belkheri	0.45	0.74	0.76	***0.47***	0.74	**0.80**	0.79
	Manot	0.45	0.79	0.79	***0.63***	0.79	**0.81**	0.80
	Bamni Banjar	0.37	0.71	0.72	***0.67***	0.72	**0.75**	0.71
	Patan	0.37	***0.80***	***0.80***	0.83	-	**0.84**	0.83
	Anthroli	0.37	0.69	0.68	***0.65***	0.68	0.68	**0.75**
	MEAN		0.72	0.72	***0.59***	0.70	**0.76**	0.74
D R Y	Kogaon	0.35	0.67	0.68	***0.40***	0.66	0.66	**0.72**
	Barchi	0.35	***0.39***	0.41	0.65	0.40	0.61	**0.72**
	Mohegaon	0.35	0.76	0.75	***0.45***	0.77	0.75	**0.78**
	Amachi	0.29	0.49	0.49	**0.55**	0.50	0.51	***0.41***
	Hridaynagar	0.24	0.60	0.58	***0.54***	0.59	**0.65**	**0.65**
	MEAN		0.58	0.58	***0.52***	0.58	0.64	**0.66**

Table 5.9 R^2 estimates obtained during calibration process for all the studied catchments by the proposed hybrid and existing versions of the Xinanjiang model

Climatic Condition	**Name of Catchment**	**Runoff Coefficient**	**EXISTING**				**PROPOSED**	
			Zhao (1992)	**Nirupama (1996)**	**HU (2005)**	**Lin (2014)**	**XIN-CN**	**DVIC**
WET	Haladi	0.93	0.84	0.84	***0.83***	***0.83***	0.85	**0.89**
	Jadkal	0.92	0.85	0.85	***0.81***	0.84	0.86	**0.89**
	Dasanakatte	0.90	0.83	0.83	***0.78***	0.82	0.83	**0.86**
	Halkal	0.89	0.91	0.90	***0.88***	0.90	0.91	**0.93**
	Kokkarne	0.79	0.89	0.89	***0.84***	0.89	**0.90**	**0.90**
	Hemavati	0.78	0.86	0.86	***0.84***	0.86	0.87	**0.88**
	MEAN		0.86	0.86	***0.83***	0.86	0.87	**0.89**
AVERAGE	Khanpur	0.60	***0.66***	0.68	0.73	0.68	**0.81**	0.76
	Dindori	0.51	0.75	0.77	***0.49***	0.74	**0.81**	**0.81**
	Chidgaon	0.50	0.75	0.76	***0.37***	0.75	**0.79**	0.72
	Gadarwara	0.49	0.55	0.55	***0.50***	0.55	**0.56**	0.55
	Belkheri	0.45	0.75	0.76	***0.47***	0.74	**0.80**	**0.80**
	Manot	0.45	0.80	0.79	***0.63***	0.79	**0.81**	0.80
	Bamni Banjar	0.37	0.71	0.72	***0.67***	0.72	**0.75**	0.72
	Patan	0.37	***0.80***	0.81	0.83	-	**0.84**	0.83
	Anthroli	0.37	0.70	0.70	***0.65***	0.69	0.68	**0.75**
	MEAN		0.72	0.73	***0.59***	0.71	**0.76**	0.75
DRY	Kogaon	0.35	0.67	0.68	***0.42***	0.66	0.66	**0.74**
	Barchi	0.35	***0.41***	0.42	0.65	***0.41***	0.64	**0.72**
	Mohegaon	0.35	0.76	0.76	***0.45***	0.77	0.75	**0.80**
	Amachi	0.29	0.50	0.50	0.56	0.50	**0.58**	***0.42***
	Hridaynagar	0.24	0.61	0.59	***0.53***	0.59	0.65	**0.66**
	MEAN		0.59	0.59	***0.52***	0.59	0.66	**0.67**

Table 5.10 RMSE estimates obtained during calibration process for all the studied catchments by proposed hybrid and existing versions of the Xinanjiang model

Climatic Condition	**Name of Catchment**	**Runoff Coefficient**	**EXISTING**				**PROPOSED**	
			Zhao (1992)	**Nirupama (1996)**	**HU (2005)**	**Lin (2014)**	**XIN-CN**	**DVIC**
W E T	Haladi	0.93	6.80	6.88	**6.96**	6.89	6.64	***5.75***
	Jadkal	0.92	9.12	9.04	**10.14**	9.15	8.83	***7.85***
	Dasanakatte	0.90	7.56	7.56	**8.49**	7.65	7.58	***6.93***
	Halkal	0.89	6.27	6.28	***1.39***	**6.33**	6.08	5.44
	Kokkarne	0.79	6.33	6.33	**7.82**	6.55	6.19	***6.13***
	Hemavati	0.78	3.70	3.69	**3.94**	3.68	3.61	***3.48***
	MEAN		6.63	6.63	6.46	**6.71**	6.49	***5.93***
A V E R A G E	Khanpur	0.60	6.73	**6.75**	6.11	6.74	***5.04***	5.77
	Dindori	0.51	2.51	2.41	**3.56**	2.55	***2.18***	2.20
	Chidgaon	0.50	4.85	4.80	**7.66**	4.83	***4.53***	5.20
	Gadarwara	0.49	3.70	3.73	**3.90**	***3.70***	3.70	3.73
	Belkheri	0.45	3.26	3.18	**4.67**	3.25	***2.86***	2.94
	Manot	0.45	2.05	2.07	**2.73**	2.06	***1.97***	2.03
	Bamni Banjar	0.37	2.00	1.98	**2.15**	1.97	***1.88***	2.00
	Patan	0.37	**1.89**	1.86	1.72	-	***1.69***	1.73
	Anthroli	0.37	1.16	1.16	**1.22**	1.16	1.16	***1.04***
	MEAN		3.13	3.10	**3.75**	3.28	***2.78***	2.96
D R Y	Kogaon	0.35	2.90	2.87	**3.90**	2.93	2.95	***2.67***
	Barchi	0.35	**2.78**	2.74	***2.11***	2.76	2.22	2.61
	Mohegaon	0.35	2.24	2.25	**3.37**	2.19	2.26	***2.11***
	Amachi	0.29	1.73	1.74	1.64	1.73	***1.58***	**1.87**
	Hridaynagar	0.24	1.77	1.82	**1.92**	1.77	1.66	***1.66***
	MEAN		2.28	2.28	**2.59**	2.28	***2.13***	2.18

Table 5.11 RE estimates (in %) made in the calibration process for all the studied catchments by the proposed hybrid and existing versions of the Xinanjiang model

Climatic Condition	**Name of Catchment**	**Runoff Coefficient**	**EXISTING**				**PROPOSED**	
			Zhao (1992)	**Nirupama (1996)**	**HU (2005)**	**Lin (2014)**	**XIN-CN**	**DVIC**
WET	Haladi	0.93	-1.58	0.19	**-4.82**	***0.09***	-1.57	1.26
	Jadkal	0.92	***-0.14***	-1.20	**-9.66**	0.24	-0.86	3.74
	Dasanakatte	0.90	-0.56	-0.35	**-3.27**	0.44	***-0.17***	0.44
	Halkal	0.89	-0.78	-0.56	-3.99	**-6.54**	-0.79	***-0.53***
	Kokkarne	0.79	-1.77	-2.10	-3.77	***-0.08***	-0.89	**5.22**
	Hemavati	0.78	-2.08	-2.40	***-0.70***	**-3.33**	-1.32	-2.24
AVERAGE	Khanpur	0.60	9.70	11.50	***3.04***	**13.70**	16.52	5.84
	Dindori	0.51	-4.23	**-9.54**	-5.75	-2.43	***-1.40***	-5.22
	Chidgaon	0.50	***0.88***	3.26	3.60	-3.42	-4.38	**-7.82**
	Gadarwara	0.49	-1.64	0.29	***0.51***	-2.05	**11.94**	4.88
	Belkheri	0.45	***-0.64***	**3.87**	-1.95	2.53	-1.93	-3.05
	Manot	0.45	0.89	-3.31	-4.62	0.33	***-0.24***	**-6.10**
	Bamni Banjar	0.37	3.47	-4.78	-7.95	***-0.66***	-1.02	**-13.84**
	Patan	0.37	***0.12***	-3.04	-1.68	-	**-11.01**	-2.55
	Anthroli	0.37	10.04	6.16	6.96	**19.25**	***-0.33***	-0.79
DRY	Kogaon	0.35	-4.53	-4.83	9.36	***-4.42***	9.62	**-12.21**
	Barchi	0.35	***8.02***	**23.60**	-21.81	21.01	22.81	10.23
	Mohegaon	0.35	3.63	**4.26**	3.23	***2.22***	2.97	-2.85
	Amachi	0.29	8.29	***3.22***	**12.94**	9.43	10.42	-11.60
	Hridaynagar	0.24	4.75	**-12.95**	4.94	1.71	***-0.91***	8.00

Table 5.11 shows the values of RE (in %) obtained for the calibration period of all the studied models and for all the studied catchments. RE = 0.0 % indicates no over or underestimation from the observed value. Values of RE with (-) sign implies the under estimation, while the positive values imply the overestimation. It can be seen from Table 5.11 that during the calibration period, the RE (in %) varies from – 0.08 to – 9.66 which is in both the proposed hybrid models vary between -0.17 to -2.24, indicating a good model performance by both of the proposed hybrid models under the condition of under estimation. Under the condition of over estimation the RE (in %) estimates varies between 0.09 to 5.22 and both of the models of Nirupama (1996) and Lin et al. (2014) display a tendency for over estimation. Overall, the performance of the studied models show the variation of RE (in %) (< ±10.0), especially the proposed XIN-CN and DVIC models display the tendency of good simulation of the observed events in the wet catchments (Donigian et al. 1983; Harmel et al. 2006; and Jain et al. 2012).

Comparison of Performance of the models by graphical representation using boxplot and hydrographs for wet catchments

A boxplot aims to summarize a batch of data by displaying several main features, like median, lower/upper quartile, whiskers, i.e., showing how large is the "spread" of the data and the outliers, i.e., the data which does not fit to that batch of the data. The boxplot, a popular univariate data display developed by Tukey (1977) is available in many statistical software packages. Velleman and Hoaglin (1981) discussed this display and its construction in detail. We have used the boxplot, to represent that how the different hydrological models are performing statistically. The span of the box represents interquartile range (25th–75th percentile) with the horizontal line inside the box indicating the median value (50th percentile, Q_2). The structure of the boxplot is based on the following formulations:

Interquartile range (IQR) = $Q_3 - Q_1$

Lower outlier < $Q_1 - 1.5 \times \text{IQR}$

Upper outlier > $Q_3 + 1.5 \times \text{IQR}$

where, Q_1 is the first quartile or 25th percentile of the data and Q_3 is the third quartile or 75th percentile of the data. The vertical lines end to horizontal line are known as whisker of the data, which starts from end of the boxplot and ends from where the range of the outliers starts. The whiskers show the extent of the rest of the data, which is close to the box plot.

Figures 5.2 and 5.3 show the boxplots of NSE and R^2 values obtained during calibration for wet catchments, in which the variability in the performances of the models are shown. It can be seen from Figures 5.2 and 5.3 that during the calibration process, the median of the NSE values are greater for both the proposed XIN-CN and DVIC model while the Xinanjiang model (Zhao (1992)) and Nirupama (1996) models having same median values but slightly higher than the Lin et al. (2014) model.

If there are no outliers, then the whiskers show the extreme values of the data set and if there is, no whisker then box of the boxplots itself show the extreme value of the data set. The upper whisker of the DVIC model, having higher value than all other models, also the upper whisker of the XIN-CN model having higher value than all other existing versions of the Xinanjiang model, also, the lower whisker of both the proposed models are higher in their NSE values, which imply that both the proposed models perform better than all other versions of the Xinanjiang model.

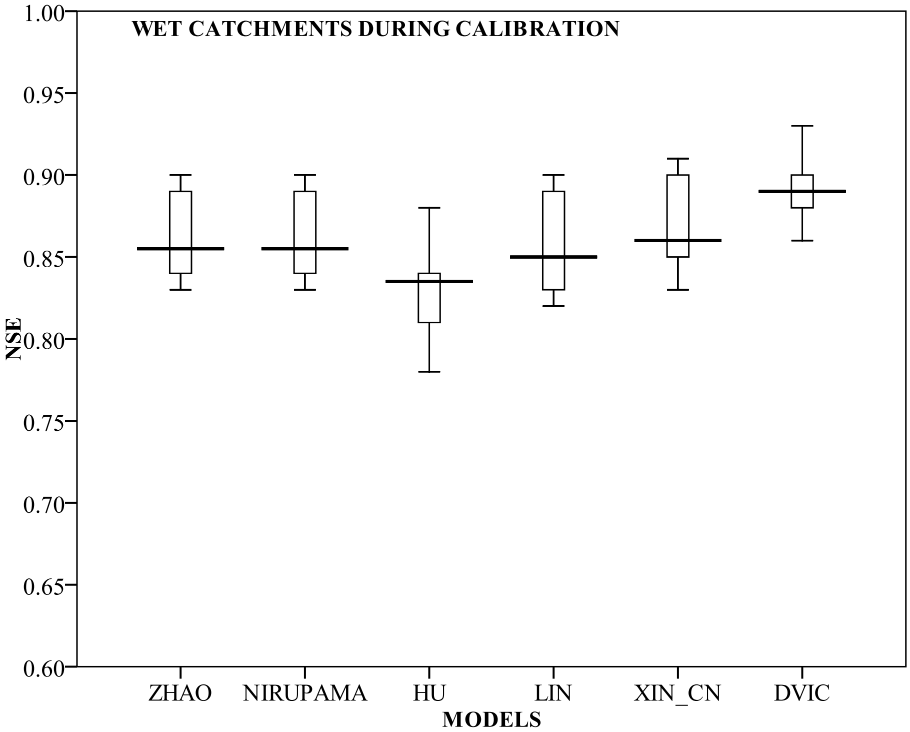


Figure 5.2 Boxplots of the NSE values for wet catchments for Comparative performance between the existing and proposed versions of the Xinanjiang model

The main part of the boxplots is their IQR, which is nothing but the box of the boxplots. The middle 50% of the data is represented by the IQR; it can be seen from Figure 5.2 that during the calibration process, the Zhao (1992), Nirupama (1996), Lin et al. (2014) and XIN-CN and also the Hu et al. (2005) model are wider in IQR, which shows that the 50% of the wet catchments are having more variability in their NSE values for these models while the DVIC model having shortest IQR among all other models which implies that 50% of the wet catchments having NSE values in a close range which demonstrates that in the calibration process, the performance of the DVIC model for wet catchments is best among all other versions of the Xinanjiang model. During the calibration process the Zhao (1992) and Nirupama (1996) models having almost the same box plots along with the expansion of the whisker and also the median of these models are the same which indicate that the Zhao (1992) and Nirupama (1996) models are having same performance for wet catchments in the calibration process. It is seen from Figures 5.2 and 5.3 that the boxplots of the NSE and R^2 are quiet similar and therefore no need to explain separately the boxplots based on the R^2 criterion.

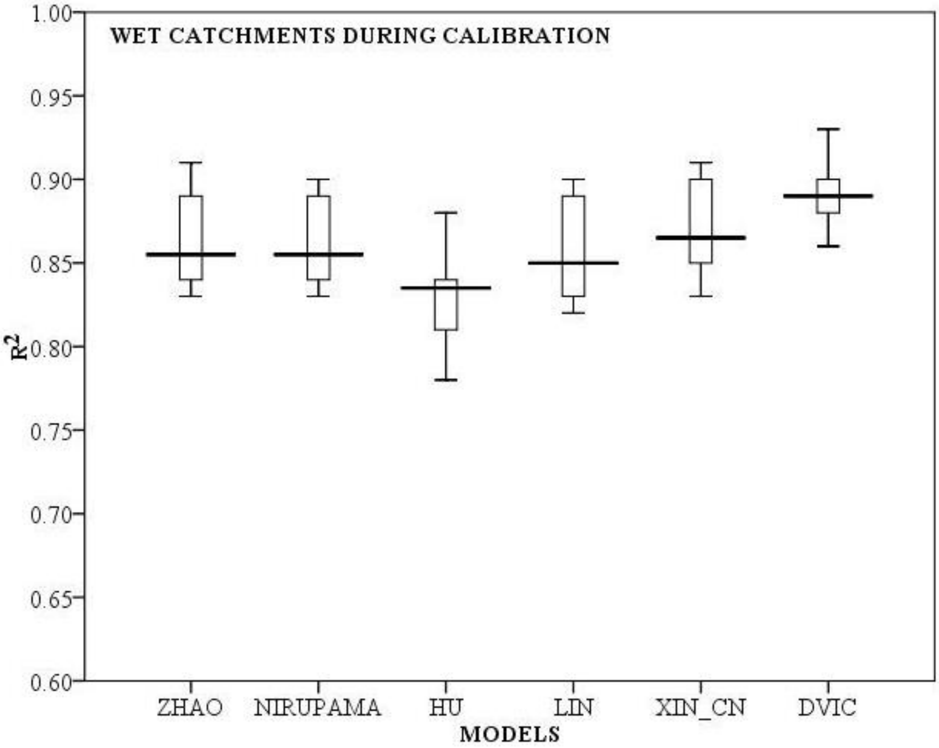


Figure 5.3 Boxplots of the R^2 values for wet catchments for Comparative performance between existing and proposed versions of the Xinanjiang model

Figure 5.4 shows the boxplots of the RMSE values obtained during the calibration process by the models for wet catchments. It can be seen from Figure 5.4 that the smaller span of boxplots in all variants of the Xinanjiang model are almost same, except in the Hu et al. (2005) model which is having a large span of the boxplot. Having smaller span in box plots indicates that the values of RMSE are clustering around some value indicating a more stability of the model response towards runoff generation process, and if these values are closer to zero than the predictability by the model is best. The median of the boxplots is closer in both of the proposed modified Xinanjiang model as compared to the existing variants of the Xinanjiang models which imply that both the proposed modified Xinanjiang model are performing better than the existing variants of the Xinanjiang model.

Figure 5.5 shows the boxplots of the evaluation measure RE (in %) of the models during the calibration process for the wet catchments. As discussed already that the lower RE (in %) (close to zero) better is the performance of the model. It is seen from Figure 5.5 that the Lin et al. (2014) model obtained the RE (in %) median value close to zero among all other studied models which suggests a good model response, but expansion of its box and lower whisker to the negative side is indicative of under prediction which implies a poorer performance of the Lin et al. (2014) model. On the other hand, the proposed hybrid XIN-CN and DVIC and the original Xinanjiang model, i.e., by Zhao (1992) and the modified Xinanjiang model by Nirupama (1996) also have the median of RE (in %) nearer to zero. But the XIN-CN model not only has a lower median value, but also has the shortest IQR with the smallest whisker suggesting a good model response. The Xinanjiang model by Zhao (1992) and by Nirupama (1996) are also displaying a short IQR with small whisker values but not lower than the proposed hybrid XIN-CN model. The proposed DVIC model also estimate the median and lower whisker values nearer to zero, but the larger spread of the IQR and large upper whisker show its fair performance as compared to that of the XIN-CN model. The Hu et al. (2005) model clustered in a box with higher IQR than the other models, as well as two outliers, in which one of the outlier having very higher value towards negative side, shows the condition of much under prediction than the all other models which implies very poor performance by the Hu et al. (2005) model.

To assess the closeness of reproduction of peaks and the overall pattern of the simulated discharges in comparison with the observed stream flow, the simulated daily stream flows during the calibration period have been plotted against the corresponding observed discharge data for the selected years and for all the studied catchments. One such a plot showing the observed and the corresponding simulated discharges using all the models studied herein is given in Figure 5.6 for the Kokkarne catchment for the year 1986-87 for the purpose of illustration. As can be seen from Figure 5.6 and other such figures (APPENDIX-I), the closeness between the model simulated discharge hydrographs by the DVIC and the XIN-CN models with the corresponding observed discharge hydrograph is good in comparison with the simulated hydrograph by the other models.

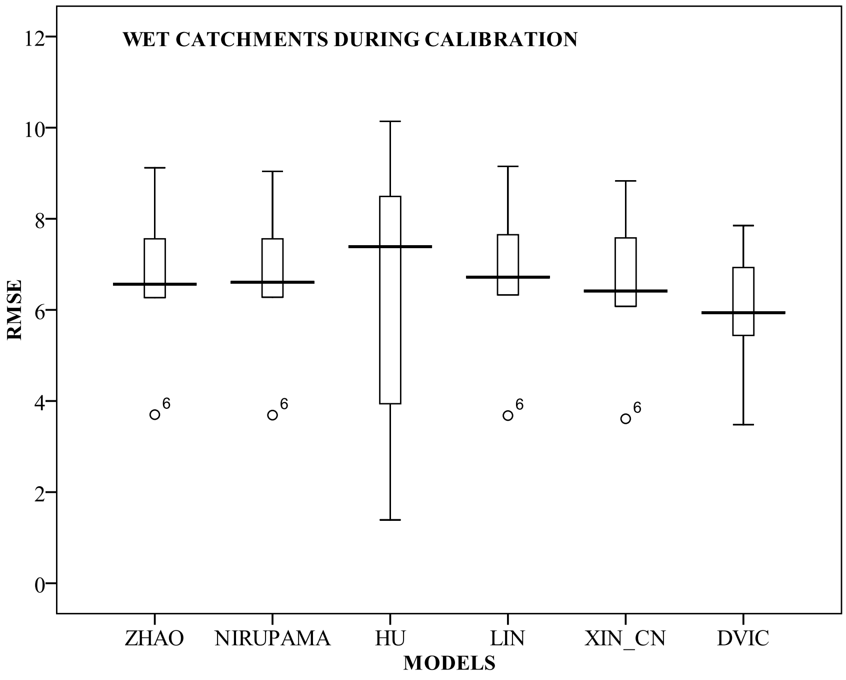


Figure 5.4 Boxplots of the RMSE values for wet catchments for the comparative performance between the existing and the proposed versions of the Xinanjiang model

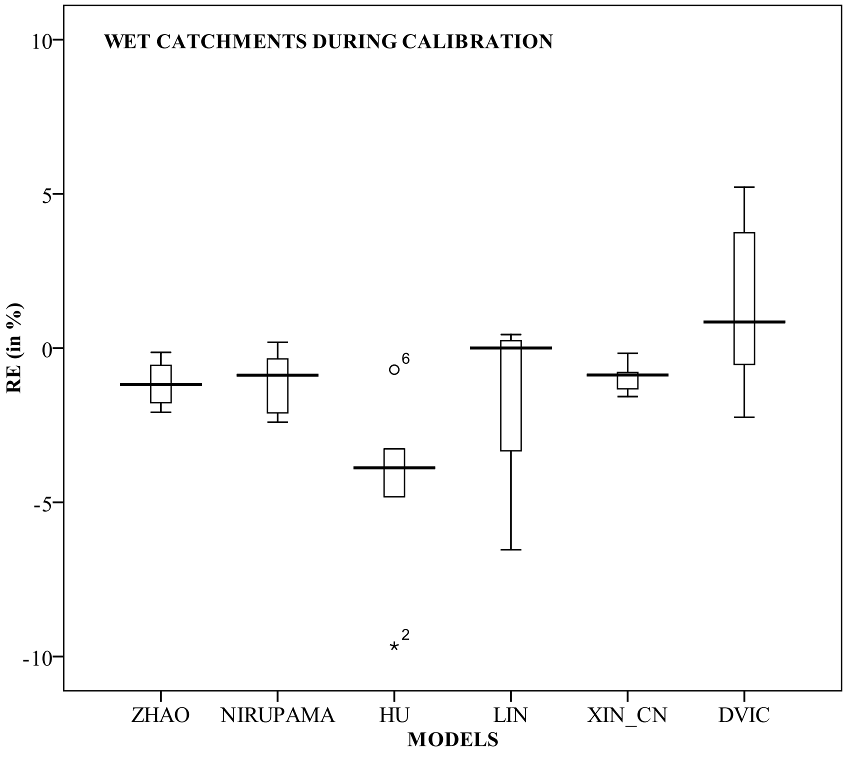


Figure 5.5 Boxplots of the % RE values for wet catchments for the comparative performance between the existing and the proposed versions of the Xinanjiang model

The peaks are better simulated by the proposed models. Figure 5.6 also show a separate plot of the simulated stream flows for the entire calibration period along with the corresponding observed streamflows for the Kokkarne catchment, while such plots of the other considered catchments are given in APPENDIX-II.

To assess the closeness of reproduction of peaks and the overall pattern of the simulated discharges in comparison with the observed stream flow, the simulated daily stream flows during the calibration period have been plotted against the corresponding observed discharge data for the selected years and for all the studied catchments. One such a plot showing the observed and the corresponding simulated discharges using all the models studied herein is given in Figure 5.6 for the Kokkarne catchment for the year 1986-87 for the purpose of illustration. As can be seen from Figure 5.6 and other such figures (APPENDIX-I), the closeness between the model simulated discharge hydrographs by the DVIC and the XIN-CN models with the corresponding observed discharge hydrograph is good in comparison with the simulated hydrograph by the other models. The peaks are better simulated by the proposed models. Figure 5.6 also show a separate plot of the simulated stream flows for the entire calibration period along with the corresponding observed streamflows for the Kokkarne catchment, while such plots of the other considered catchments are given in APPENDIX-II.

5.2.2.2 Model Performance for the Catchments under Average Climatic Conditions

Table 5.8 shows the estimated NSE values for the simulated hydrographs for the catchments subjected to average climatic condition. It can be seen from Table 5.8 that for simulation of the calibration period, the maximum estimated NSE values have been found for the simulation of the XIN-CN model for almost all the catchments under average climatic condition, except that of the Anthroli catchment. For Anthroli catchment, the maximum estimated NSE value of 0.75 was obtained using the DVIC model which indicates that the proposed model especially the XIN-CN model shows better model performance over the other studied models for catchments of average climatic condition. The minimum NSE values have been found for the simulations using Hu et al. (2005) model for almost all the catchments under average climatic condition, except for the cases of Khanpur and Patan catchments which indicate a very poor reproduction by the Hu et al. (2005) model in catchments under average climatic condition. It can also be seen from Table 5.8, that the estimated NSE values for both the proposed models in calibration varies from 0.68 to 0.84 for all the average climatic condition catchments except for the Gadarwara catchment, where the NSE attained a value of 0.55, indicating a good model response. Also it is seen from the Table 5.8 that for average catchments, the mean NSE value during calibration period varies from 0.59 to 0.76, in that the maximum NSE values found as 0.76 and 0.74 in XIN-CN and DVIC model respectively, which show a better performance by the proposed models. Similar to the NSE, another evaluation criterion, i.e., R^2 also reaffirms that the proposed models exhibit a good model performance in comparison with the existing versions of the Xinanjiang model, which is depicted in Table 5.9.

The computed values of the evaluation measures RMSE and RE (%) for all the models of average catchments are given in Tables 5.10 and 5.11, respectively. It can be seen from Table 5.10 that during the calibration process, the values of RMSE varies between 1.04 to 6.75 which are lower than the values obtained for the catchments of wet category, indicating that all the studied models perform better for the catchments exhibiting average runoff generation condition. The mean value of RMSE for the average catchments are found to be the lowest for both of the proposed modified Xinanjiang models, i.e., the mean RMSE values for the XIN-CN model is 2.78, and for the DVIC model it is 2.96. These indicate that both the proposed modified Xinanjiang models perform better in terms of RMSE values as compared to the other existing variants of the Xinanjiang model. During the calibration period, it is inferred from Table 5.11 that the measure RE (in %) varies from – 0.66 to – 13.84 (indicating under prediction) and 0.12 to 19.25 (indicating over prediction) in that RE (in %) found to be lower for most of the catchments simulations for both the proposed models indicating better performance of the proposed models in comparison with the corresponding estimates of other models considered in this study.

Similar to the boxplots of wet catchments, Figure 5.7 shows the boxplot of the NSE values estimated for calibration process of catchments under average climatic condition category, but the variability in the performances of the models for the NSE values are quite different for catchments under average climatic condition.

During the calibration process, the median of the NSE values was found to be highest only in the proposed XIN-CN model, while for the original Xinanjiang model, i.e., Zhao (1992) and for the modified Xinanjiang models of Nirupama (1996), Lin et al. (2014) and DVIC almost the same median values, but higher than the Hu et al. (2005) model were obtained. The Hu et al. (2005) model having the lowest median value of NSE in the calibration process shows the poorest performance amongst all other studied models.

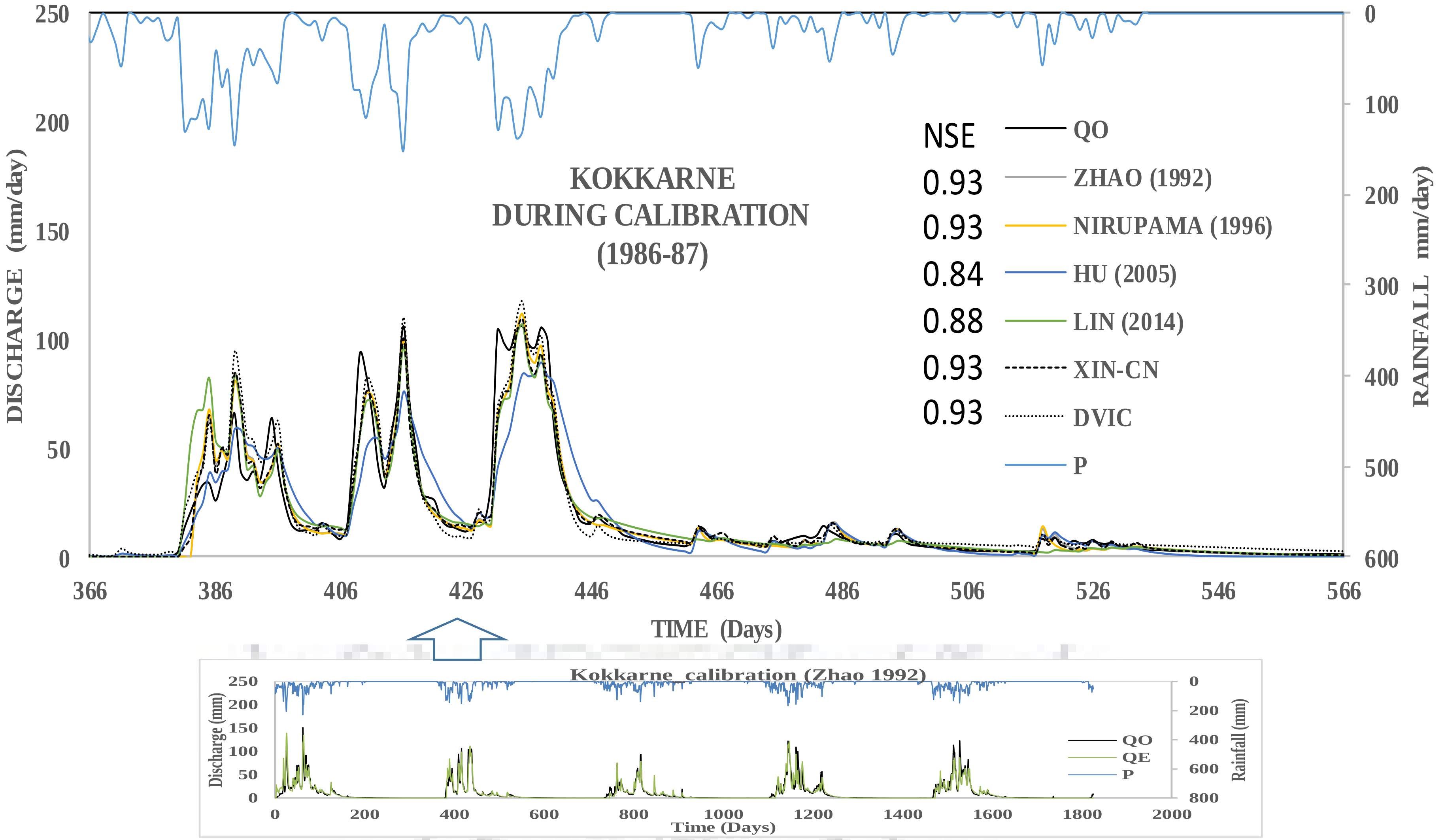


Figure 5.6 Comparative performance between the existing and proposed versions of the Xinanjiang model in terms of observed and computed discharge in Kokkarne catchment (wet category)

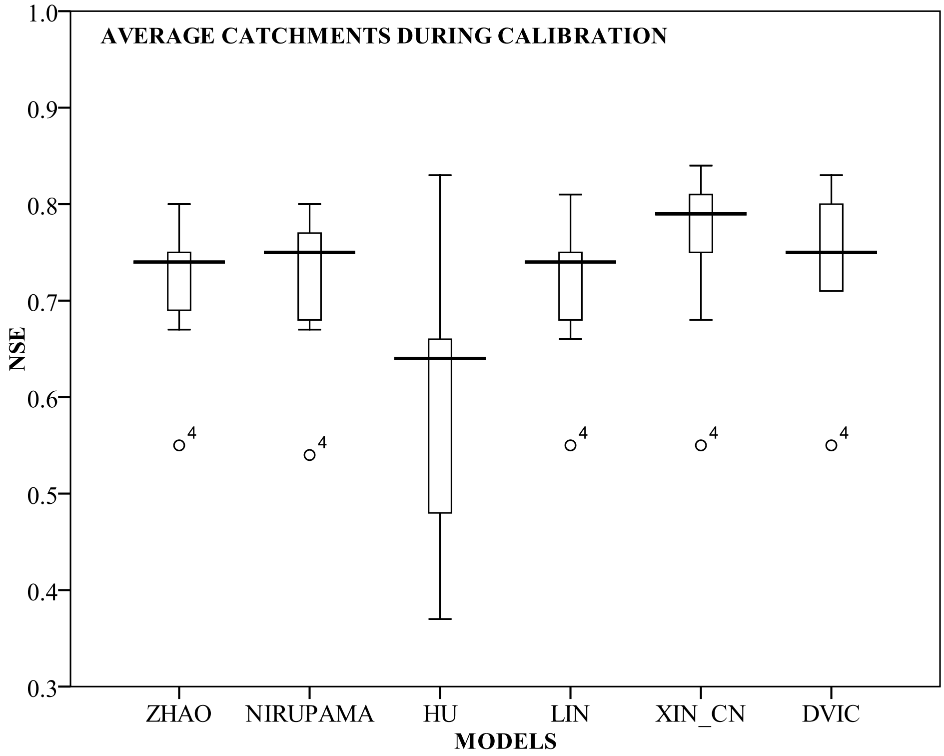


Figure 5.7 Boxplots of the NSE values for average catchments for comparative performance between existing and proposed versions of the Xinanjiang model in calibration process

For the average climatic condition catchments, both the upper and lower whisker of the proposed XIN-CN and DVIC model are having the higher NSE values, except for the single case of Hu et al. (2005) model for its upper whisker for Patan catchment, which suggests a better performance of the proposed models over all other versions of the Xinanjiang model. Some lower outliers are also shown in the box plots for all the models, except for the Hu et al. (2005) model as it already has the lower whisker value, even lower than the lower outliers of the other model. This demonstrates that the performance of all the models are comparatively poor and similar for this catchment (Gadarwara).

Further it can be seen from Figure 5.7 that the spread of the IQR are very short for all the models, except for the Hu et al. (2005) model which indicate that the performance of these models is stable during the calibration process, but a wide variation exists in the performance of Hu et al. (2005) model. It can be seen from Figure 5.7 that the upper limit of the boxplot is higher for the proposed XIN-CN and DVIC models, which suggest a better performance of the proposed models over all other versions of the Xinanjiang model in the catchments of average climate category. For the catchments of average category, the boxplots of R^2 values, also have been shown in Figure 5.8. It can be seen from this figure that the boxplots of R^2 values are almost same as in the boxplots of NSE, which is depicted in Figure 5.7 and, therefore, further discussion is not needed for these boxplots.

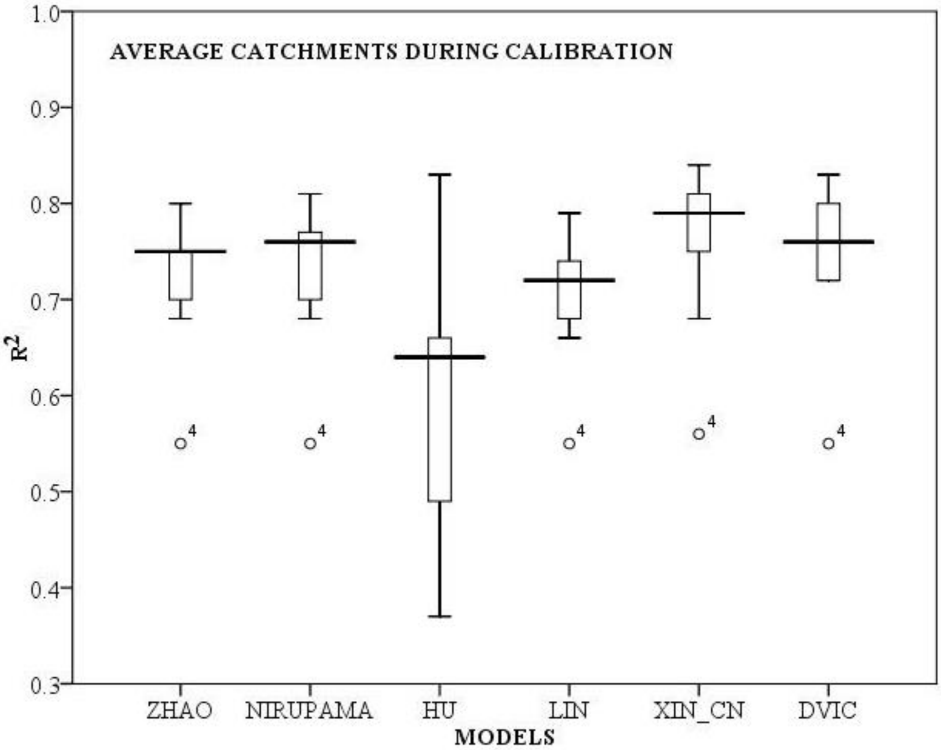


Figure 5.8 Boxplots of the R^2 values for average catchments for comparative performance between existing and proposed versions of the Xinanjiang model in calibration process

Figure 5.9 shows the boxplots of the RMSE values estimated for the studied models for the simulation of the calibration period for all the catchments under average climate category. It can be seen from Figure 5.9 that similar to that of the wet catchments, the distributions of the span in the boxplots are similar for all the models, except for the Hu et al. (2005) model, but the lower whisker is more close to zero as compared to that of the wet catchments. This implies that all the variants of the Xinanjiang model are performing well in terms of the RMSE values. Also it can be seen from Figure 5.9 that on the upper part of the boxplots, the expansion in the upper whisker is very high for Hu et al. (2005) model and also the upper outliers can be seen for the other existing variants of the Xinanjiang model except for both the proposed hybrid models. This leads to the inference that both the proposed hybrid models are slightly better than the other existing variants of the Xinanjiang model. It can be seen from Figure 5.9 that the median value of RMSE is lesser and more close to zero for both the proposed modified Xinanjiang model as compared to the existing variants of the Xinanjiang model indicating that both the proposed modified Xinanjiang model are performing better than the existing variants of the Xinanjiang model.

Figure 5.10 shows the boxplots of the measure RE (in %) for all the studied models during the calibration process of the catchments of average climate category. It is seen from Figure 5.10 that the original (Zhao, 1992) and the modified Xinanjiang model of Lin et al. (2014) exhibit the lowest span of the boxplot and closer to zero in comparison with all other existing variants of the Xinanjiang model, indicating a good performance of these models. However, both these models also produce outliers towards positive side implying the performance of over prediction by these models. The proposed XIN-CN model achieved the shortest span of the boxplot than all other models, but it has three large outliers, i.e., two outliers towards the positive side (indicating over prediction) and one outlier towards the negative side (indicating under prediction). The modified Xinanjiang model by Nirupama (1996) display large expansions in the boxplots and also the whisker is expanded on both sides which indicate that this model has both conditions, i.e., under prediction as well as over prediction. The proposed DVIC model is characterised by a small boxplot as compared to the existing variants of the Xinanjiang model implying a good model response, but it also has a larger whisker on both the sides which shows that the proposed DVIC model also has both conditions, i.e., under predictions as well as over predictions in some catchments of average climate category.

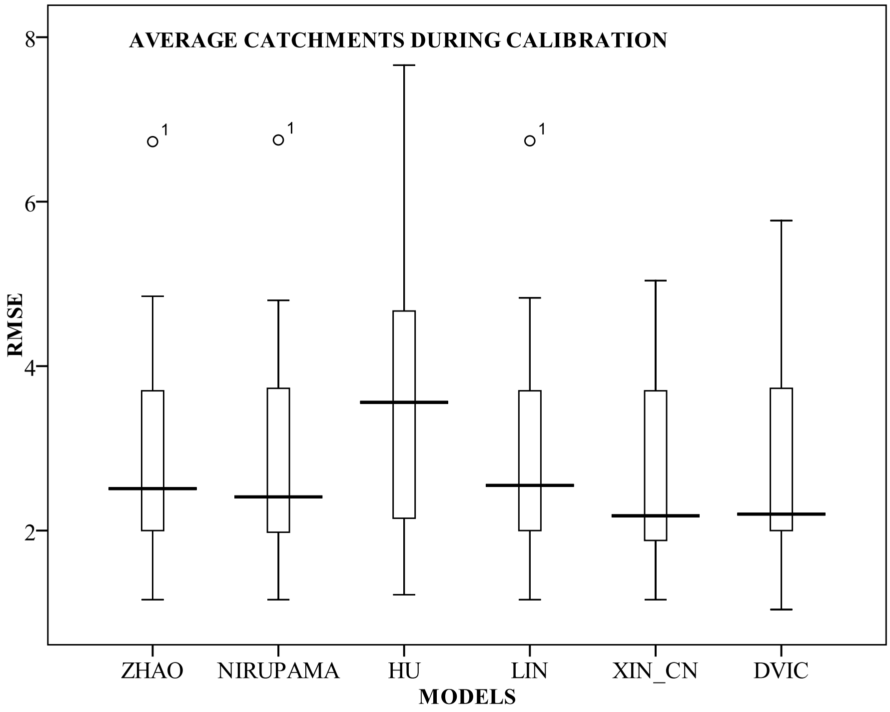


Figure 5.9 Boxplots of the RMSE values in average catchments for Comparative performance between existing and proposed versions of the Xinanjiang model

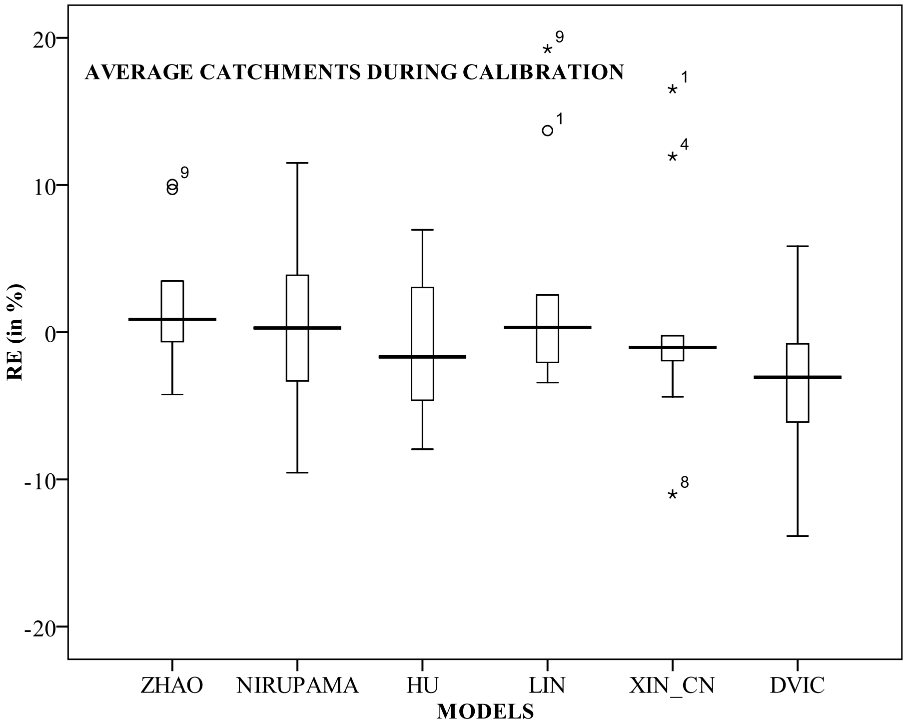


Figure 5.10 Boxplots of the % RE values in average catchments for Comparative performance between existing and proposed versions of the Xinanjiang model

To assess the closeness of reproduction of peaks and overall pattern of the simulated discharges with the observed stream flows, the simulated daily streamflows for the calibration period have been plotted against the corresponding observed discharge series data for the selected years as well as for all the calibrated period and for all the studied catchments. A typical results from the average climate category catchment showing observed and corresponding computed discharges with the results of the studied models all are given in Figure 5.11 for the Dindori catchment for the year 1991-92. As can be seen from Figure 5.11 and other such figures shown in APPENDIX-I and APPENDIX-II the closeness between the model computed discharge by the proposed hybrid XIN-CN and DVIC models with corresponding observed discharge is better compared to other models. Also it can be seen from Figure 5.11 that the Hu et al. (2005) model performs very poorly and the peaks are better simulated by both the proposed hybrid models.

5.2.2.3 Model Performance in Catchments of Dry Climatic Condition

The NSE values for the catchments of dry climatic condition are shown in Table 5.8. It is seen from this table that during the calibration process, the maximum NSE values have been achieved by both the proposed models, i.e., XIN-CN and DVIC models for almost all the catchments having dry climatic condition, except for the case of Amachi catchment.

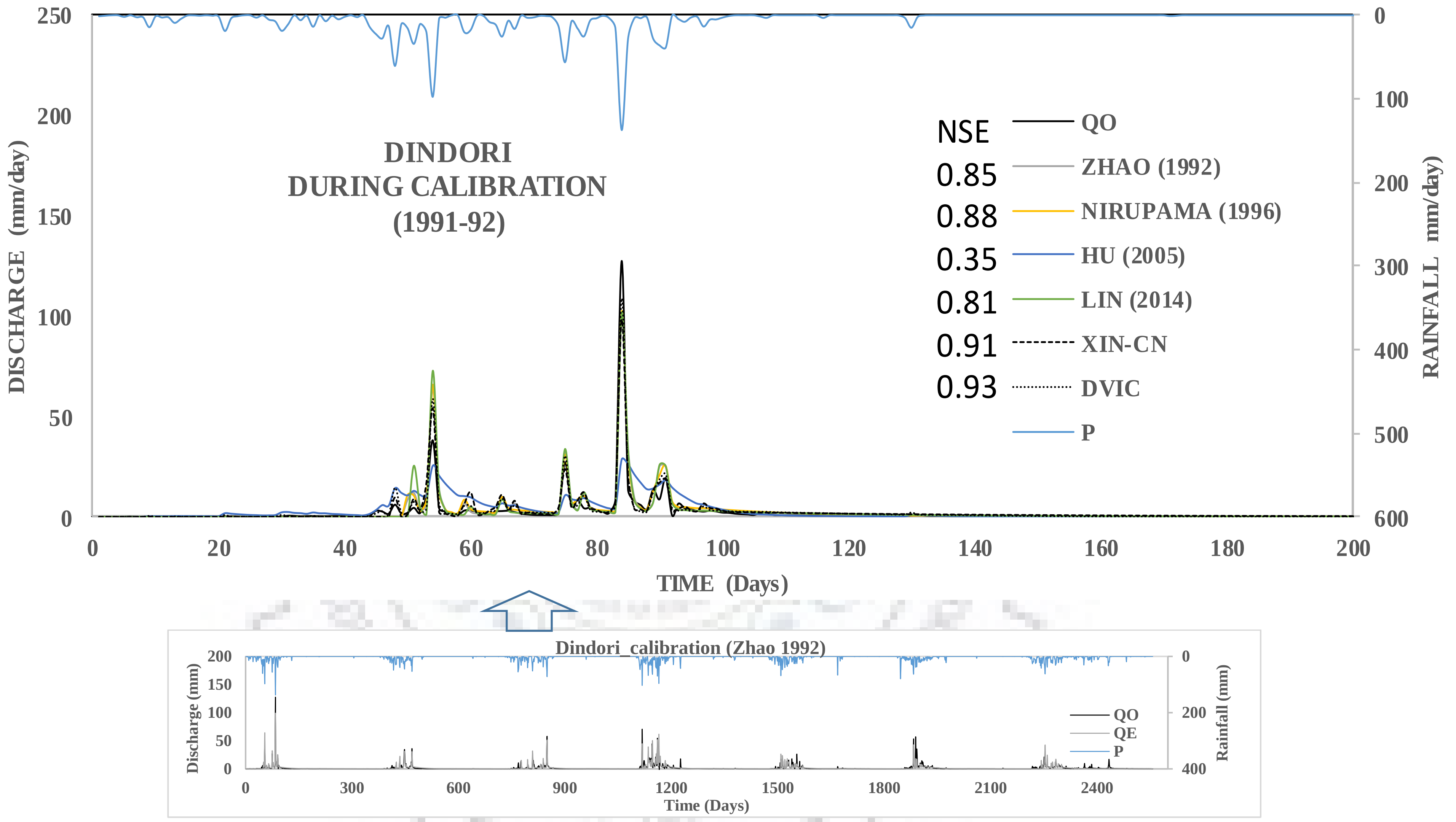


Figure 5.11 Comparative performance between the existing and the proposed versions of the Xinanjiang model in terms of observed and computed discharge in Dindori catchment (average category)

It can be seen from this table that the NSE values for both the proposed hybrid models for the calibration period varies from 0.51 to 0.78 for all the dry catchments, except for the case of Amachi catchment with the estimated NSE = 0.41 for the DVIC model, indicating a good to average model response for the dry catchments. It can also be seen from Table 5.8 that the NSE values for the existing versions of the Xinanjiang model for the calibration period varies from 0.39 to 0.77, and the minimum NSE value has been estimated for the Hu et al. (2005) model simulations for most of the catchments. It can be seen from Table 5.8 that for the dry catchments, the mean NSE value during calibration period varies from 0.52 to 0.66, in that the maximum NSE found as 0.66 and 0.64 in DVIC and XIN-CN model respectively. This demonstrates that both the proposed models are exhibiting better runoff simulation in capability comparison to those simulations given by existing models. Comparative performance of all the models is further evaluated using R^2 for all the studied catchments of different categories. A similar pattern as obtained for the NSE estimates can be seen for the estimates R^2 also. Table 5.9 shows the estimated values of R^2 for the model simulations for calibration period and for all studied dry catchments.

For the catchments of dry category, the evaluation measures of RMSE and RE (in %) are shown in Tables 5.10 and 5.11, respectively. It can be seen from Table 5.10 that the RMSE estimate varies between 1.58 and 3.90, which is less than the corresponding estimates for catchments of wet and average categories which implies a good predictability by the models while simulating flows for dry catchments climate. The mean value of RMSE was found to be the lowest for both the proposed models, i.e., for XIN-CN model with RMSE 2.13 and for the DVIC model it is 2.18. This suggests that both the proposed hybrid models have the better ability in comparison with the performance of other existing variants of the Xinanjiang model. It is inferred from Table 5.11 that during the calibration period, the RE (in %) varies from - 0.91 to - 21.81 implying under prediction and +2.22 to +23.60, implying over prediction and in that the RE (in %) found to be lower most for all the dry category catchments for both the proposed models for the calibration period. Also it can be seen from Table 5.11 that RE (in %) is near to a value of 10.0 for the studied models for all the catchments, except for the Barchi catchment, indicating a good model performance for the calibration period.

Figures 5.12 – 5.15 show the boxplot of the model evaluations measures NSE, R^2, RMSE and RE (in %) values estimated during calibration process for the catchments of dry category, respectively. It is seen from Figure 5.12 that the span in the boxplots of the existing versions of the Xinanjiang model is large, implying that the stability of the existing versions of the

Xinanjiang model in dry catchments are low. However, the span of the boxplots of the proposed model is very less, especially the proposed XIN-CN model is clustered around a very close and higher values of the NSE, implying that the proposed models are showing stable performance while simulating discharges of dry catchments. Also it is seen from Figure 5.12 that the median values of NSE for both of the proposed models are higher than those of the existing versions of the Xinanjiang model implying that the proposed models are more appropriate for discharge estimation of the dry catchments.

The boxplots of the metric R^2 are almost same as that of NSE values as shown in Figure 5.13. The boxplots of the RMSE metric for dry catchments are shown in Figure 5.14. It can be seen from this figure that the span of boxplots obtained from the discharge simulation using the existing variants of the Xinanjiang model are very large in comparison to those obtained using the proposed modified Xinanjiang model. The median value can be seen less than a value of 2.5 for all the studied models, specifically nearer to zero metric was estimated for the proposed DVIC model, and the Hu et al. (2005) model. The lower whisker is more close to zero in the proposed hybrid XN-CN and DVIC models and also the upper whisker can be seen smaller in the proposed DVIC model as compare to the other variants of the Xinanjiang model. Overall, these boxplots analysis suggests that both the proposed modified Xinanjiang models are performing better than the exiting variants of the Xinanjiang model in terms RMSE metric when the performance of these models are assessed for the flow simulation of dry catchment category.

It is inferred from the boxplots of the metric RE (in %) shown in Figure 5.15 that the median values of all the existing variants of the Xinanjiang model are close to zero and towards the positive side, which implies over prediction of runoff by the model, but the span of the boxplots are quiet large which imply the instability of the models. For the boxplots of the proposed hybrid DVIC model, the median value is closer to zero, but the span of the boxplot is very large as compared to the XIN-CN model implying the XIN-CN model is more stable as compared to the DVIC model. The boxplots developed for the other existing variants of the Xinanjiang model are similar in characteristics in terms of RE (in %) obtained from the calibration results of dry catchments.

To assess the closeness of the calibration period simulated hydrographs of the existing and proposed different forms of the Xinanjiang models for visual comparison with the observed stream flow of the dry catchments, these models simulated hydrographs have been plotted against the corresponding observed discharge data for the selected years of all the studied catchments in the calibration period.

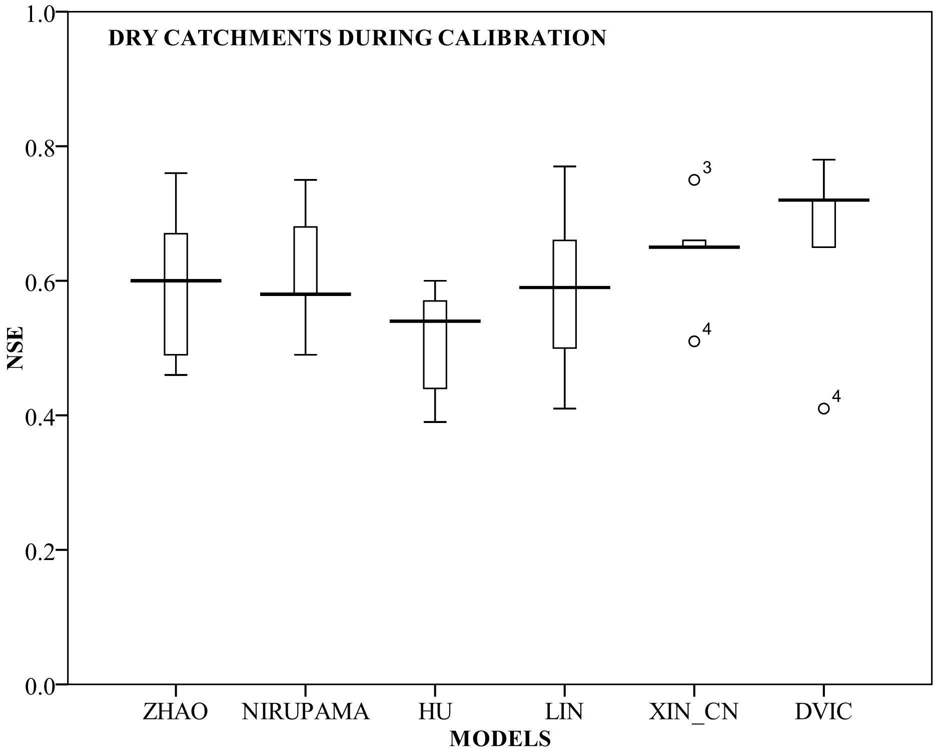


Figure 5.12 Boxplots of the NSE values for dry catchments for comparative performance between existing and proposed versions of the Xinanjiang model in calibration process

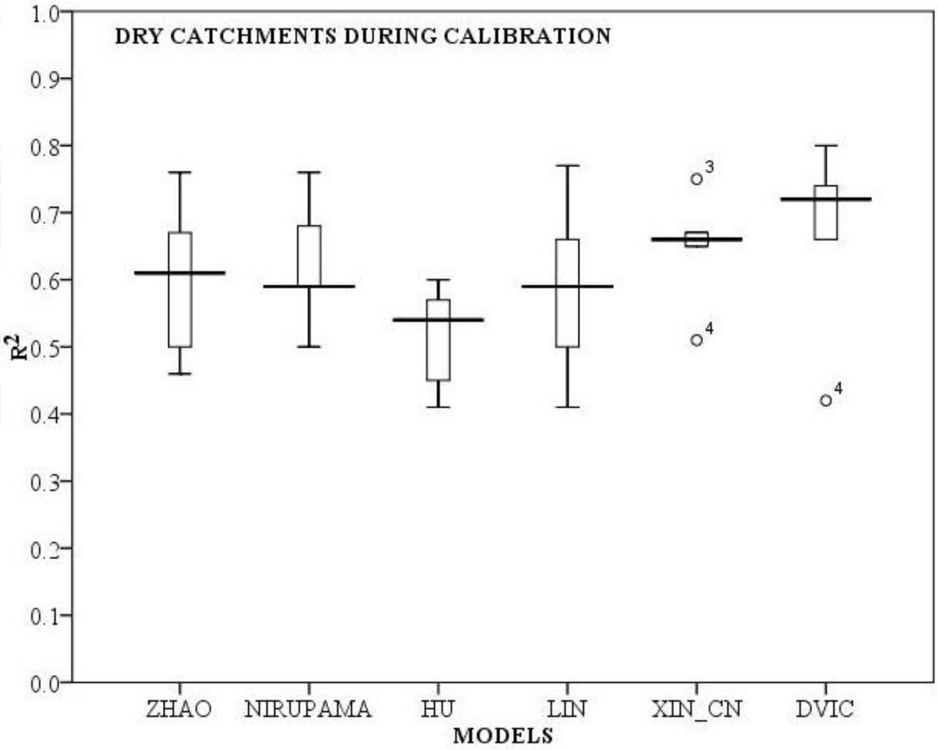


Figure 5.13 Boxplots of the R^2 values in dry catchments for comparative performance between existing and proposed versions of the Xinanjiang model in calibration process

A typical comparison plot of a dry category catchment showing the observed and the corresponding simulated discharge hydrographs obtained using all the models studied herein is given in Figure 5.16 for the Hridaynagar catchment for the year 1984-85. Also a separate plot of the simulated daily stream flow for the entire calibration period using the original Xinanjiang model (Zhao, 1992) is compared against the corresponding observed hydrograph for the case of illustration. As can be inferred from Figure 5.16 and other such figures given in APPENDIX-I and II the closeness between the model simulated discharges obtained using the DVIC and the XIN-CN models with corresponding observed hydrograph is better in comparison with the simulations of other models. Although, it is seen from Figure 5.16 that the existing version of the Xinanjiang model display a higher efficiency for the considered year of the Hridaynagar catchment.

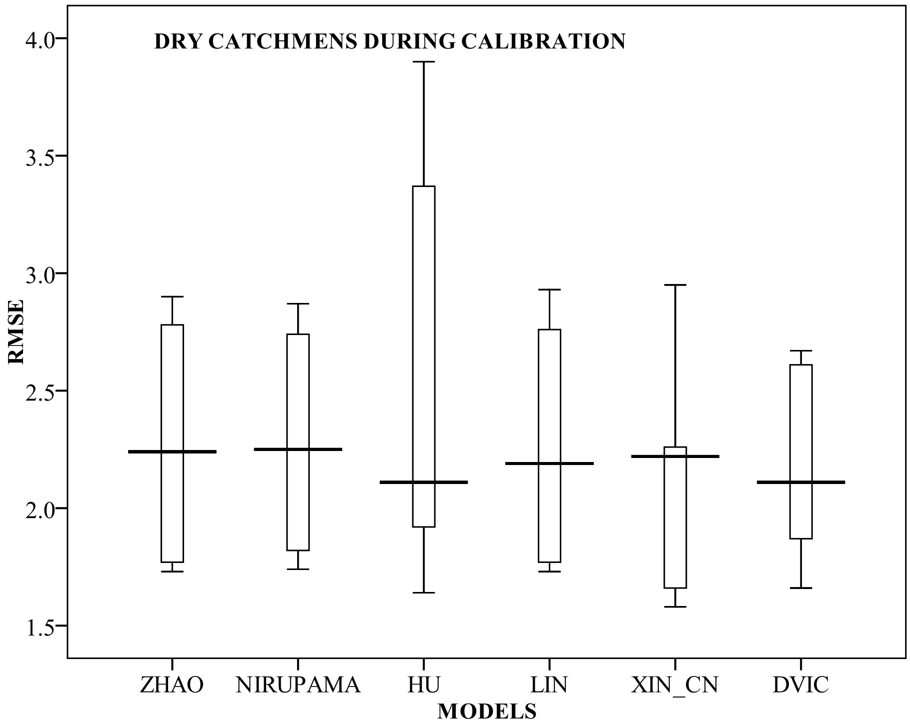


Figure 5.14 Boxplots of the RMSE values in dry catchments for Comparative performance between existing and proposed versions of the Xinanjiang model

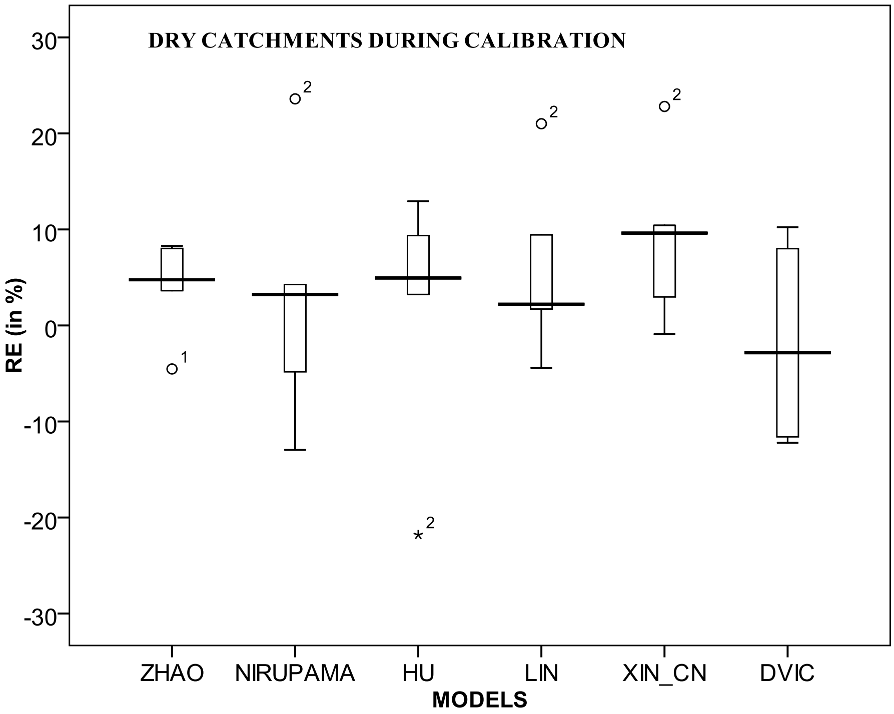


Figure 5.15 Boxplots of the % RE values in dry catchments for Comparative performance between existing and proposed versions of the Xinanjiang model

5.3 VALIDATION OF MODELS

Validation of a hydrological model is an important step of the modelling protocol to check its suitability in reproducing the hydrological behaviour of the developed model by employing the data not used in the calibration. Validation methods are commonly used to check, whether the developed model is capable or not in reproducing the catchment behaviour for simulating stream flow when the catchment response is unknown (Parkin et al., 1996). In this study, the validation of the studied models have been performed using the second set of data that was not used in the calibration of parameters of the models. Similar to the calibration process, the performance of the competing models are assessed using the evaluation metrics NSE, R^2, RMSE and RE (in %).

5.3.1 Performance evaluation and comparative study of models

For performance assessment and comparison of all the calibrated variants of the Xinanjiang models considered in the study and proposed models in simulating the recorded discharge hydrographs for the independent set of data these calibrated models were applied for the same catchments as used in the calibration process, but in the validation process.

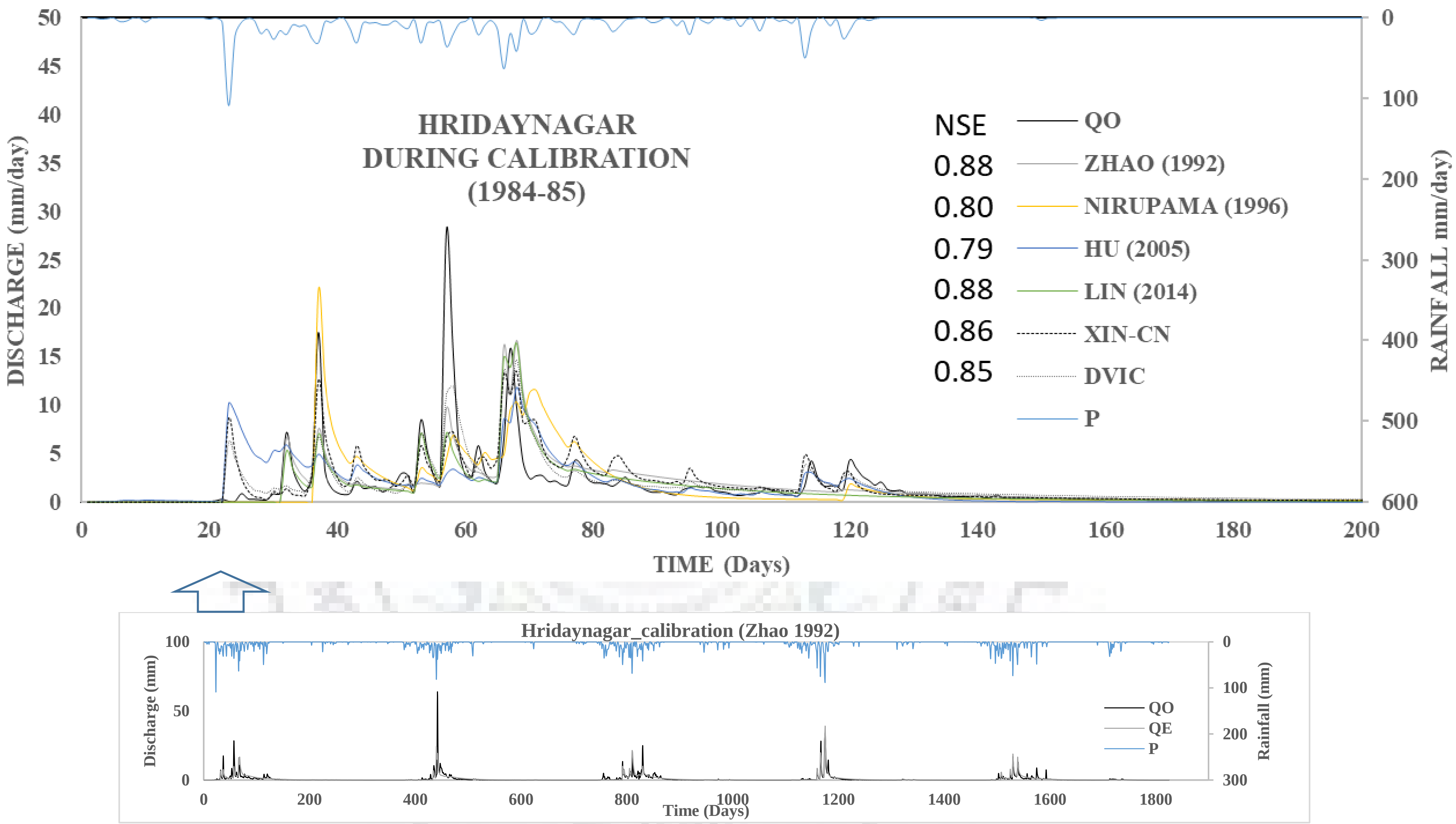


Figure 5.16 Comparative performance between existing and proposed versions of the Xinanjiang model in terms of the observed and computed discharge

The parameter set obtained through calibration process of the respective variants models are used directly without changing their values using the independent set of data so that the independent performance of the models can be assessed. Tables 5.12 – 5.15 show the values of statistical indices obtained in the validation process for all the studied variants of the Xinanjiang model and those of the proposed modified versions of the Xinanjiang model, i.e., the XIN-CN and DVIC models. Similar to the procedure followed in the calibration process, the maximum and minimum values of the statistical indices for each of the catchments is shown with the bold font numbers to represent the estimated maximum value and using the underlined italic bold numbers to represent the minimum values obtained for the competing models applied for the studied catchments are also given in Tables 5.12 to 5.15.

It can be seen from Tables 5.12 – 5.13 that for the wet catchments, the obtained NSE and R^2 values are found to be in the range of 0.70 to 0.92 for the proposed models whereas these values are found between 0.68 to 0.90 for existing variants of the Xinanjiang models and, thereby, indicating better performance of the proposed hybrid models over the existing variants of the Xinanjiang models applied for the wet catchments during the validation process. It can be seen from Table 5.14 describing the simulation metrics for the wet catchments studied, the values of RMSE varies between 7.01 to 11.65 which suggests good response by all the studied variants of the Xinanjiang model in the validation process. The mean RMSE value varies between 7.88 to 9.12 and the lowest value (=7.88) has been achieved by the proposed hybrid XIN-CN model. Also the proposed DVIC model have the lower value of mean RMSE estimate as compared to the Hu et al. (2005) model. This narrow clusters of RMSE estimates both for the proposed modified variants of the Xinanjiang model implies good model performance while studying wet catchments during the validation process also. It can be seen from Table 5.15 that for the wet catchments, the RE (in %) varies between – 0.79 to – 11.20 (indicating under prediction) and 0.03 to 7.95 (indicating over prediction) which suggests a good model performance in the validation process (for RE (in %) < ±10.0, Donigian et al. 1983; Harmel et al. 2006; and Jain et al. 2012). It is also seen from Table 5.14 that for all the catchments (except for two catchments) the upper value of RE (in %) is smaller in both of the proposed modified Xinanjiang models than the existing variants of the Xinanjiang model, which imply that the predictability of stream flow in validation process is better for the proposed hybrid models than the existing variants of the Xinanjiang model when applied for the wet catchments.

Table 5.12 NSE estimates during validation process for all studied catchments by proposed and existing versions of the Xinanjiang model

Climatic Condition	Name of Catchment	Runoff Coefficient	EXISTING				PROPOSED	
			Zhao (1992)	**Nirupama (1996)**	**HU (2005)**	**Lin (2014)**	**XIN-CN**	**DVIC**
WET	Haladi	0.93	***0.68***	***0.68***	**0.73**	0.69	0.70	0.71
	Jadkal	0.92	0.90	0.90	***0.86***	0.90	**0.92**	0.88
	Dasanakatte	0.90	**0.78**	**0.78**	**0.78**	**0.78**	**0.78**	***0.74***
	Halkal	0.89	0.88	0.88	***0.83***	0.87	**0.89**	0.88
	Kokkarne	0.79	**0.90**	**0.90**	***0.83***	**0.90**	**0.90**	**0.90**
	Hemavati	0.78	**0.89**	0.88	***0.83***	**0.89**	0.88	0.87
	MEAN		0.84	0.84	***0.81***	0.84	**0.85**	0.83
AVERAGE	Khanpur	0.60	***0.64***	0.67	0.71	0.69	**0.81**	0.74
	Dindori	0.51	0.54	***0.45***	***0.45***	***0.45***	0.64	**0.67**
	Chidgaon	0.50	**0.62**	**0.62**	***0.39***	0.61	0.60	**0.62**
	Gadarwara	0.49	0.68	0.67	***0.56***	0.68	0.63	**0.71**
	Belkheri	0.45	0.59	0.57	***0.35***	**0.61**	0.59	0.60
	Manot	0.45	0.71	**0.72**	***0.45***	0.71	0.70	0.71
	Bamni Banjar	0.37	***0.28***	0.32	0.54	0.32	**0.57**	0.56
	Patan	0.37	***0.74***	***0.74***	0.81	-	0.78	**0.83**
	Anthroli	0.37	0.49	***0.42***	0.49	0.50	**0.54**	0.43
	MEAN		0.59	0.58	***0.53***	0.57	0.65	**0.65**
DRY	Kogaon	0.35	0.40	0.37	***0.35***	0.39	**0.48**	***0.35***
	Barchi	0.35	0.50	0.43	0.50	***0.38***	**0.74**	0.47
	Mohegaon	0.35	0.25	***0.24***	0.35	0.25	**0.43**	0.35
	Amachi	0.29	0.24	0.27	***0.11***	0.24	**0.50**	0.47
	Hridaynagar	0.24	0.54	0.50	***0.49***	0.53	**0.61**	0.55
	MEAN		0.39	***0.36***	***0.36***	***0.36***	**0.55**	0.44

Table 5.13 R^2 estimates during validation process for all studied catchments by proposed and existing versions of the Xinanjiang model

Climatic Condition	**Name of Catchment**	**Runoff Coefficient**	**EXISTING**				**PROPOSED**	
			Zhao (1992)	**Nirupama (1996)**	**HU (2005)**	**Lin (2014)**	**XIN-CN**	**DVIC**
WET	Haladi	0.93	***0.77***	***0.77***	0.79	***0.77***	0.78	**0.81**
	Jadkal	0.92	0.90	0.90	***0.86***	0.90	**0.92**	0.88
	Dasanakatte	0.90	**0.80**	**0.80**	0.78	**0.80**	**0.80**	***0.77***
	Halkal	0.89	0.88	0.88	***0.83***	0.87	**0.89**	0.88
	Kokkarne	0.79	0.90	0.90	***0.83***	0.90	0.90	**0.91**
	Hemavati	0.78	**0.92**	0.91	***0.86***	0.91	0.91	0.89
	MEAN		0.86	0.86	***0.83***	0.86	**0.87**	0.86
AVERAGE	Khanpur	0.60	***0.65***	0.68	0.73	0.70	**0.83**	0.77
	Dindori	0.51	0.62	0.52	***0.45***	0.54	0.65	**0.69**
	Chidgaon	0.50	0.62	0.62	***0.42***	0.62	0.60	**0.64**
	Gadarwara	0.49	0.68	0.67	***0.57***	0.68	0.64	**0.71**
	Belkheri	0.45	0.59	0.57	***0.36***	**0.61**	0.60	0.60
	Manot	0.45	0.73	**0.74**	***0.48***	0.73	0.71	**0.74**
	Bamni Banjar	0.37	***0.50***	***0.50***	0.62	***0.50***	**0.65**	0.59
	Patan	0.37	***0.74***	***0.74***	0.81	-	0.79	**0.84**
	Anthroli	0.37	0.53	0.49	0.50	0.54	**0.58**	***0.47***
	MEAN		0.63	0.61	***0.55***	0.62	**0.67**	**0.67**
DRY	Kogaon	0.35	0.50	0.48	***0.36***	0.49	**0.54**	0.48
	Barchi	0.35	0.50	0.43	0.70	***0.39***	**0.75**	0.48
	Mohegaon	0.35	0.62	0.62	***0.44***	0.63	**0.66**	0.60
	Amachi	0.29	***0.30***	0.33	0.40	***0.30***	**0.56**	0.53
	Hridaynagar	0.24	0.59	0.55	***0.52***	0.58	**0.67**	0.56
	MEAN		0.50	0.48	**0.48**	***0.48***	**0.64**	**0.53**

Table 5.14 RMSE estimates during validation process for all studied catchments by proposed and existing versions of the Xinanjiang model

Climatic Condition	**Name of Catchment**	**Runoff Coefficient**	**EXISTING**				**PROPOSED**	
			Zhao (1992)	**Nirupama (1996)**	**HU (2005)**	**Lin (2014)**	**XIN-CN**	**DVIC**
WET	Haladi	0.93	9.07	**9.10**	***8.28***	8.97	8.69	8.67
	Jadkal	0.92	8.43	8.43	**10.01**	8.45	***7.63***	9.26
	Dasanakatte	0.90	9.31	9.31	9.36	9.35	***9.23***	**10.19**
	Halkal	0.89	9.78	9.78	**11.65**	10.28	***9.54***	9.84
	Kokkarne	0.79	7.18	7.15	**9.43**	7.34	7.10	***7.01***
	Hemavati	0.78	4.88	4.90	**6.00**	***4.87***	5.07	5.27
	MEAN		8.11	8.11	**9.12**	8.21	***7.88***	8.37
AVERAGE	Khanpur	0.60	**8.89**	8.86	7.98	8.24	***6.51***	7.55
	Dindori	0.51	2.90	3.18	**3.20**	3.18	2.58	***2.48***
	Chidgaon	0.50	5.81	5.82	**7.34**	5.87	5.94	***5.78***
	Gadarwara	0.49	4.54	4.59	**5.27**	4.54	4.84	***4.33***
	Belkheri	0.45	5.73	5.91	**7.23**	***5.61***	5.73	5.72
	Manot	0.45	3.21	***3.19***	**4.42**	3.21	3.30	3.23
	Bamni Banjar	0.37	**1.52**	1.49	1.22	1.48	***1.19***	1.19
	Patan	0.37	1.85	**1.86**	1.59	-	1.69	***1.50***
	Anthroli	0.37	1.66	**1.77**	1.66	1.64	***1.58***	1.75
	MEAN		4.01	4.07	**4.43**	4.22	***3.71***	3.73
DRY	Kogaon	0.35	4.57	4.69	**4.76**	4.60	***4.26***	4.75
	Barchi	0.35	2.59	2.77	2.59	**2.86**	***1.85***	2.46
	Mohegaon	0.35	3.28	**3.31**	3.05	3.28	***2.86***	3.05
	Amachi	0.29	2.96	2.89	**3.20**	2.96	***2.39***	2.46
	Hridaynagar	0.24	2.11	2.19	**2.22**	2.05	***1.94***	2.08
	MEAN		3.10	**3.17**	3.17	3.15	***2.66***	2.96

Table 5.15 RE (in %) estimates during validation process for all studied catchments by proposed and existing versions of the Xinanjiang model

Climatic Condition	**Name of Catchment**	**Runoff Coefficient**	**EXISTING**				**PROPOSED**	
			Zhao (1992)	**Nirupama (1996)**	**HU (2005)**	**Lin (2014)**	**XIN-CN**	**DVIC**
WET	Haladi	0.93	-2.17	-0.84	**-4.26**	-0.84	-2.15	***0.03***
	Jadkal	0.92	1.76	***0.84***	**-5.35**	2.04	0.97	4.74
	Dasanakatte	0.90	7.57	7.80	***5.40***	**7.95**	7.88	7.45
	Halkal	0.89	-3.44	***-3.26***	-5.52	***-7.91***	-3.49	-3.96
	Kokkarne	0.79	0.61	***0.45***	-0.79	0.75	1.50	**6.59**
	Hemavati	0.78	-8.34	-8.17	***-6.69***	-8.79	-7.51	**-11.20**
AVERAGE	Khanpur	0.60	-3.50	-2.53	-7.37	***-1.36***	1.53	**-10.04**
	Dindori	0.51	***-2.10***	-9.38	**-10.00**	-5.54	-2.85	-6.07
	Chidgaon	0.50	-11.16	-8.82	***-0.14***	-17.77	**-18.70**	-17.83
	Gadarwara	0.49	1.78	3.25	10.34	***1.66***	**14.53**	12.74
	Belkheri	0.45	-4.81	2.10	***-0.28***	-2.69	**-8.40**	-6.64
	Manot	0.45	-15.98	**-20.67**	-19.01	***-16.10***	-16.58	-16.78
	Bamni Banjar	0.37	**38.79**	28.88	16.82	33.07	22.64	***1.92***
	Patan	0.37	-26.15	-25.43	***-15.30***	-	**-32.80**	-19.58
	Anthroli	0.37	21.15	21.42	7.17	**28.92**	18.32	***2.21***
DRY	Kogaon	0.35	16.02	16.46	**41.54**	15.94	31.86	***9.15***
	Barchi	0.35	***-1.66***	10.93	**-33.53**	-1.69	9.83	-5.70
	Mohegaon	0.35	***28.59***	29.03	**43.75**	31.78	32.52	36.27
	Amachi	0.29	46.65	42.87	**52.55**	46.96	49.87	***-19.55***
	Hridaynagar	0.24	-24.30	**-35.03**	-19.95	-19.65	-22.23	***-11.95***

For the catchments of average category, it can be seen from Tables 5.12 and 5.13 that the NSE and R^2 estimates for the proposed hybrid models are in the range of 0.43 to 0.84 and for the existing versions of the Xinanjiang model, these estimates vary between 0.28 to 0.81, which have a wide variability between their lower and upper range of the existing and the proposed variants of the Xinanjiang model. This inference suggests that even for the catchments of average category, both the proposed hybrid models are performing better than the existing versions of the Xinanjiang model. In the case of RMSE metric estimated for the catchments of average category, it can be seen from Table 5.14 that the values of RMSE varies in the range of 1.19 to 8.89 which shows a good model response. It can also be seen that for the catchments of average category, the mean RMSE value varies between 3.71 to 4.43, and the lowest values have been achieved by both the proposed models, i.e., XIN-CN (mean RMSE = 3.71) and DVIC (mean RMSE = 3.73) which suggest that in terms of RMSE, the predictability of the stream flow by both the proposed models in the validation process is better than that of the existing variants of the Xinanjiang model. The estimates of RE (in %) are shown in Table 5.15 for the catchments of average climate category. It can be seen from Table 5.15 that during under prediction scenario, the RE (in %) varies in the range of – 0.28 to – 32.80 and during over prediction scenario, the RE (in %) varies between 1.78 to 38.79, which demonstrate a very large variability in terms of both under prediction as well as over prediction of the observations by all the studied models. It is also seen from Table 5.15 that the catchments having more RE (in %) (both over and under prediction scenario) for the existing variants of the Xinanjiang model while the RE (in %) are found to be lower for both the proposed hybrid models, indicating a good model performance by both the proposed hybrid models over the existing variants of the Xinanjiang model.

For the catchments of dry category, it is seen from Tables 5.12 and 5.13 that the combine NSE and R^2 estimated obtained from the proposed hybrid models ranges between 0.35 to 0.75 and by the existing versions of the model these are ranging between 0.21 to 0.62, which shows that the proposed hybrids models are performing better than the existing version of the Xinanjiang model. Also the range of NSE and R^2 estimates are good to average in the dry catchments by both the proposed hybrid models, which suggests that the proposed hybrid models have good predictability of the stream flow generation in the catchments of dry category also. The estimated values of RMSE are shown in Table 5.14 for the catchments of dry category. It can be seen from this Table that the estimates of RMSE varies between 1.85 to 4.76 which could be considered very nearer to zero, suggesting a good model performance in terms of RMSE estimates. It can be seen from Table 5.14 that the mean RMSE values for the dry catchments varies in the range 2.66 to 3.17, in that the lowest value (= 2.66) is achieved by the proposed hybrid XIN-CN model and the highest value (= 3.17) is achieved by the Nirupama (1996) model. It is also seen from Table 5.14 that for the catchments of dry category, the mean value of RMSE is lower for both of the proposed models which indicate that both the proposed hybrid models are performing better than the existing variants of the Xinanjiang model. The RE (in %) are shown in the Table 5.15. It can be seen from Table 5.15 that for the dry catchments that during the scenario of under prediction the estimates of RE (in %) varies between – 1.66 to – 35.03 and for the proposed hybrid models it varies between – 5.70 to – 22.23 which demonstrate that the range achieved by the proposed hybrid models is lower than that of the existing variants of the Xinanjiang model. For the conditions of over predictions, the estimates of RE (in %) varies in the range 9.83 to 52.55 in that both the lower and upper values are lower for both the proposed hybrid models than those estimated by existing variants of the Xinanjiang model. This inference implies a comparatively better performance by the proposed hybrid models in the estimation of discharge in the catchments of dry category during the validation process.

Other than the tabular comparisons given by statistical indices for all the studied models, the performance evaluation of the studied models has also been evaluated using the boxplots during the validation process. Figures 5.17 – 5.28 show the boxplots of all the four criteria values for all three catchment categories, during the validation process.

It can be seen from Figures 5.17 and 5.18 that for the wet catchments, the span of the boxplots of NSE and R^2 metrics for all the studied models are very large except for that of Hu et al. (2005) model. This implies that during the validation process, the Hu et al. (2005) model is comparatively stable than the other variants of the Xinanjiang model but the range of NSE and R^2 estimates are lower than that of the other studied models, which implies the poor performance by the Hu et al. (2005) model.

Figure 5.19 shows the boxplots of RMSE estimates for the catchments of wet category during validation process. It can be seen from Figure 5.19 that the span of the boxplots of the existing variants of the Xinanjiang model are almost same except that of the Hu et al. (2005) model, which is slightly less expanded but located far away from zero. Also its median is away from zero as compared to other variants of the Xinanjiang model. The median is more close to zero for the proposed hybrid XIN-CN model as compared to the other existing variants and the median of DVIC model is almost similar as that of the other variants of the Xinanjiang model. The lower whisker values are more close to zero in all models except for the Hu et al. (2005) model. Overall, it is inferred from Figure 5.19 that in terms of RMSE metric estimates, the proposed hybrid XIN-CN model is performing better than all other variants of the Xinanjiang model and that of the proposed DVIC model. However, RMSE estimate obtained using DVIC model is better than that of the Hu et al. (2005) model.

The boxplots of the estimates RE (in %) for the wet catchments are shown in Figure 5.20. It is seen from this Figure that for the existing variants of the Xinanjiang model the span of the boxplots are found small, but very large for the Lin et al. (2014) model, which suggests that these models are stable under certain range, but the median of the Hu et al. (2005) model is quite far away from zero and it is towards the negative side as compared to other variants of the Xinanjiang model, suggesting under predictability by Hu et al. (2005) model. The RE (in %) estimated by the proposed hybrid XIN-CN model also exhibits a small span of the boxplot and also the median is close to zero. But the proposed DVIC model has quite a large span and also median is far away from zero and towards the positive side as compared to the other variants of the Xinanjiang model suggesting the condition of over prediction by the proposed DVIC model in the validation process.

For the catchments of average category, the boxplots of the NSE, R^2, RMSE and RE (in %) estimates are plotted in Figures 5.21 – 5.24. It can be seen from these Figures that the span of the boxplots of the metrics NSE and R^2 estimates for the proposed hybrid Xinanjiang models are smaller than the other variants of the Xinanjiang model. Also the upper and lower limits are higher along with the median values of the proposed hybrid models, which imply that during the validation process, the proposed hybrid models are more stable and better in the estimation of runoff production than the other variants of the Xinanjiang model when applied for the catchments of average climate category. The boxplots of the RMSE metric are shown in Figure 5.23. It can be seen from this figure that the shortest boxplot is found for the Lin et al. (2014) model and the longest boxplots for the Hu et al. (2005) model. It is pertinent to note here that the lower and upper whisker are found to be smaller and nearer to the zero for both of the proposed hybrid XIN-CN and DVIC models which indicate that in terms of RMSE values, both the proposed models exhibit good model performance in reproducing observed runoff during the validation process for the average climate category catchments. For these catchments, the boxplots of the metric RE (in %) are shown in Figure 5.24. It can be seen from this figure that the mean value of RE (in %) of the existing variants of the Xinanjiang model are very close to zero and towards negative side and the span of the boxplots are also small in size which implies more stability of the model, but some outliers towards the positive side can also be seen from the runoff reproduction of the existing variants of the Xinanjiang model, except for the Hu et al. (2005) model which shows a clear over estimation. The proposed hybrid XIN-CN model and

DVIC model also display the median nearer to zero, but slightly far away from the existing variants of the Xinanjiang model with no exhibition of outliers. Also the DVIC model exhibit comparatively small span in the boxplots, with small extensions of lower and upper whisker which indicate a good model performance in terms of RE (in %) for the catchments of average climate category during the validation process.

Figures 5.25 – 5.28 show the boxplots of all the four metric estimates used in performance evaluation viz., NSE, R^2, RMSE and RE (in %) during validation period of dry climate catchments. It can be seen from Figure 5.25 that the span of the boxplots of the NSE estimates are almost similar for all the studied models, but exhibit different characteristics, for example, for the proposed hybrid Xinanjiang models, the boxplots are placed at higher range than the competing models and also their median values are higher than the other models. This inference indicate that both the proposed hybrid Xinanjiang models are more stable and better in performance for the reproduction of discharge from dry catchment over the other variants of the Xinanjiang model.

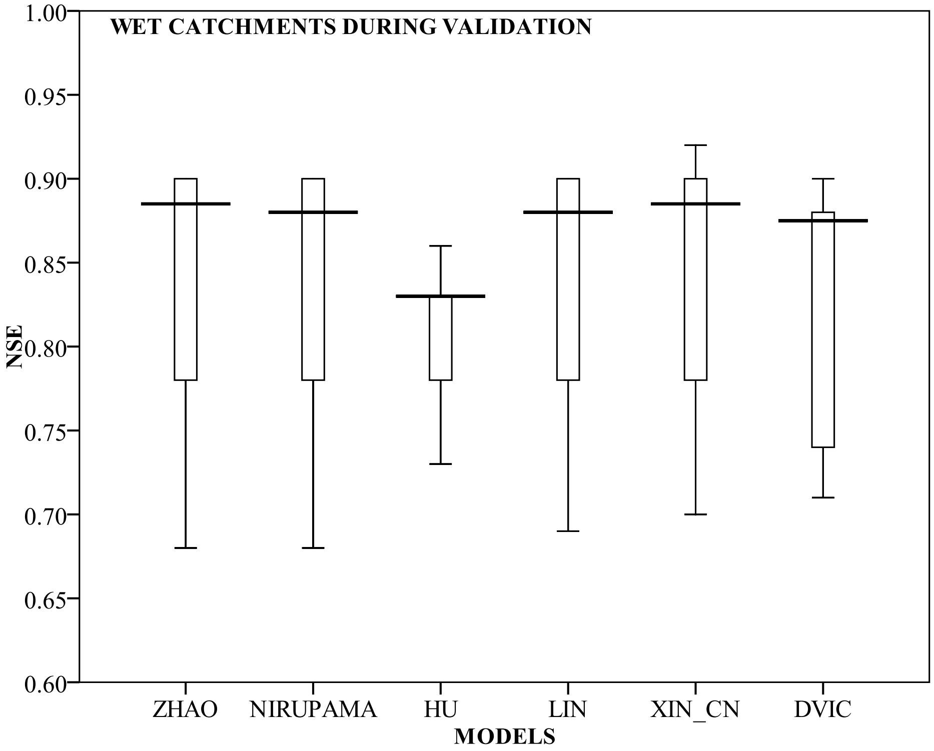


Figure 5.17 Boxplots of the NSE values for wet catchments showing comparative performance between existing and proposed versions of the Xinanjiang model in validation process

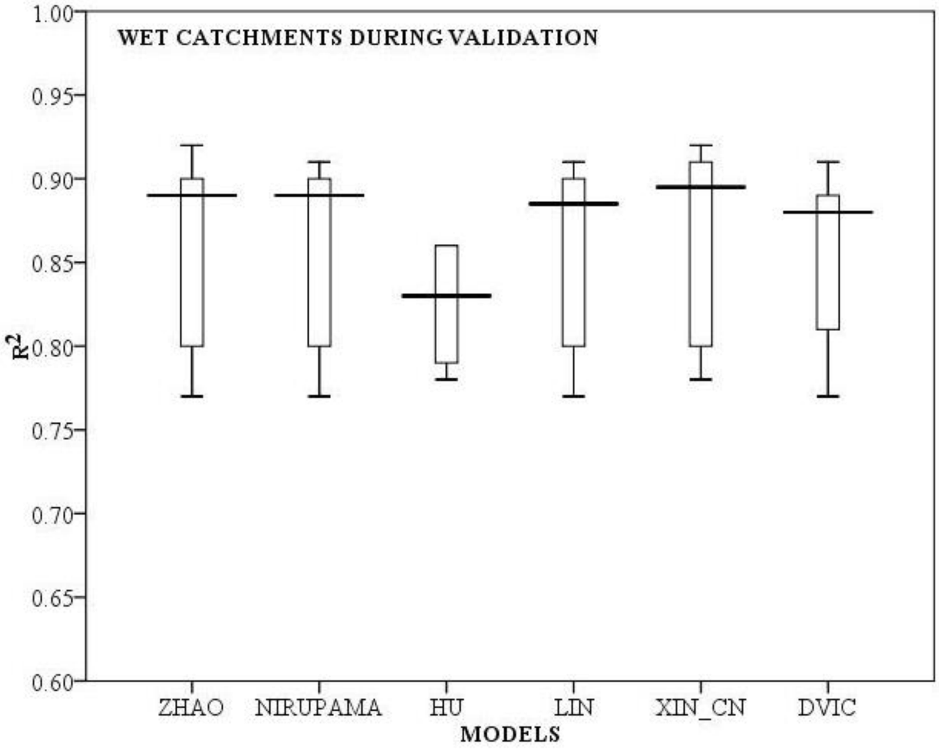


Figure 5.18 Boxplots of the R^2 values for wet catchments showing comparative performance between existing and proposed versions of the Xinanjiang model in validation process

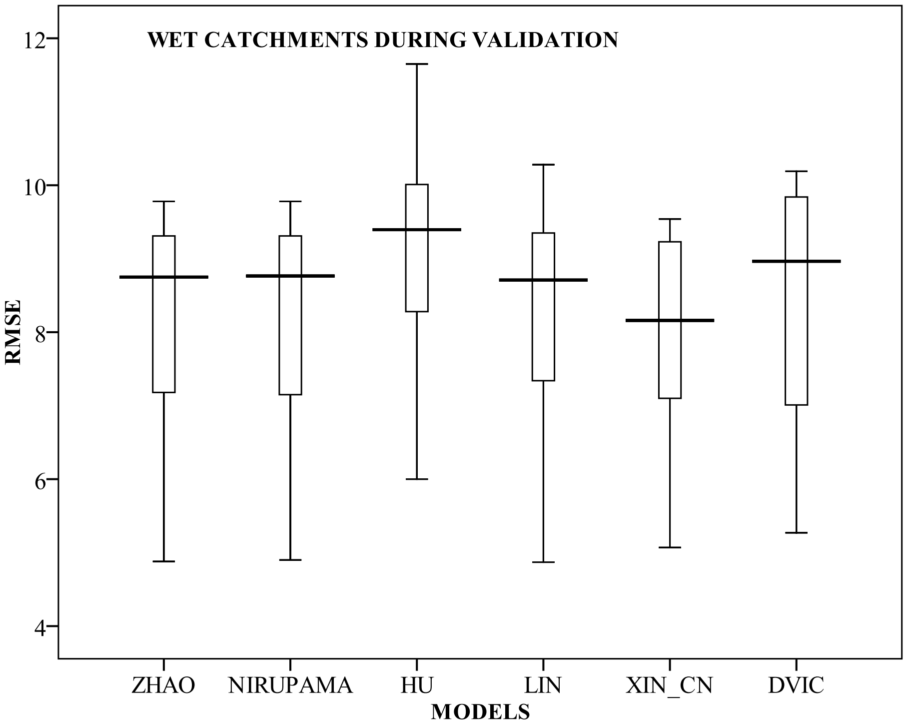


Figure 5.19 Boxplots of the RMSE values in wet catchments showing Comparative performance between existing and proposed versions of the Xinanjiang model

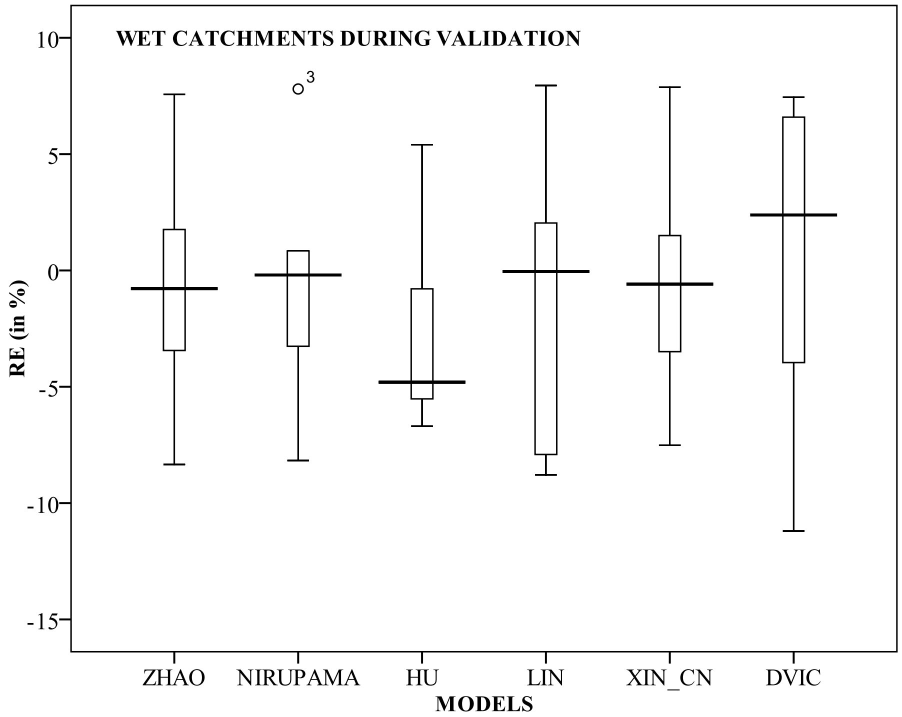


Figure 5.20 Boxplots of the % RE values in wet catchments showing Comparative performance between existing and proposed versions of the Xinanjiang model

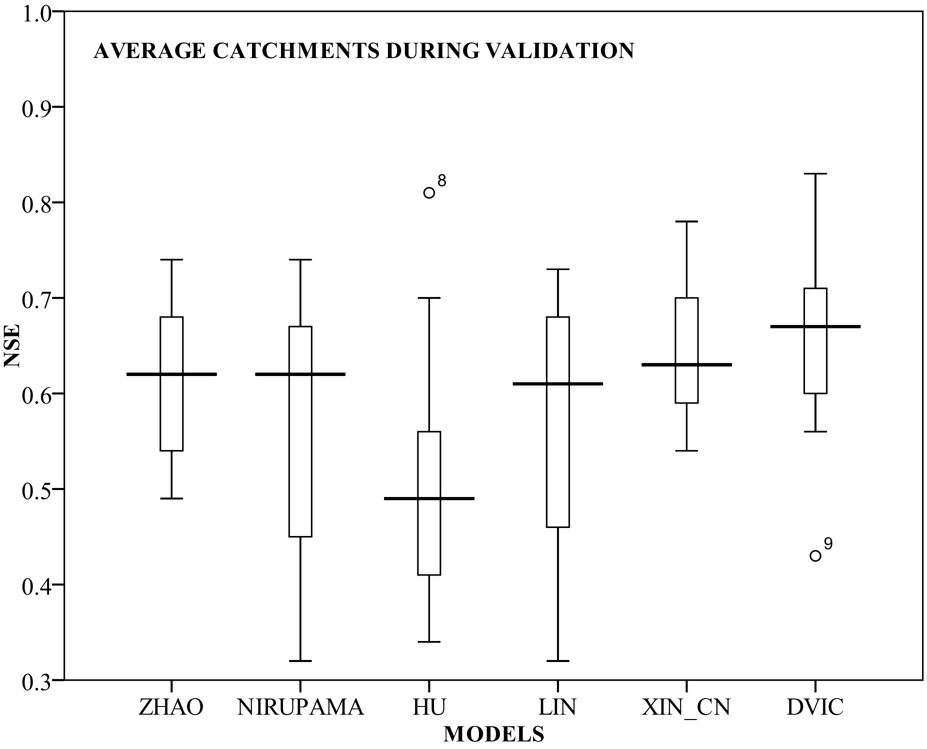


Figure 5.21 Boxplots of the NSE values for average catchments showing comparative performance between existing and proposed versions of the Xinanjiang model in validation process

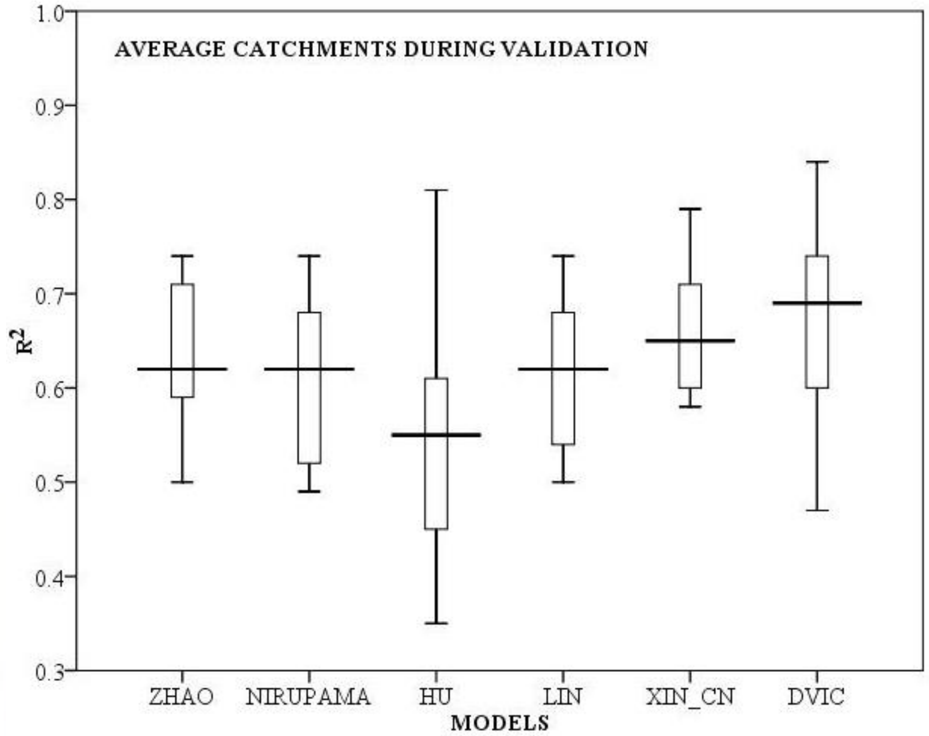


Figure 5.22 Boxplots of the R^2 values for average catchments showing comparative performance between existing and proposed versions of the Xinanjiang model in validation process

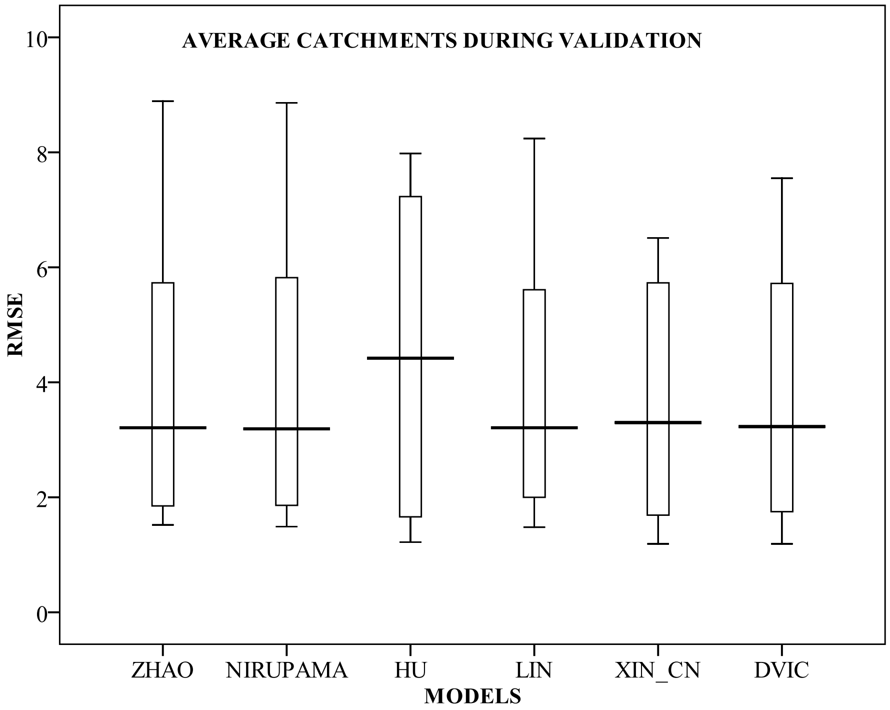


Figure 5.23 Boxplots of the RMSE values in average catchments showing Comparative performance between existing and proposed versions of the Xinanjiang model

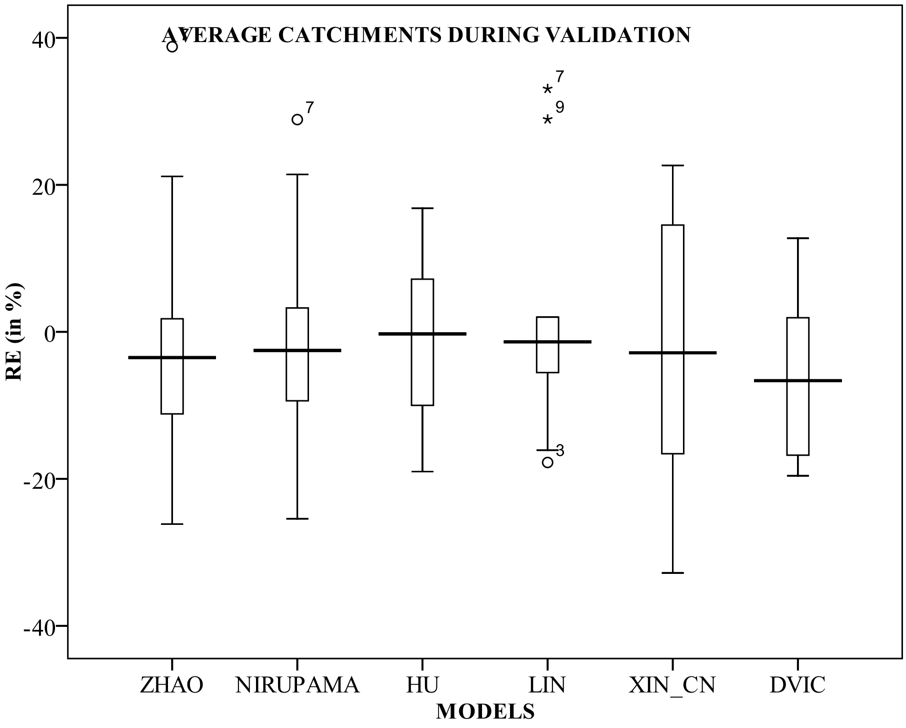


Figure 5.24 Boxplots of the % RE values in average catchments showing Comparative performance between existing and proposed versions of the Xinanjiang model

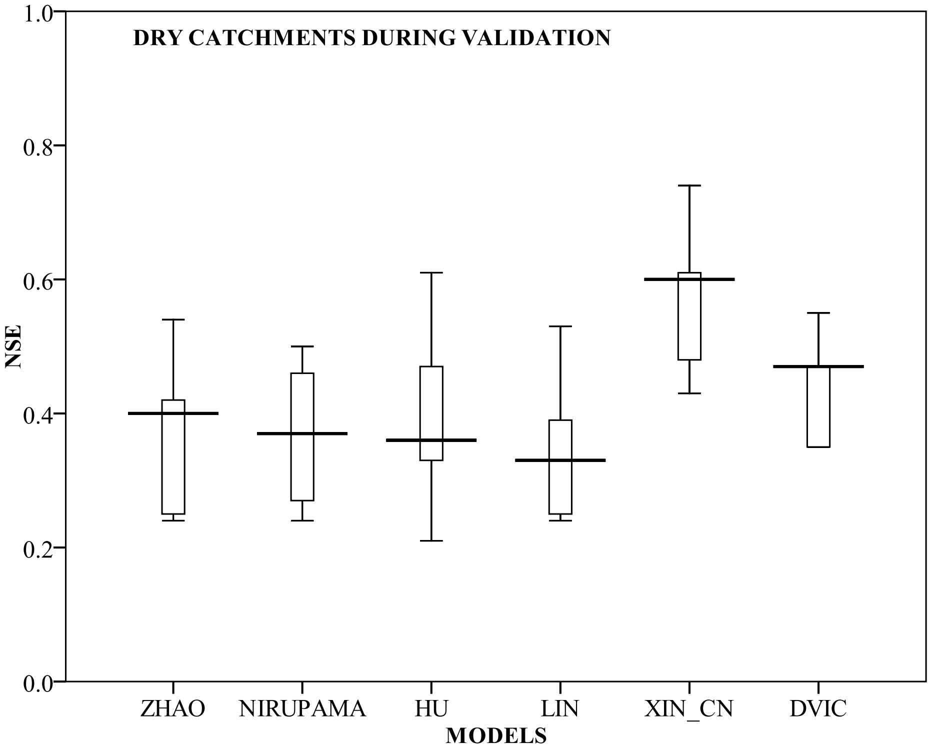


Figure 5.25 Boxplots of the NSE values for dry catchments showing comparative performance between existing and proposed versions of the Xinanjiang model in validation process

Also it can be seen from the Figure 5.26 that the span of boxplots of R^2 estimates for the proposed hybrid Xinanjiang model are very small, especially that of the proposed XIN-CN model which is clustered around the R^2 value of 0.65 and also the median value is higher for the proposed hybrid Xinanjiang models, which imply that both the proposed hybrid Xinanjiang models are more stable on the basis of the R^2 metric in reproducing the discharge from the catchments of dry climate.

The boxplots of the RMSE values obtained for the dry catchments are shown in Figure 5.27. It can be seen from Figure 5.27 that the span of the boxplots is smaller as compared to that obtained for wet and average catchments. However, an upper outlier can be seen, but the value of this outlier is also not very far from zero which indicate that all the studied models are exhibiting good model performance in catchments of dry climate. However, the model performance of the proposed hybrid Xinanjiang models is better compared to all existing variants in catchments of dry climate. Box plot depicted in Figure 5.27 indicate that the median as well as the lower whisker of RMSE values are more close to the zero for both of the proposed hybrid models indicating that the predictability of discharge in terms of RMSE is more accurate for the proposed hybrid models in comparison to that obtained using existing variants of the Xinanjiang model for the catchments of dry climate.

The boxplots of RE (in %) obtained during model validation period for the catchments of dry climate are shown in Figure 5.28. It can be seen from Figure 5.28 that the span of the boxplots for both of the proposed hybrid Xinanjiang models are smaller than that of the existing variants of the Xinanjiang model and also the median value of RE (in %) obtained for DVIC model is more close to zero but towards negative side as compare to the other studied models indicating comparatively good response by the proposed DVIC model with slight under prediction.

It is also seen from Figure 5.28 that the RE (in %) obtained using proposed XIN-CN model have the median value far away from zero and towards the positive side indicating slight over prediction by proposed XIN-CN model however, the span of the whisker is not that much high as obtained for the Hu et al. (2005) model indicates better performance by XIN-CN model as compare to that obtained using Hu et al. (2005) model.

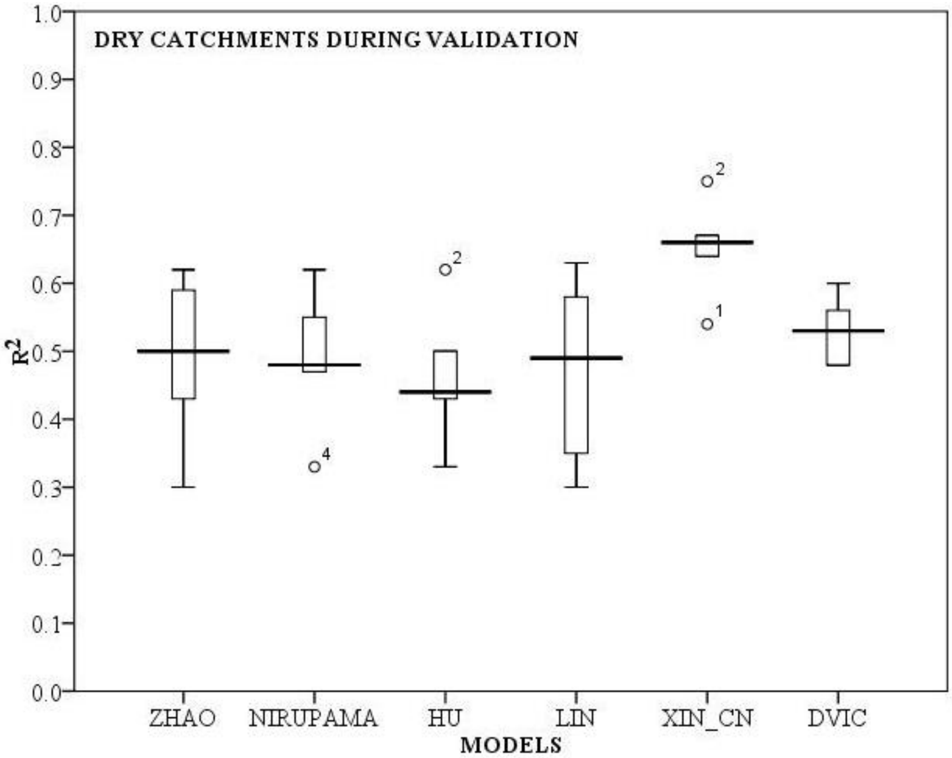


Figure 5.26 Boxplots of the R^2 values for average catchments showing comparative performance between existing and proposed versions of the Xinanjiang model in validation process

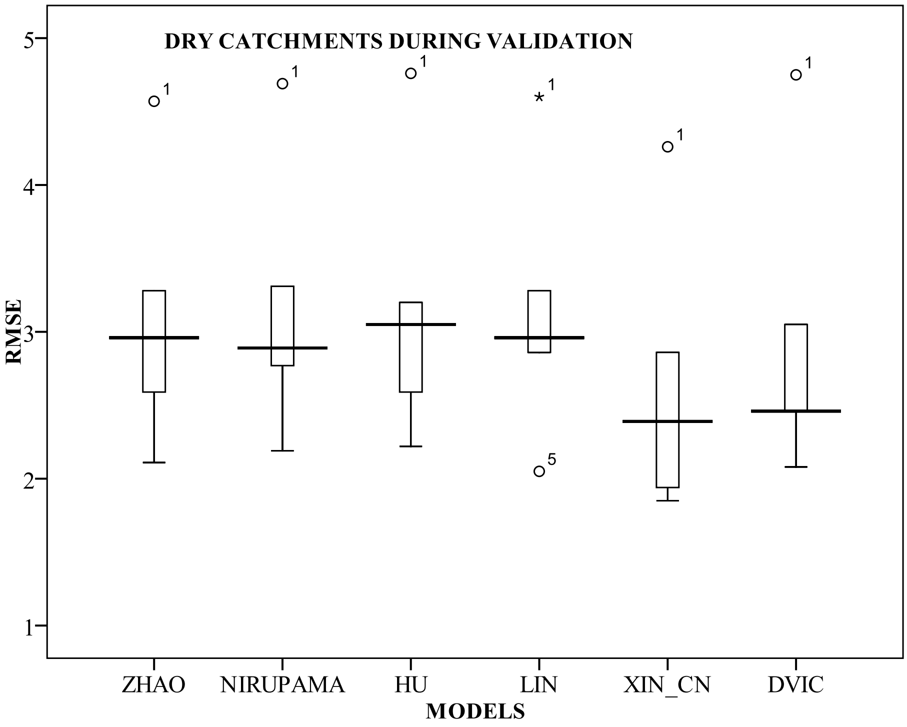


Figure 5.27 Boxplots of the RMSE values in wet catchments showing Comparative performance between existing and proposed versions of the Xinanjiang model

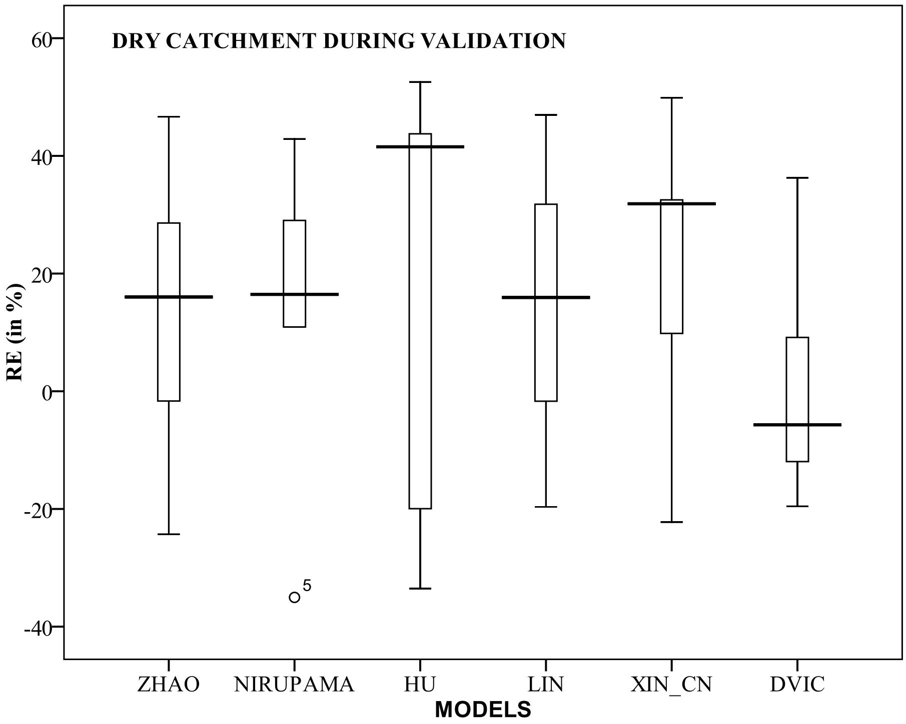


Figure 5.28 Boxplots of the RE (in %) values in wet catchments showing Comparative performance between existing and proposed versions of the Xinanjiang model

Visual Comparison of Hydrographs

Visual comparison between observed and model computed discharge helps in evaluating qualitative performance of a hydrological model in terms of matching of rising portion of flood hydrograph, matching of the estimated peak flow in comparison to corresponding observed flows as well as overall matching of the computed hydrograph with that of the observed hydrograph. Visual comparison of the model estimated and observed hydrographs, plays an important role in evaluating ability of the model in terms comparison of observed and simulated time to peak discharge, over or under estimation of peak flows and behaviour of the model in simulating flows during low flow period in comparison to corresponding observations. Therefore, to compare the closeness of observed and model reproduced hydrographs, plots between observed and model computed hydrograph with all models studied during calibration and validation time periods for have been prepared. Some of these plots of hydrographs are shown in Figures 5.29, 5.30 and 5.31 for the wet, average and dry catchments respectively as illustration and rest of the plots are shown in the APPENDIX I – II. Plots showing observed and model computed hydrographs for the wet (Kokkarne), average (Dindori) and dry (Hridaynagar) catchments are shown in Figures 5.29, 5.30 and 5.31 as illustration in the following text during validation time periods for the visual comparison of the results. Other such plots given in APPENDIX I and II follows similar behaviour and therefore, not discussed in details. It can be seen from Figure 5.29 that for the year 1992 – 93, the computed peak discharge obtained using proposed hybrid Xinanjiang models is more close to the corresponding observed peaks and also the model estimated discharge during low flow periods is matching well with the corresponding observations in comparison to all existing versions of the Xinanjiang model used in this study, indicating a good model performance by the proposed hybrid Xinanjiang models during the validation time period.

Figure 5.30 shows the plot between observed and model computed hydrographs for the Dindori catchment falling in the average climatic category. Comparison of observed and model computed hydrographs by proposed as well as existing versions of Xininjiang models indicate that closeness between observed peak flows corresponding computed peaks flows obtained through proposed hybrid Xinanjiang models is more in comparison to peaks obtained with existing variants of Xinanjiang model studied herein. It indicates that in the catchments of average category, both the proposed hybrid models are performing better.

Similarly, Figure 5.31 shows the plots between observed and corresponding model computed hydrographs for the Hridaynagar catchment classified under dry climatic category. It can be seen from Figure 5.31 that few high peaks have been observed in the catchment due to high intensity rainfall occurring for short durations. As can be seen from Figure 5.31 that the peak discharge computed using both of the proposed hybrid Xinanjiang models are more closer to corresponding observed peak values compared to all other variants of Xinanjiang model used in this study. The closeness between observed and computed peak discharge by the proposed DVIC model, which includes the runoff generation by infiltration excess runoff mechanism by dynamically varying infiltration capacity is better compared to other models. Also, the XIN-CN model is performing better in the dry catchment which is depicted in the Figure 5.31, as the XIN-CN model also incorporate the infiltration excess runoff generation mechanism by the combination of SCS-CN methodology within the framework of existing Xinanjiang model. On the other hand, it could be seen from Figure 5.31 that the Hu et al. (2005) model performed very poorly in simulating peak discharge even though it has dual runoff generation mechanism. The Hu et al. (2005) model uses hyperbolic equation concept for runoff generation, but applied in the different ways i.e. one in the saturation excess and other in the infiltration excess runoff generation process, which shows that the combination of these two runoff generation process by the same parabolic equation concept is not improving model simulation results. On the other hand, the proposed DVIC model includes only one runoff generation mechanism when it comes to storm runoff generation and the runoff generation through saturation happens only when the point soil moisture storage capacity if full and thus simulating runoff in a more realistic manner resulting in better performance of the model in comparison to all other variants of the Xinanjiang model. It indicates that use of the hyperbolic concept in a proper and realistic manner for runoff generation process can increase the modelling efficiency (which has been included in the proposed DVIC model and explained in a physical sense in Section 5.4 below) which is better than the much more complex process of the runoff generation included in the Hu et al. (2005) model.

5.4 PHYSICAL INTERPRETATION OF RUNOFF GENERATION PROCESSES INCLUDED IN THE PROPOSED DVIC MODEL

Temporal distribution of soil moisture (W), initial infiltration rate (f_0) and final constant infiltration rate (f_c) obtained from DVIC model and observed rainfall has been plotted for all studied catchments. One such plot is given in Figure 5.32 as illustration for the Kokkarne catchment from wet category.

Close examination of Figure 5.32 and other such plots given in APPENDIX-III reveals that with prolonged and continuous spell of rainfall, the soil moisture increases and eventually the soil moisture store gets filled up to the field capacity resulting in corresponding lowering of f_0 to f_c when W reaches to the field capacity. Therefore, when W reaches to the field capacity, saturation condition prevails in the watershed and infiltration can only take place at the rate of fc. This could be visualized as situation akin to generation of surface runoff in a similar way as in case of saturation excess as in Xinanjiang model. Therefore, the proposed model is capable of taking care of both Hortonian and Saturation Excess runoff generation mechanisms.

5.5 BEHAVIOUR OF TENSION WATER STORAGE CAPACITY CURVE IN RUNOFF GENERATION PROCESS IN ZHAO (1992) AND NIRUPAMA (1996) MODEL

Liu et al., (2001) showed that if the value of parameter B tends towards zero then the runoff decreases and if it is zero than catchment will behave like a tank, i.e., no runoff will be generated from the pervious area of the catchment. If the value of parameter B tends towards infinity then the production of runoff will be more and the catchment will behave like an impervious surface, i.e., all the rainfall will become runoff after eliminating the evaporation losses. In this study the behaviour of the parameter B has been studied in detail on catchments selected in this study for Xinanjiang (Zhao, 1992) and Nirupama (1996) models.

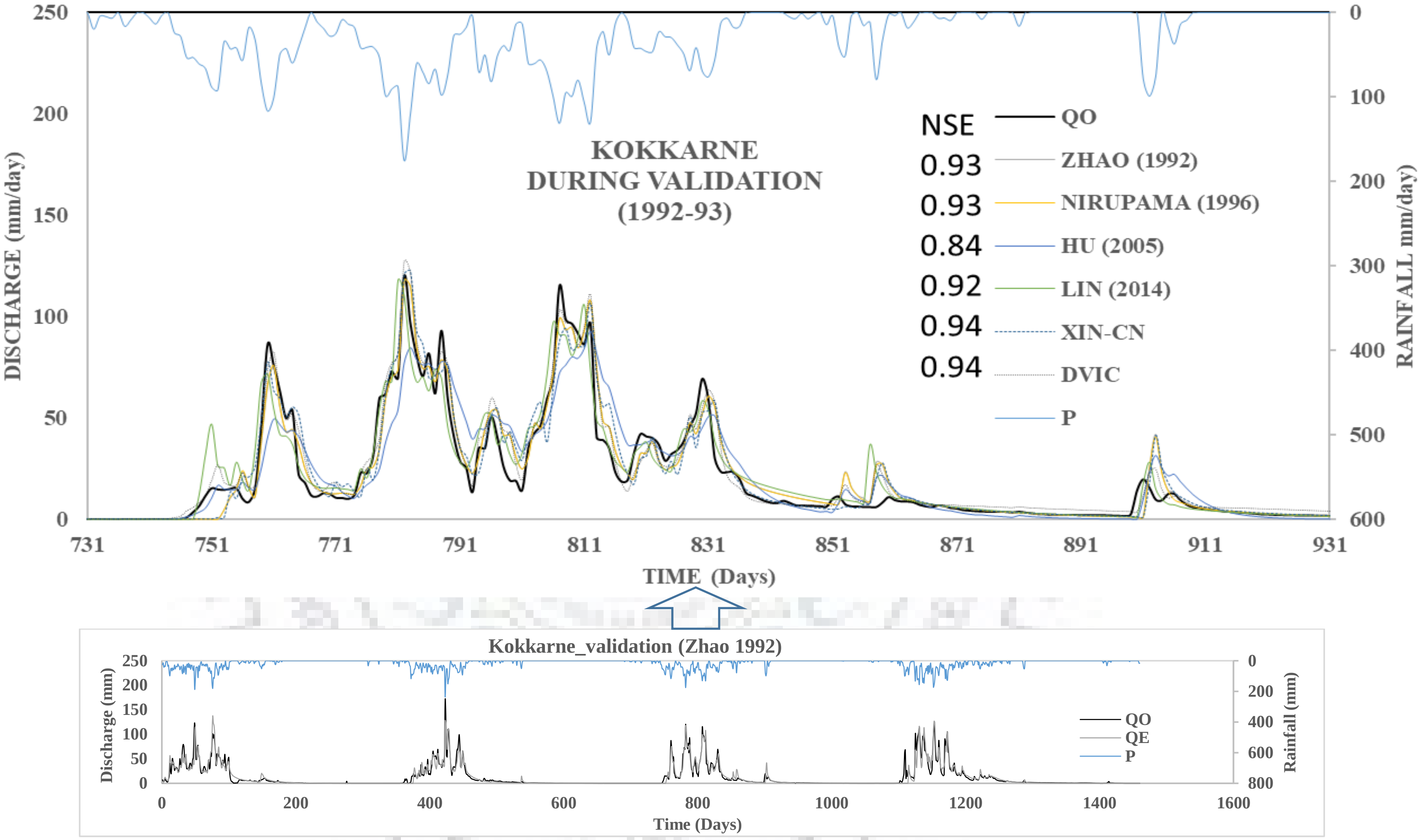


Figure 5.29 Comparative performance between existing and proposed versions of the Xinanjiang model in terms of the observed and computed discharge

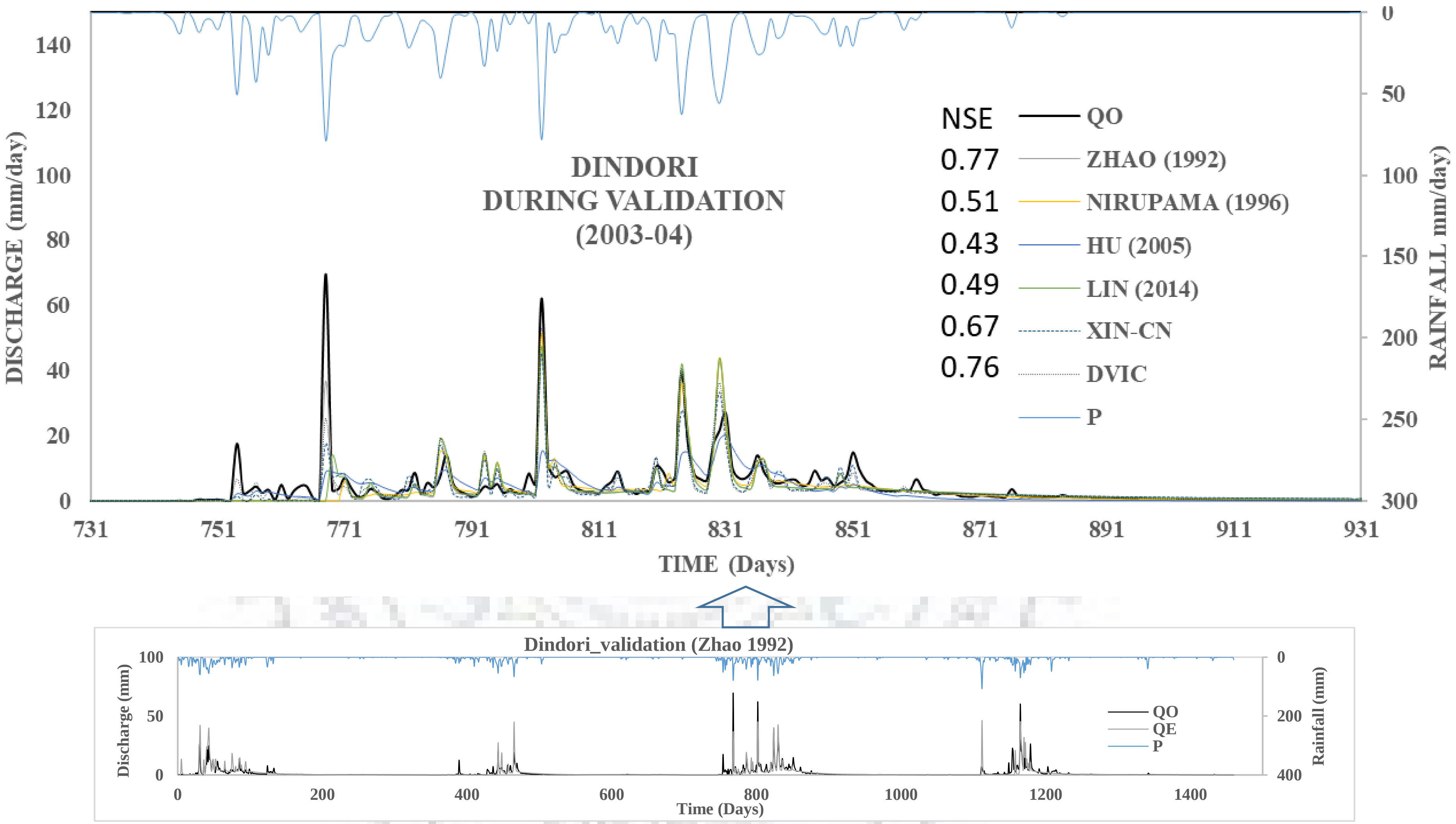


Figure 5.30 Comparative performance between existing and proposed versions of the Xinanjiang model in terms of the observed and computed discharge

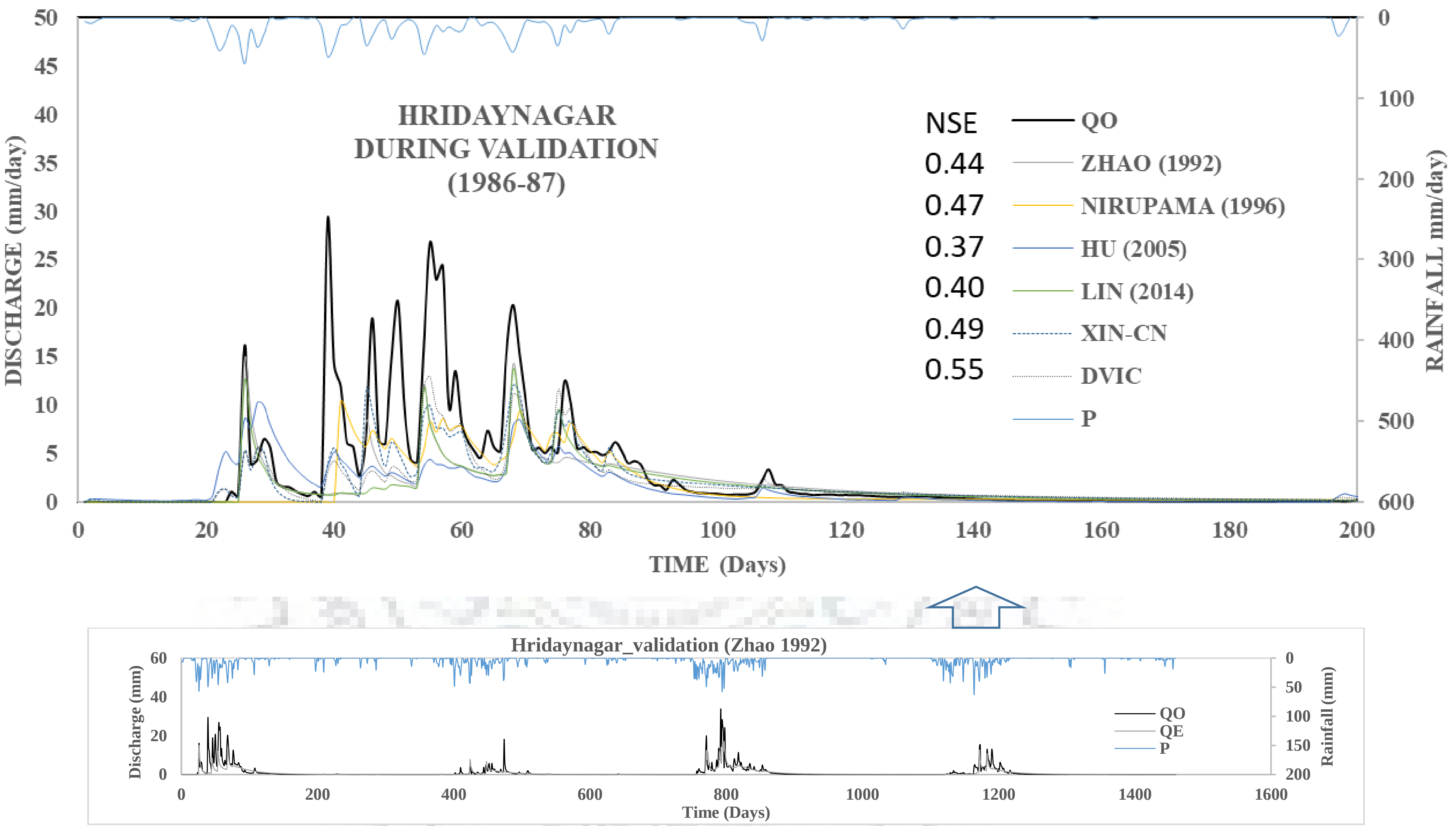


Figure 5.31 Comparative performance between existing and proposed versions of the Xinanjiang model in terms of the observed and computed discharge

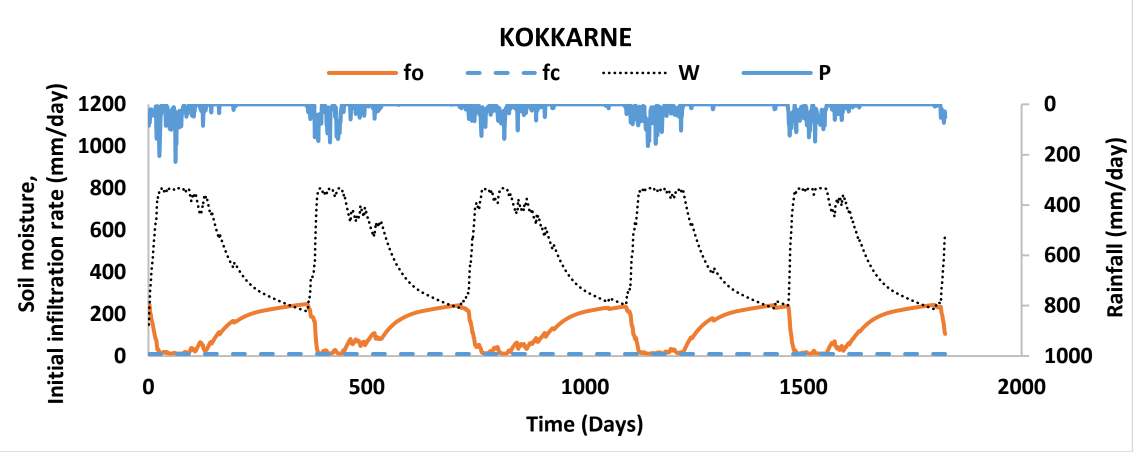


Figure 5.32 Soil moisture vs Initial infiltration rate (fo) and final constant infiltration rate (fc) in DVIC model

The heterogeneity of the soil can be understood with the help of parameter B (Liu et al. 2001; Manfreda, 2008). The area under the tension water distribution capacity curve represents the average soil moisture capacity therefore, the study of shape of tension water storage capacity curve obtained from the Xinanjiang model can through some light on the runoff generation characteristics of studied catchments. The shapes and inclination of the curves towards different axis give an idea about the runoff generation characteristics of a catchment. If the inclination of the tension water storage capacity curve or infiltration capacity curve is towards the primary Y-axis and secondary X-axis then the value of the parameter B would be < 1, which indicate that the catchment has greater capacity to store water or have more tension water storage capacity, consequently such catchments would exhibit lesser potential for runoff generation. Alternatively, if the inclination of the tension water storage capacity curve is towards secondary Y-axis and primary X-axis then the value of the parameter B would be >1, which indicate lesser capacity of the catchment to store water resulting in more runoff production. It could be seen from Figure 5.33 that Jadkal, Dasanakatte, Kokkarne, Dindori, Anthroli and Hridaynagar watersheds are characterised by the tension water capacity curve having inclination towards the secondary Y-axis and towards primary X-axis with the estimated value of B > 1, suggesting more runoff production potential from these catchments. However, it can be seen from Figure 5.33 that the rest of the watersheds are characterised by the tension water capacity distribution curve with the estimates of B < 1 having inclination towards the primary Y-axis and secondary X-axis, which indicates higher moisture absorption due to presence of high soil moisture storage capacity as depicted in Tables 5.2 and 5.3.

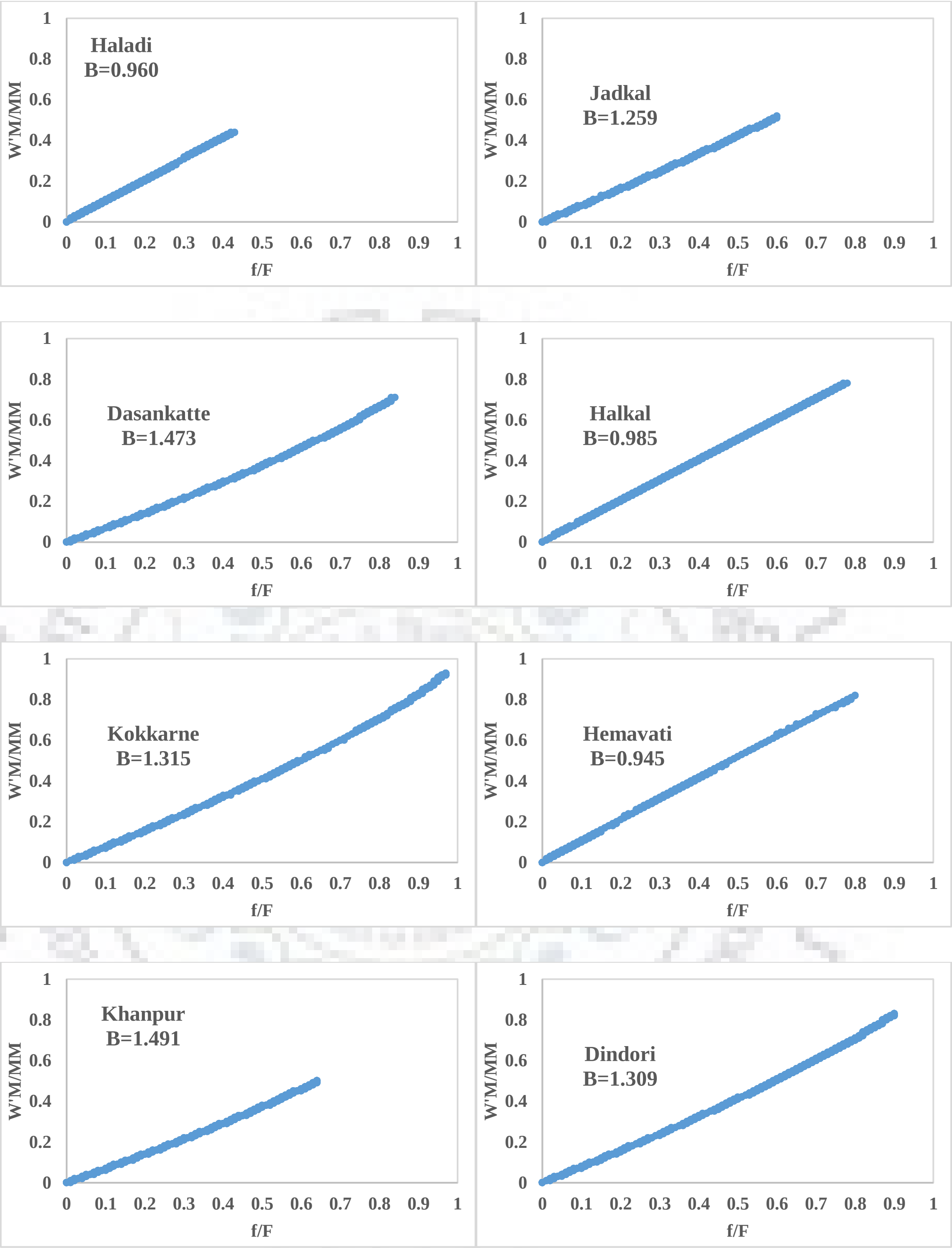


Figure 5.33 Characteristics of tension water capacity distribution curve in the Xinanjiang model (Zhao 1992)

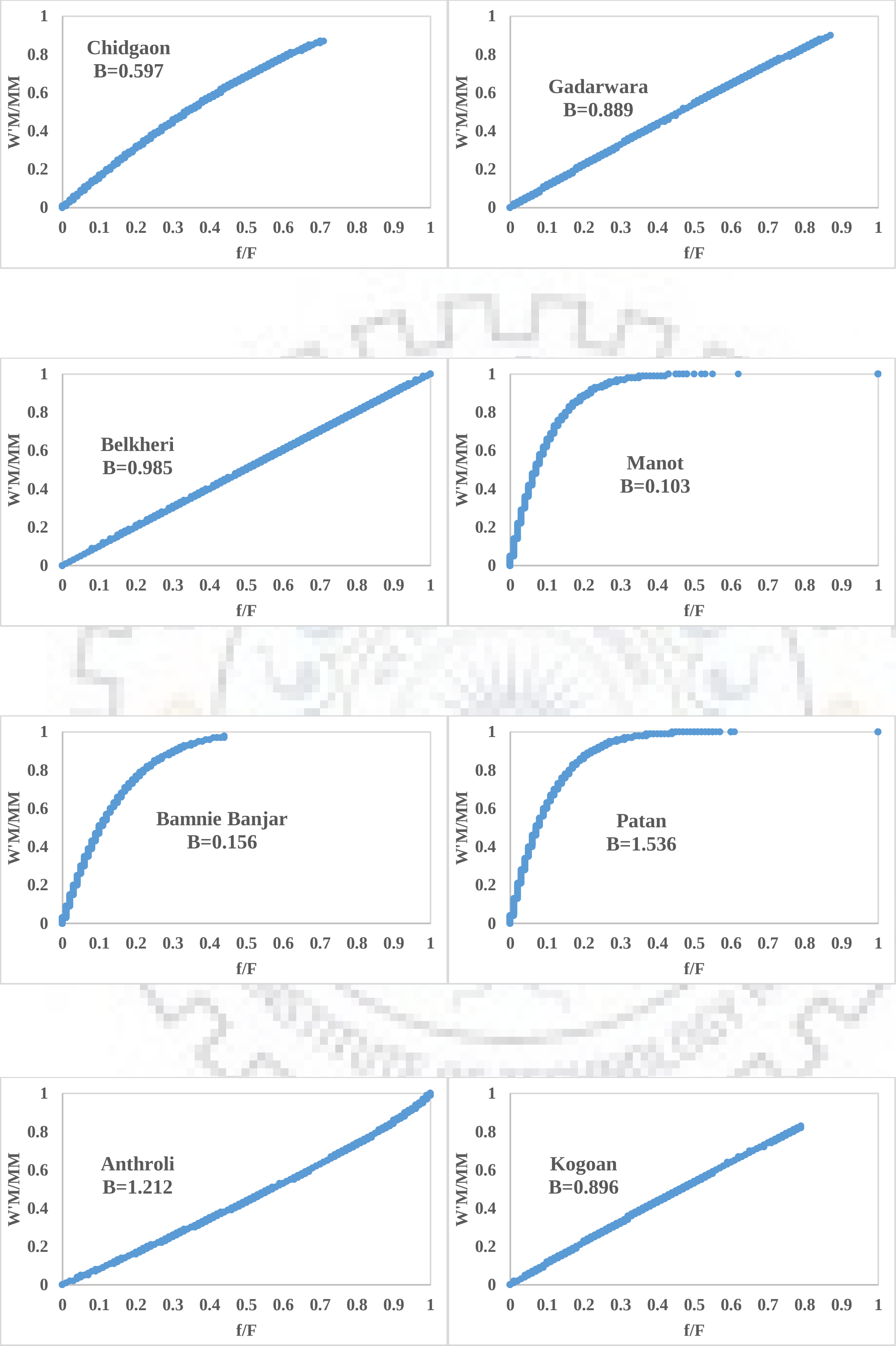


Figure 5.33 Continue…

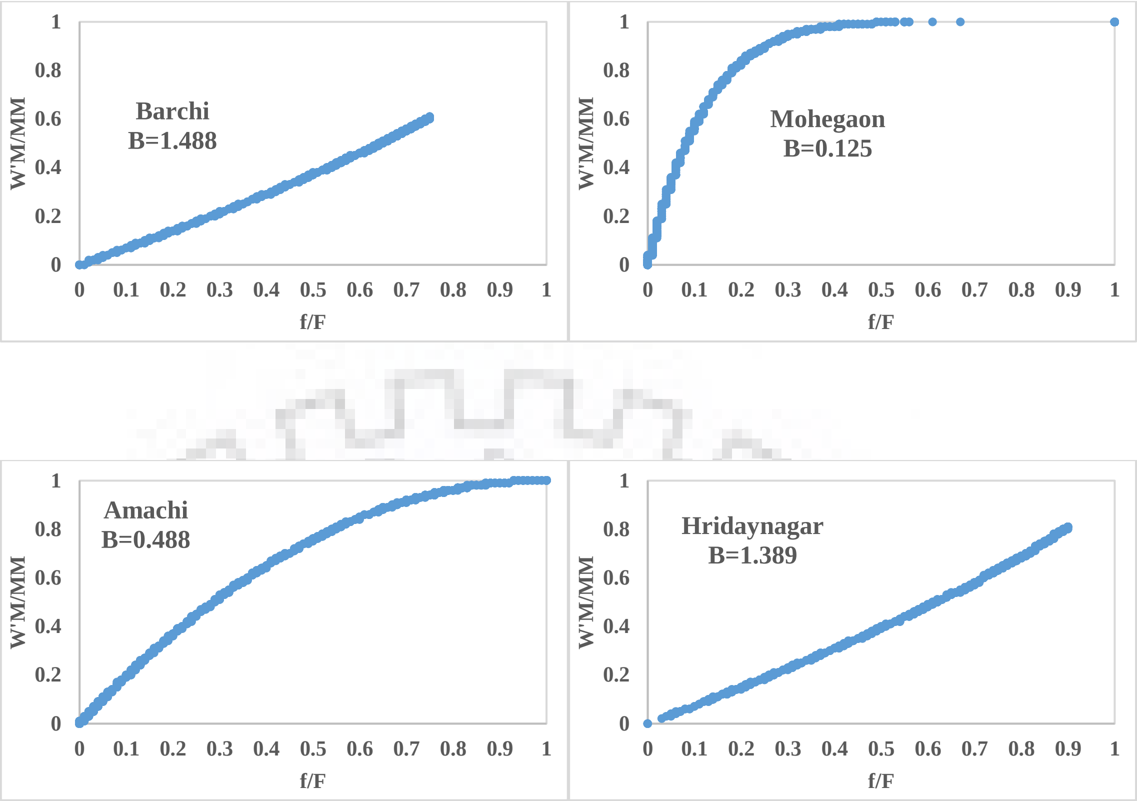


Figure 5.33 Continue…

The tension water capacity distribution curve for Nirupama (1996) model have also been plotted and shown in Figure 5.34. The speciality of these curves is that the inclination of the curves is toward both the axis simultaneously, it is due to the presence of parameter ‘m’ added by Nirupama et al. (1996) in the Xinanjiang model. In this model, the parameter ‘m’ is responsible for changing the shape of the curve from single parabolic curve to the double parabolic curve. The higher values of the parameter ‘m’ represent more runoff production as compare to Zhao (1992) model.

The tension water distribution capacity curve obtained by Zhao (1992) model have the inclination of the curve in dual direction only i.e. the inclination of the curve has either towards primary X-axis and secondary Y-axis or secondary X-axis and primary Y-axis only while in Nirupama (1996) model the inclination of the curve have three directions simultaneously. It is seen from the Figure 5.33 that in case of Amachi watershed, which belongs to the dry category, it has the value of parameter B<1 in Zhao (1992) model which shows lower runoff production due to presence of higher area covered by the curve which is the areal average soil moisture capacity of the watersheds. In case of Nirupama (1996) model, the Amachi watershed (Figure 5.34) has the value of parameter B<1 but the value of parameter ‘m’ is quiet high therefore, the curve changes its shape. It is seen in the Table 5.2 and 5.3 that in most of the catchments, the values of areal average soil moisture capacity (WM) are found lower in the Nirupama (1996) model as compare to Zhao (1992) model which shows the evidence that the parameter has a role in reduction of the value in WM which is also evident from Figure 5.34 for most of the catchments. However, analysis of results in terms of increase in model efficiency (NSE) and other statistical indices for Nirupama (1996) model in comparison with those obtained using Xinanjiang model is not significant which clearly indicate addition of one more parameter in this manner does not improve results and may be avoided.

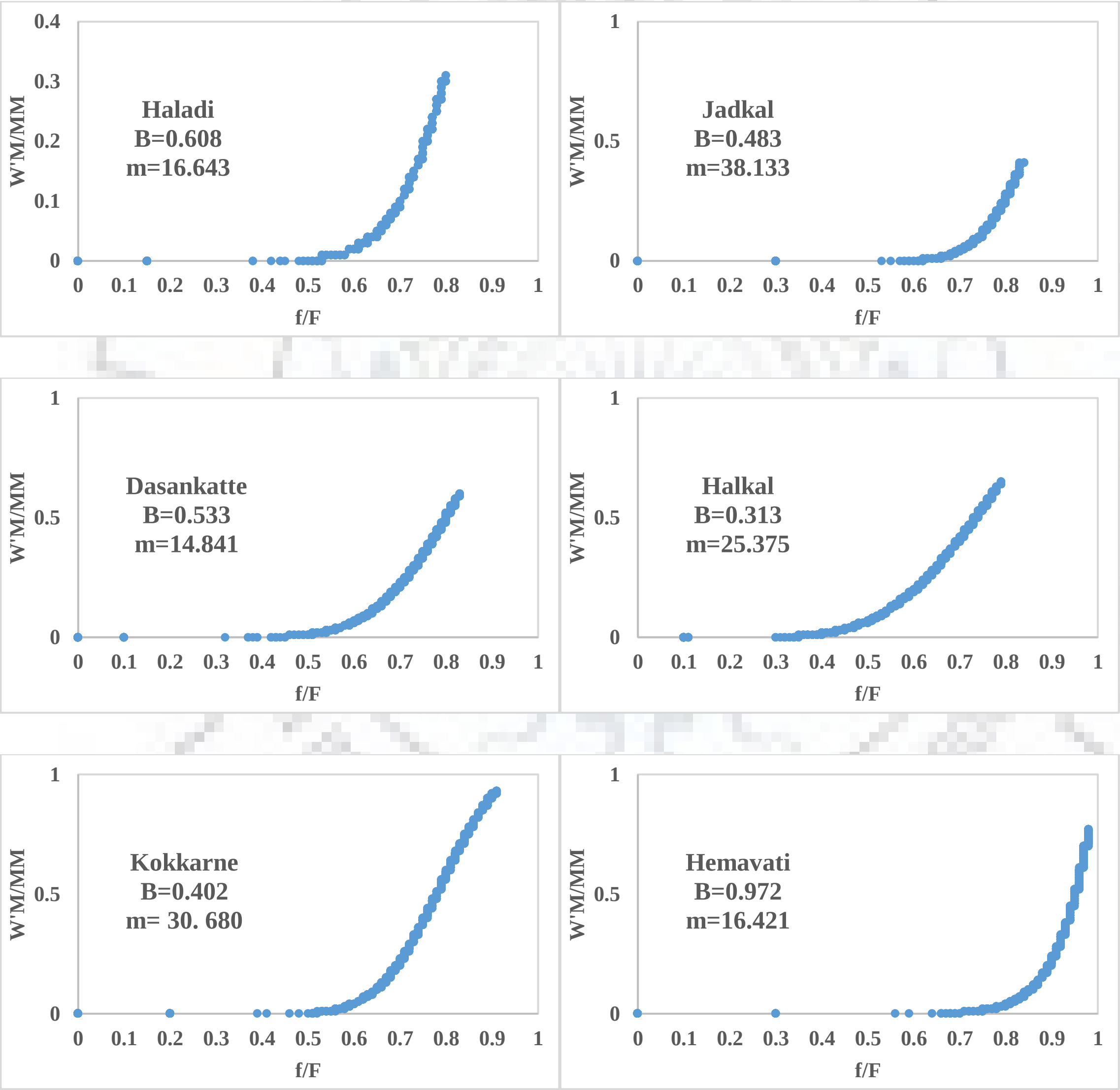


Figure 5.34 Characteristics of tension water capacity distribution curve in the Nirupama (1996)

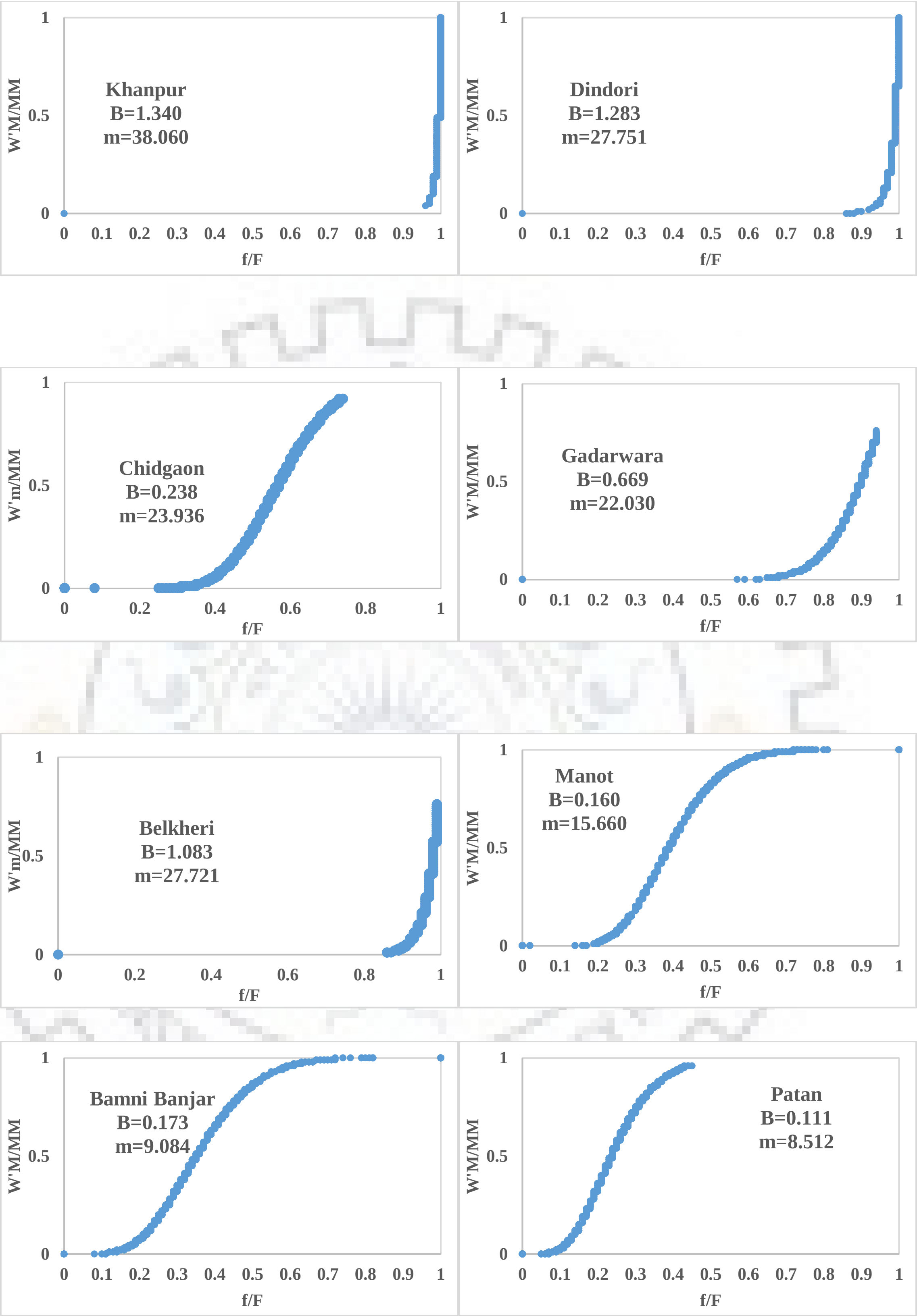


Figure 5.34 Continue…

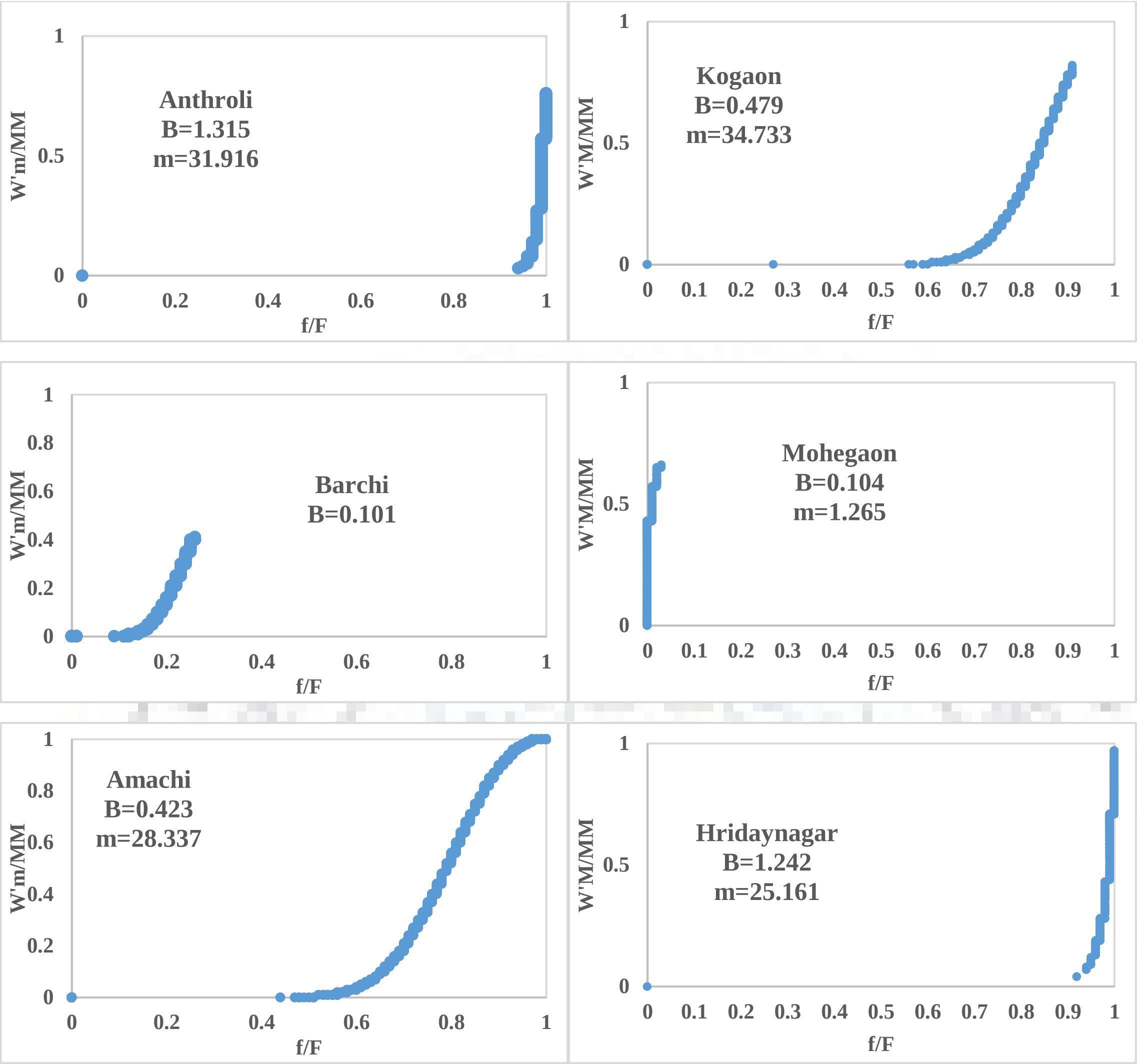


Figure 5.34 Continue…

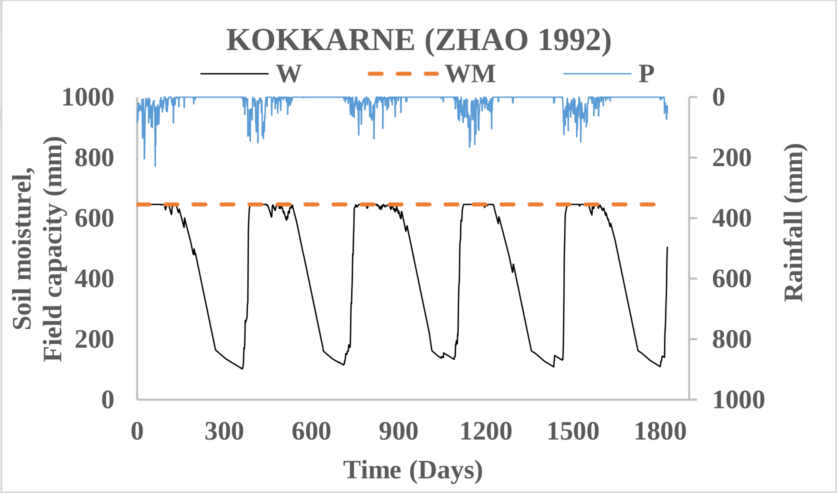
5.6 SOIL MOISTURE PROFILE OF THE CATCHMENTS AND AVERAGE SOIL MOISTURE DEFICIT

Understanding the variability of soil moisture and rainfall pattern across spatial – temporal scales is of great interest in many scientific and operational applications such as forecasting, flood predictions and irrigation scheduling (Brocca et al., 2010c; Koster et al., 2010; Corradini et al., 2011; Brocca et al., 2012; Brocca et al., 2013; Corradini, 2014; Korres et al., 2015; Ojha and Govindaraju, 2015; Morbidelli et al. 2016). The soil moisture profile for all the studied catchments have been plotted for Zhao (1992), Lin et al. (2014), XIN-CN model and DVIC models. Figure 5.35 shows a set of soil moisture profiles for Kokkarne catchment. For rest of the catchments these plots are shown in the APPENDIX-IV. As can be seen from Figure 5.35 that the pattern of soil moisture variation is same for Zhao (1992), Lin et al. (2014) and XIN-CN models while for the DVIC model, it is different than the other models. Therefore, for comparison purposes, average annual soil moisture deficit obtained for each catchment have been plotted in Figure 5.36 and the values are shown in Table 5.16. The average annual soil moisture deficit is a non-dimensional value similar to runoff coefficient, also its value is estimated on yearly basis so that it can be compared with runoff coefficient. The following relationship is used to obtain the value of average annual soil moisture deficit

$$Average\ soil\ moisture\ deficit = \frac{\sum_{i=1}^{N}\left(\frac{WM - W_i}{WM}\right)}{N} \qquad (1)$$

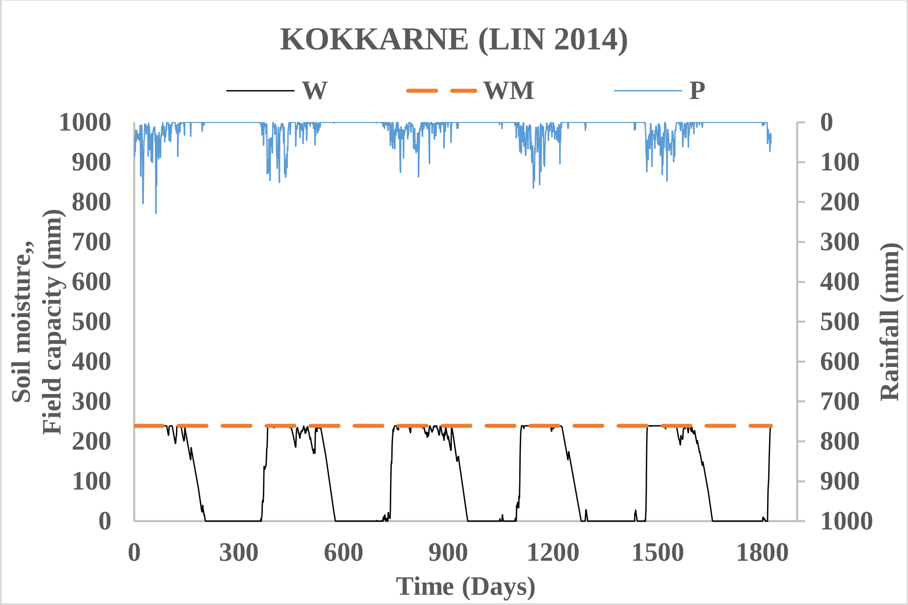
Where, N is the total number of days which is equal to 365.

It can be seen from the Table 5.16 and Figure 5.36 that the average soil moisture deficit has inverse relationship with the runoff coefficient, i.e., the catchments having higher soil moisture deficit values are characterized by lower runoff coefficients and vice-versa. In addition, when a catchment exhibiting average wetness conditions then in that condition the coefficient of average soil moisture deficit is likely to be directly proportional to the runoff coefficient. It can be seen from Figure 5.36 that the soil moisture deficit for watersheds under wet category and those under dry category exhibit inverse relation with runoff coefficient for both the models. Nevertheless, in average category catchments the curve of soil moisture deficit of Zhao (1992) model is less close as the curve from proposed DVIC model to the curve from runoff coefficient, which shows better soil moisture accounting by DVIC model over Zhao (1992) model. Therefore, it can be inferred from this study that the DVIC model generated soil moisture deficit values/coefficients can also be used for the categorisation of the watersheds as wet, average or dry catchments in addition to the use of the runoff coefficient as a criterion.

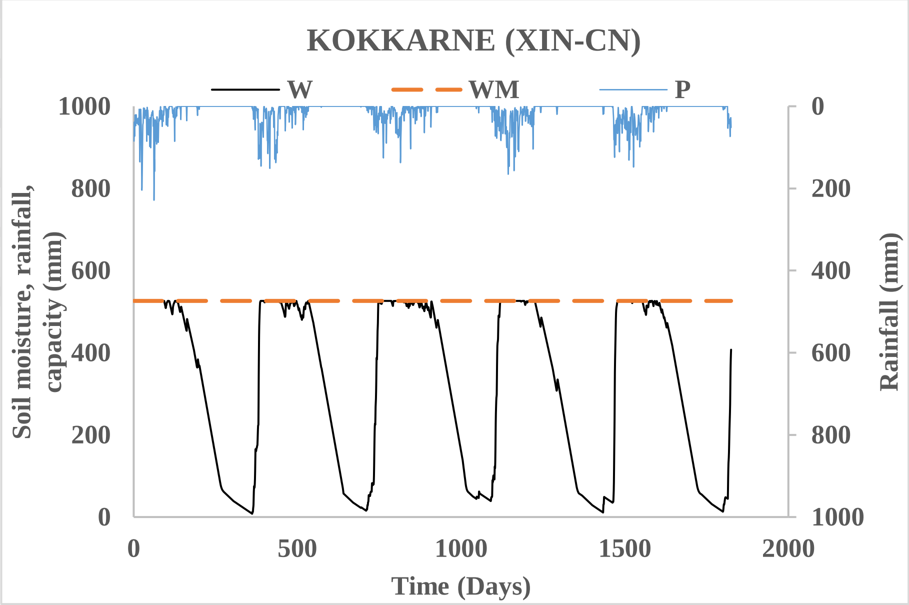


(a)

Figure 5.35 Soil moisture profile of Kokkarne catchment by different studied models

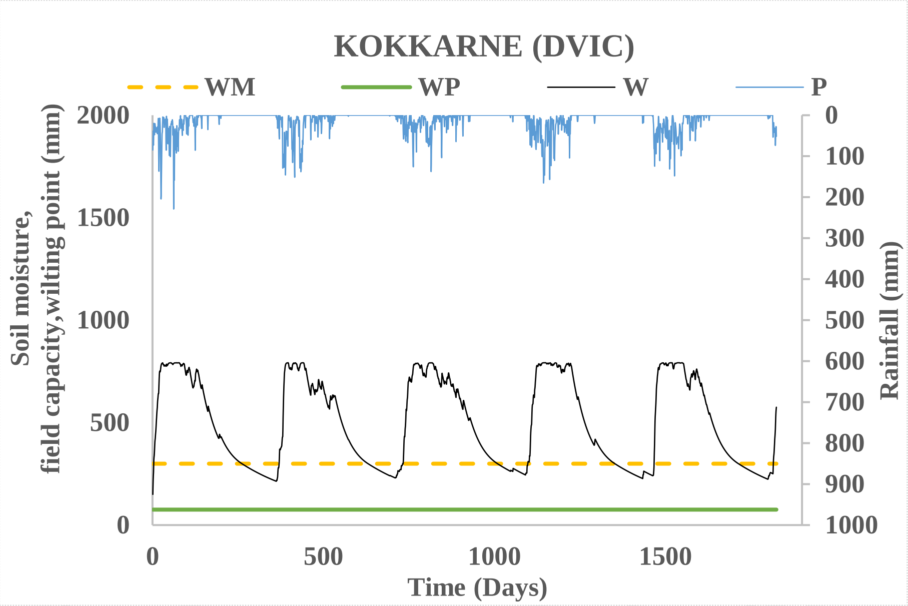


(b)



(c)

Figure 5.35 Continue…



(d)

Figure 5.35 Continue…

5.7 PERFORMANCE EVALUATION OF MODELS ON ANNUAL BASIS

Values of statistical efficiency indicators obtained for each of the water years have been tabulated for all models for all studied catchments. One such Table showing the results for Haladi catchment is presented as Table 5.17 and the remaining Tables are given in the APPENDIX (V). It can be seen from the Table 5.17 and other such Tables included in APPENDIX (V) that on the yearly basis, the Zhao (1992) and Nirupama (1996) model are performing in a similar way for all categories of the catchments affirming the interpretation of results presented in Section 5.5 of this thesis. Also it can be seen from Table 5.17 and other such Tables included in APPENDIX (V) that the model of Lin et al. (2014) performed slightly better as compared to Zhao (1992) and Nirupama (1996) models. The Hu et al. (2005) model performed very poorly as compare to all studied variants of the Xinanjiang model and both the proposed variants of the hybrid Xinanjiang model are showing better results for most of the years as compare to all existing variants of the Xinanjiang model which confirms that both the proposed hybrid models are performing better even for individual years.

Table 5.16. Comparison of Average soil moisture deficit of studied catchments between Zhao (1992) and proposed DVIC model

		Zhao (1992)						DVIC					
Name of Catchment	**Runoff coefficient**	Average soil moisture Deficit per water year					**Average soil moisture deficit**	Average soil moisture Deficit per water year					**Average soil moisture deficit**
		1	2	3	4	5		1	2	3	4	5	
Haladi	0.93	0.06	0.06	0.04	0.07	0.05	0.06	0.00	0.00	0.00	0.00	0.00	0.00
Jadkal	0.92	0.06	0.07	0.06	0.06	0.06	0.06	0.22	0.26	0.19	0.24	0.22	0.23
Dasanakatte	0.90	0.12	0.13	0.09	0.13	0.11	0.12	0.01	0.00	0.00	0.01	0.01	0.01
Halkal	0.89	0.17	0.19	0.13	0.20	0.17	0.17	0.03	0.02	0.01	0.01	0.02	0.02
Kokkarne	0.79	0.33	0.34	0.30	0.37	0.35	0.34	0.05	0.04	0.02	0.04	0.04	0.04
Hemavati	0.78	0.18	0.20	0.20	0.16	0.15	0.18	0.08	0.05	0.05	0.06	0.04	0.06
Khanpur	0.60	0.57	0.55	0.53	0.61	0.56	0.56	0.04	0.04	0.02	0.02	0.03	0.03
Dindori	0.51	0.33	0.38	0.32	0.29	0.32	0.33	0.23	0.23	0.20	0.16	0.15	0.19
Chidgaon	0.50	0.35	0.41	0.33	0.38	0.40	0.37	0.29	0.29	0.22	0.27	0.28	0.27
Gadarwara	0.49	0.37	0.40	0.36	0.36	0.38	0.37	0.34	0.33	0.30	0.30	0.33	0.32
Belkheri	0.45	0.52	0.52	0.45	0.36	0.40	0.45	0.43	0.40	0.35	0.32	0.35	0.37
Manot	0.45	0.62	0.75	0.62	0.72	0.69	0.68	0.31	0.36	0.29	0.34	0.31	0.32
Bamni Banjar	0.37	0.21	0.24	0.26	0.23	0.25	0.24	0.32	0.33	0.32	0.33	0.30	0.32
Patan	0.37	0.63	0.72	0.64	0.63	0.67	0.66	0.54	0.55	0.51	0.49	0.53	0.52
Anthroli	0.37	0.49	0.46	0.38	0.51	0.41	0.45	0.22	0.20	0.15	0.20	0.17	0.19
Kogaon	0.35	0.22	0.27	0.25	0.21	0.24	0.24	0.48	0.52	0.47	0.44	0.52	0.49
Barchi	0.35	0.55	0.58	0.51	0.51	0.49	0.53	0.44	0.42	0.39	0.41	0.41	0.41
Mohegaon	0.35	0.61	0.74	0.63	0.72	0.66	0.67	0.34	0.38	0.33	0.37	0.33	0.35
Amachi	0.29	0.56	0.74	0.60	0.66	0.63	0.64	0.55	0.56	0.55	0.55	0.54	0.55
Hridaynagar	0.24	0.21	0.29	0.26	0.28	0.26	0.26	0.41	0.47	0.41	0.48	0.40	0.43

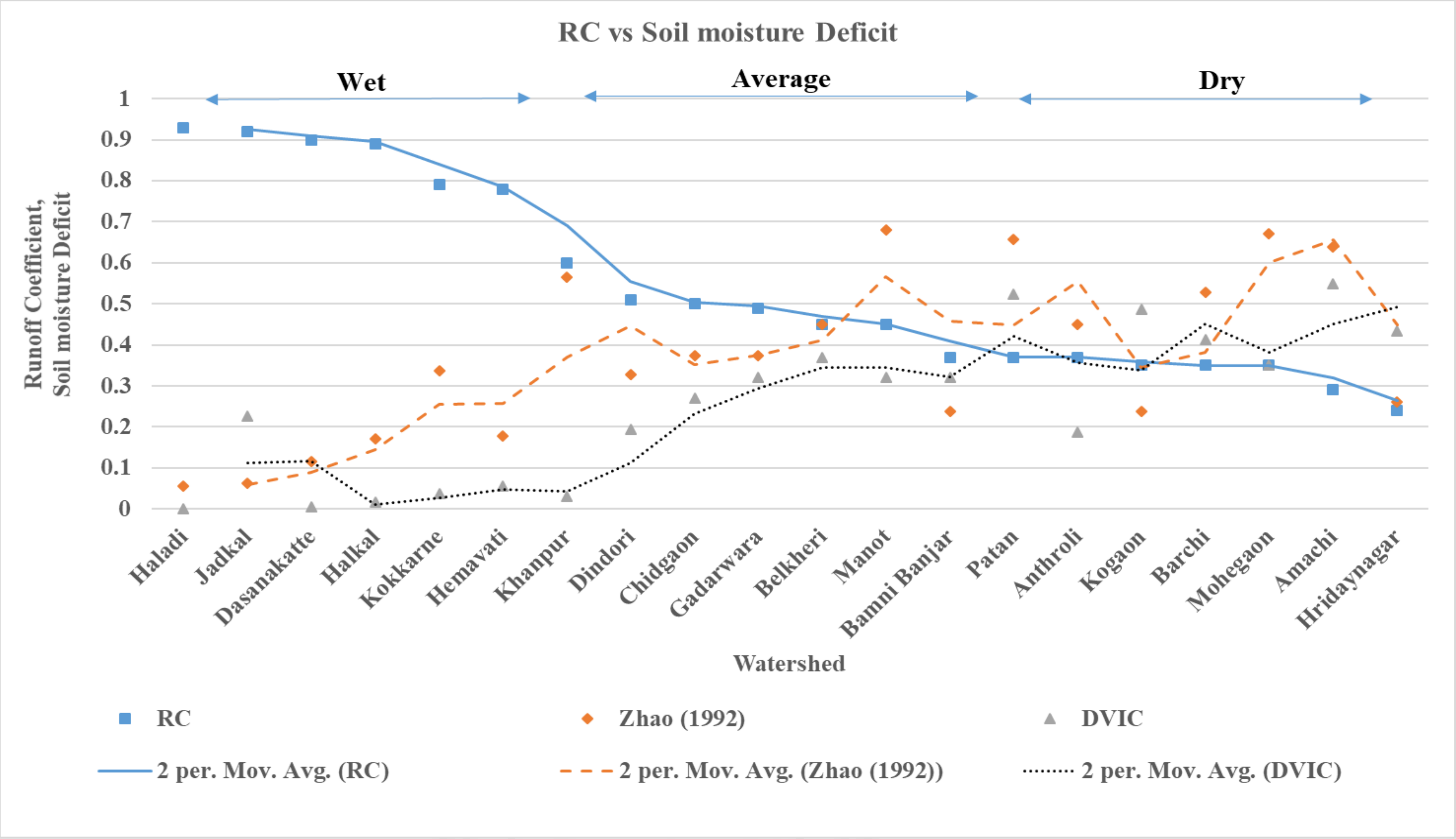


Figure 5.36 Soil moisture profile deficit vs Runoff coefficient between Zhao (1992) and DVIC model

Table 5.17. Comparative Model Evaluation on Yearly basis between Original Xinanjiang Model and its modified versions with proposed modified versions of Xinanjiang model in calibration and validation periods

Name of catchment - Haladi

Area (km^2) = 505

Climatic condition - Wet; Runoff Coefficient = 0.93

Comparative Model Evaluation on Yearly basis between Original Xinanjiang Model and its modified versions with proposed modified versions of Xinanjiang model

	During Calibration																									
Year	Observed Values		Existing versions of the Xinanjiang model																Proposed versions of the Xinanjiang model							
			ZHAO(1992)				NIRUPAMA(1996)				HU (2005)				LIN (2014)				XIN-CN				DVIC			
	P (mm)	Qo (mm)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)
1985-86	4397	4105	0.88	0.88	6.95	2.13	0.88	0.88	6.98	2.47	0.80	0.81	8.81	1.99	0.87	0.88	7.10	2.53	0.88	0.89	6.81	2.03	0.92	0.92	5.77	2.32
1986-87	4473	4177	0.82	0.83	5.58	0.79	0.82	0.83	5.63	2.63	0.87	0.87	4.79	-3.15	0.82	0.82	5.63	2.71	0.83	0.83	5.42	0.79	0.89	0.90	4.34	4.06
1987-88	3357	3137	0.74	0.78	3.16	-0.24	0.72	0.78	3.25	2.57	0.78	0.80	2.88	-3.68	0.73	0.78	3.21	2.49	0.74	0.79	3.10	-0.23	0.74	0.83	3.11	5.54
1988-89	4142	3921	0.90	0.90	3.17	0.55	0.90	0.90	3.17	1.99	0.85	0.86	3.89	-3.42	0.90	0.90	3.22	2.08	0.90	0.91	3.17	0.55	0.92	0.92	2.80	3.55
1989-90	4184	4117	0.71	0.73	3.18	-10.73	0.69	0.72	3.24	-8.07	0.80	0.82	2.59	-15.52	0.70	0.73	3.21	-8.71	0.73	0.75	3.04	-10.59	0.80	0.82	2.60	-8.11
Mean	**4111**	**3892**	**0.81**	**0.82**	**4.41**	**-1.50**	**0.80**	**0.82**	**4.45**	**0.32**	**0.82**	**0.83**	**4.59**	**-4.76**	**0.80**	**0.82**	**4.47**	**0.22**	**0.82**	**0.83**	**4.31**	**-1.49**	**0.85**	**0.88**	**3.72**	**1.47**

	During Validation																									
Year	Observed Values		Existing versions of the Xinanjiang model																Proposed versions of the Xinanjiang model							
			ZHAO(1992)				NIRUPAMA(1996)				HU (2005)				LIN (2014)				XIN-CN				DVIC			
	P (mm)	Qo (mm)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)
1990-91	5859	5574	0.80	0.87	7.18	-0.27	0.81	0.87	7.12	0.52	0.77	0.83	7.76	-0.25	0.81	0.86	7.06	0.61	0.82	0.87	6.88	0.00	0.77	0.84	7.80	-0.50
1991-92	4272	4058	0.77	0.85	4.77	3.26	0.77	0.85	4.79	4.40	0.86	0.91	3.72	-0.39	0.78	0.85	4.69	4.48	0.79	0.85	4.55	2.78	0.81	0.90	4.32	5.69
1992-93	5280	4985	0.61	0.72	6.72	0.71	0.60	0.72	6.76	2.26	0.70	0.76	5.89	-1.87	0.62	0.72	6.65	2.24	0.64	0.73	6.47	0.86	0.66	0.78	6.27	4.10
1993-94	4590	4854	0.53	0.66	4.92	-11.84	0.53	0.66	4.93	-9.96	0.60	0.69	4.53	-14.57	0.54	0.66	4.88	-10.13	0.57	0.68	4.69	-11.84	0.59	0.73	4.60	-8.29
Mean	**5000**	**4868**	**0.68**	**0.78**	**5.90**	**-2.04**	**0.68**	**0.78**	**5.90**	**-0.70**	**0.73**	**0.80**	**5.48**	**-4.27**	**0.69**	**0.77**	**5.82**	**-0.70**	**0.71**	**0.78**	**5.65**	**-2.05**	**0.71**	**0.81**	**5.75**	**0.25**

5.8 DISCUSSION OF THE RESULTS

To evaluate the performance of the proposed models i.e. hybrid XIN-CN and DVIC model as well as existing versions of the Xinanjiang model, four statistical indices criteria NSE, R^2, RMSE and RE (as %) have been used in this study. Out of these four statistical criteria, two statistical indices i.e. NSE and R^2 represents the model efficiency while the other two criteria i.e. RMSE and RE (as %) represent the model performance in terms of error between observed and corresponding simulated discharge.

Based on the NSE values obtained for the calibration period, the model efficiency by proposed hybrid Xinanjiang models could attain a maximum value of 0.93 while during validation it reaches upto 0.92 indicating very good performance of proposed hybrid models in terms of NSE criteria. For the existing versions of the Xinanjiang model, maximum value of NSE could reach up to 0.90 during calibration and validation periods which is slightly lower that that achieved with proposed hybrid models indicating superiority of proposed models. The results show that the Nirupama (1996) model, which is the modified form of the Xinanjiang model (Zhao 1992), performs more or less similarly as that of the Zhao (1992) model even though it uses one more parameter in runoff production as compare to Zhao (1992) model which indicate that addition of one more parameter ‘m’ which is responsible for changing the shape of the tension water distribution capacity curve in the Xinanjiang model is inefficient in improving performance of the model. For the model given by Lin et al. (2014) in which the areal average soil moisture capacity (WM) has been linked with the maximum potential retention of the soil (S_I) of the SCS-CN method through multiplication factor α, the value of parameter α varies in range 1 to 2 indicating that the value of parameter WM can attain a maximum value of two times of the S_I which is decided based on curve number value. However, analysis of results obtained for Zhao (1992) model indicate that the value of parameter WM reaches a quiet higher value but in case of Lin et al. (2014) model the value of WM is bounded to a relatively narrow range depending on the value of S_I (obtained through CNGRIDS) as well as the maximum limit given to the parameter α. Relatively poor performance of the Lin et al. (2014) model in comparison to those obtained with the original Xinanjiang model (Zhao 1992) could be attributed to limiting value of WM based on S_I indicating need for further refinement in the concept proposed by Lin et al. (2014). In another modified version of the Xinanjiang model given by Hu et al. (2005) the major modification have been introduced in the runoff generation processes by incorporating both infiltration excess and saturation excess mechanisms of runoff generation simultaneously. Hu et al. (2005) applied this model on data sets of three catchments in wet and average climatic conditions of China and showed that this model perform better compared to original Xinanjiang model. In this study, the Hu et al. (2005) model have been applied at daily time interval and its performance have been compared with original Xinanjiang model as well other studied models. The results show that in terms of NSE value the model of Hu et al. (2005) could not perform better than the Xinanjiang model as well as the other studied models. In case of proposed hybrid models, i.e. hybrid XIN-CN and DVIC model, the results shows that in terms of the NSE values for most of the catchments of different categories as well as on the basis of mean NSE value for different categories of catchments, the proposed models outperformed the original Xinanjiang model as well as all other exiting versions of the Xinanjiang model used in this analysis. Based on the NSE value, the overall performance of studied models in all categories of catchments can be ranked as:

XIN-CN > DVIC > ZHAO (1992) > NIRUPAMA (1996) > LIN ET AL. (2014) > HU ET AL. (2005)

Comparative performance of all the studied models was further evaluated using R^2 for all the studied catchments of different categories. The similar pattern of performance as obtained for NSE have been found on the basis of R^2 also. Based on the R^2 evaluation criteria the overall performance of studied models in all categories of catchments can be ranked as:

XIN-CN > DVIC > ZHAO (1992) > NIRUPAMA (1996) > LIN ET AL. (2014) > HU ET AL. (2005)

Using the error criterion as RMSE, all the studied variants of the Xinanjiang models and proposed hybrid models were evaluated for their performance ranking. The obtained RMSE values are higher for wet catchments and reduces as we move from wet to dry catchments probably due to production of more runoff in wet catchments compared to dry catchments. Which indicates an inverse response as compare to NSE and R^2 values i.e. for the wet catchments, the values of NSE and R^2 (representing the model efficiencies) are high and reduces towards the dry catchments but the value of RMSE (representing error in estimated runoff with respect to the observed runoff) is also high in wet catchments and reducing towards the dry catchments. The results show that the variability in the RMSE is very high for Hu et al. (2005) model as compare to the all other studied models, and all other existing variants of the Xinanjiang model are more stable. Based on the RMSE value, the overall performance of studied models for all categories of catchments can be ranked as:

XIN-CN > DVIC > ZHAO (1992) > NIRUPAMA (1996) > LIN ET AL. (2014) > HU ET AL. (2005)

Comparative performance evaluation of the models was further evaluated using RE (as %). Analysis of results reveals that the discrepancy in the RE (as %) is more in dry catchments and it is slightly less in average catchments while in the wet catchments the variability is vary less as compare to dry and average categories catchments. The consistency in the RE (as %) can be seen in the Zhao (1992) model throughout all the categories of the catchments for calibration as well as in validation time periods although it slightly differs in the dry catchments during validation process. While the other existing variants of the Xinanjiang model suffers in all categories of catchments, especially for the Hu et al. (2005) model RE (as %), varies very much in both calibration and validation process for all categories of the catchments. Although, both the proposed modified models are not that much consistent comparatively but results indicate that for both the proposed model, the RE (as %) is mostly lower as compared to the existing variants of the Xinanjiang model especially in the average and dry category catchments. The performance of the studied models, in terms of RE (RE (as %) values from lower to higher) values, ranked as:

DVIC > XIN-CN > ZHAO (1992) > NIRUPAMA (1996) > LIN ET AL. (2014) > HU ET AL. (2005)

Visual Evaluation and physical interpretation of runoff generation process

To assess the closeness of reproduction of peaks and overall pattern of the computed discharge with the observed stream flow, the computed daily stream flows for calibration and validation periods have been plotted against the corresponding observed discharge data for all years and for all studied catchments. Results show that the closeness between model computed discharge by DVIC and XIN-CN models with corresponding observed discharge is better compared to other models. The peaks are better simulated by proposed models. Better results in terms of close visual match between observed and model computed discharge from DVIC and XIN-CN models indicate that the adoption and amalgamation of Hortonian runoff generation mechanism is very much need along with saturation excess mechanism to improve performance of the model for all catchments (i.e. in all climatic zones) in the present study.

Performance evaluation of the models based on soil moisture accounting procedure

In the Xinanjiang model (Zhao 1992), the accounting of soil moisture is performed by three-layer arrangement, by dividing the field capacity (WM) of the soil moisture into three different layers i.e. upper layer capacity (UM), lower layer capacity (LM) and deeper layer capacity (DM).

According to this arrangement, the evapotranspiration will start from upper layer and when soil moisture completely emptied from upper layer then evapotranspiration starts from the lower layers. When soil moisture reaches up to a certain ratio of soil moisture of lower and deeper layer then in that condition evapotranspiration starts from deeper layer and it is continuing until the soil moisture of deeper layer becomes zero.

Since the evapotranspiration process in the Xinanjiang model is obtained through three soil layer arrangement which shows a step by step estimation of soil moisture accounting. On the exhaustion of deeper layer, the soil moisture gets emptied. On practical as well as theoretical considerations attainment of the soil moisture level to zero value or almost emptied can not be justified as observations reveals that deeper soil layers for most of the times retains some amount of moisture which cannot be evaporated and this moisture cannot be used by the plants. This condition is akin to reaching of soil moisture to the wilting point. The wilting point is defined as the minimal point of soil moisture that the plant can be no longer survive in this condition of soil moisture level in the soil. To overcome this limitation of Xinanjiang model, in the proposed Dynamic Variable Infiltration capacity (DVIC) model, the soil moisture accounting is done by single layer soil moisture using the condition of wilting point of soil so that the evaporation occurs in a proportion of field capacity after deducting the wilting point of the soil from the field capacity. In addition, when a catchment having average wetness then in that condition the computed value of coefficient of average soil moisture deficit matches the condition of average category catchments i.e. a parallel relationship between runoff coefficient and soil moisture deficit. Overall, it could be said that the soil moisture scenario considered in the proposed DVIC model is more realistic than the Zhao (1992) model. So it can be inferred from this study that the proposed DVIC model generated soil moisture deficit values/coefficients can also be used for the categorisation of the catchments as wet, average or dry catchments in addition to the use of the runoff coefficient as a criterion.

5.9 CONCLUDING REMARK

This chapter presents the application, testing and inter-comparison of results obtained from different existing variants of the Xinanjiang model as Zhao (1992), Nirupama (1996), Hu et al. (2005), Lin et al. (2014) and two proposed hybrid XIN-CN and DVIC models using the data from catchments of different climatic categories, such as wet, average and dry, in India. For performance evaluation and comparative study of the studied models, four statistical criteria as NSE, R^2, RMSE and RE (as %) have been used along with the graphical comparision of observed and model computed hydrographs. The SCE-UA global automatic calibration algorithm has been adopted and used for optimization of the parameters of all studied variants of the Xinanjiang model. The calibrated parameters have used to validate all the studied models using independent data sets not used during calibration process. Overall comparison of results obtained indicate poorest performance of Hu et al. (2005) model in comparision to all other studied models in all categories of the catchments. While both the proposed hybrid conceptual models performed slightly better than all existing models in all categories of the catchments. Especially the main purpose of the proposed hybrid models was to improve model performance in the dry catchments. From the results and discussion, it is found that both the proposed models are performing good to average in the dry catchments which is quite better than the existing versions of the Xinanjiang model. Consequently, it is concluded that both the proposed hybrid models provide comparatively more realistic representation of runoff generation mechanisms existing in most of the catchment studied compared to existing variants of the Xinanjiang model. Hence, these features of both the proposed models hold a great assurance for their applicability in the catchments of diverse climatic condition in India and probably in other parts of the world as well.

6

SUMMARY AND CONCLUSIONS

6.1 SUMMARY

It is well known that the conceptual rainfall-runoff models are used for design flood estimation required for designing structures across and along rivers, water resources planning and management studies and for operational purposes, like flood forecasting, assessment of the available water in a river basin. The capability of a model to simulate the rainfall-runoff process of a catchment system depends on factors such as, proper representation of catchment processes, especially, the runoff generation processes, including infiltration and evapotranspiration over the catchment system. Various conceptual and physically based modelling approaches are available for the purpose of simulation of rainfall-runoff process of various catchments. In most of these models, the runoff generation mechanism is represented either by the infiltration excess runoff generation mechanism or by the saturation excess runoff generation mechanism. In the infiltration excess runoff generation mechanism, the runoff is generated only when rate of incident rainfall exceeds the infiltration rate over the catchment. On the other hand, the saturation excess runoff mechanism considers that the runoff from any point of the catchment is generated for the incident rainfall at that point only when the soil tension water capacity requirement at that point is fully satisfied by the incident rainfall.

It is widely believed that the catchments of humid climate zones may follow the saturation excess runoff generation mechanism, the catchments of dry and average climate zones may still follow the infiltration excess runoff generation mechanism. As a storm event may not always be evenly distributed over the catchment, even in the presence of homogeneous soil characteristics over the entire catchment, it is possible some part of the catchment may follow the saturation excess mechanism, some may follow the infiltration excess mechanism and the remaining may follow both the mechanisms of runoff generation. In essence, the runoff from a catchment when subjected to a storm event may follow both the runoff generation mechanisms. Therefore, an attempt has been made in the present study to develop two new models by proposing modifications in runoff generation mechanism of the Xinanjiang model. In the first proposed model, the spatial soil moisture capacity (WM) is considered as the function of the parameter S (maximum retention potential of soil in SCS-CN method). Under this model, the surface runoff is generated by SCS-CN method then remaining rainfall is infiltrates and add to the soil moisture and other components of total runoff are generated in the same way as in the original Xinanjiang model. The proposed SCS-CN inspired Xinanjiang model has been named as XIN-CN model. The second proposed model has been named as Dynamic Variable Infiltration Capacity (DVIC) model which is the modified form of the Hu et al. (2005) model which considers only the distribution of infiltration capacity curve for surface runoff generation, which uses only two steps for surface runoff generation and ground water runoff is generated when soil moisture exceeds the field capacity of the soil moisture.

Comparative performance of both the proposed hybrid XIN-CN and DVIC models and four existing variants of the Xinanjiang model viz. Zhao (1992), Nirupama (1996), Hu et al. (2005) and Lin et al. (2014) have been evaluated using observed data from 20 catchments exhibiting different runoff generation characteristics. The catchments selected for this study have been grouped into three categories as wet, average and dry based on average value of runoff coefficient thus representing humid, average and dry climatic conditions respectively. Available observed hydrological data have been split into two groups, data in one group has been used to calibrate parameters of the model, and data in other group have been used to validate the performance of the calibrated models.

6.2 MAJOR FINDINGS OF THE STUDY

On the basis of the study carried out in the research work of this thesis, the following conclusions can be drawn:

1. Performance evaluation of the Xinanjiang model and its variants (viz. Nirupama, 1996; Hu et al., 2005; and Lin et al., 2014) which adopts saturation excess runoff generation mechanism have been evaluated on twenty watersheds located in humid, average and dry climatic zones of India. Relatively poor performance of these models on catchments located in average and dry climatic zones which are mostly dominated by infiltration excess runoff generation mechanism compared to those in humid zones which are primarily dominated by saturation excess runoff generation mechanism clearly indicate inadequacy in runoff generation process adopted in these models.

2. The NSE values for both the proposed models (XIN-CN and DVIC) during calibration varies from 0.85 to 0.93 for all high yielding watersheds, indicating a very good model response (Motovilov et al. 1999; EI-Sadek et al. 2001: Jain et al. 2012). For wet watersheds, mean NSE value during calibration period varies from 0.83 to 0.89, in that the DVIC model obtained maximum NSE value, while in validation period, it varies from 0.81 to 0.85, in that the maximum NSE as 0.85 found in XIN-CN model and for DVIC model, it was 0.83. For watersheds having average climatic conditions, the mean NSE value during calibration varies from 0.59 to 0.76, in that the maximum NSE found in XIN-CN model while in validation period it varies from 0.52 to 0.65 in that the maximum NSE found in DVIC model. The watersheds having dry climatic conditions mean NSE value during calibration varies from 0.51 to 0.66, in that the maximum NSE found in DVIC model while in validation period it varies from 0.37 to 0.57 in that the maximum NSE found in XIN-CN model. These values have been found better in comparison to existing variants of Xinanjiang models, in both calibration and validation period.
3. In the validation process the existing variants of the Xinanjiang model having mean NSE and R^2 values upto 0.40 and 0.59 (dry catchments) respectively while the proposed modified Xinanjiang model, XIN-CN having mean NSE as 0.57 and R^2 as 0.65 and DVIC model having mean NSE as 0.44 and R^2 as 0.53 in the dry catchments. It is inferred from this criterion that proposed hybrid XIN-CN model is satisfactory even in the validation process and the proposed DVIC model is close the criteria but having mean NSE value greater than the existing variants of the Xinanjiang model. The overall performance ranking based on statistical evaluation indicators of the proposed models (DVIC and XIN-CN) and existing versions of Xinanjiang model is indicated below:

XIN-CN > DVIC > ZHAO (1992) > NIRUPAMA (1996) > LIN (2014) > HU (2005)

4. Better results in terms of close visual match between observed and model computed discharge from DVIC and XIN-CN models indicate that the adoption and amalgamation of Hortonian runoff generation mechanism is very much needed along with saturation excess mechanism to improve performance of the model for all catchments (i.e. in all climatic zones) in the present study.
5. From the study of the behaviour of tension water storage capacity curve in runoff generation process it is confirmed that the values of the parameter ‘B’ and shape of the capacity curve can be helpful in the assessment of physical characteristics of the catchments.

6. Study of temporal distribution of soil moisture (W), initial infiltration rate (f_0) and final constant infiltration rate (f_c) obtained from DVIC model and rainfall reveals that with prolonged and continuous rainfall spell, the soil moisture increases and eventually the soil moisture store gets filled upto field capacity resulting in corresponding lowering of f_0 to f_c when W reaches field capacity. Therefore, when W reaches field capacity, saturation condition prevails in the watershed and infiltration can only take place at rate of fc. This could be visualized as situation akin to generation of surface runoff in a similar way as in case of saturation excess as in Xinanjiang model. Therefore, the proposed DVIC model is capable of taking care of both Hortonian and Saturation Excess runoff generation mechanisms. Better performance of DVIC and XIN-CN models on watersheds in all three climatic conditions i.e. humid, average and dry as compared to Xinanjiang models and its variants also affirm the above argument.
7. The generated average soil moisture deficit from DVIC model, which is a non-dimensional value similar to runoff coefficient estimated on yearly basis, can also be used for the categorisation of the catchments as wet, average or dry catchments in addition to the use of the runoff coefficient as a criterion.
8. Both of the proposed models have simple structure and can simulate both infiltration excess and saturation excess runoff generation mechanisms based on catchment wetness status and can be used as a flexible tool for rainfall runoff modelling in all categories of catchments.
9. From the results and discussion, it is found that both the proposed models are performing good to average in the dry catchments which is quite better than the existing versions of the Xinanjiang model. Consequently, it is concluded that both the proposed hybrid models provide comparatively more realistic representation of runoff generation mechanisms existing in most of the catchment studied compared to existing variants of the Xinanjiang model. Hence, these features of both the proposed models hold a great assurance for their applicability in the catchments of diverse climatic condition in India and probably in other parts of the world as well.

6.3 SCOPE FOR FURTHER WORK

1. In the present study, the proposed and existing versions of the Xinanjiang model have been used as the lumped model due to the limitations of data availability. The present work could be extended further by including channel routing components, as a semi-distributed hydrological model for Indian catchments.

2. The study could be extended further by incorporate uncertainties due to input variables as well as climate change effect on the studied models in Indian climatic scenario.

No scientific study is ever complete, so is true for this case as well. Therefore, the future studies should be undertaken to overcome the limitations of the present study.

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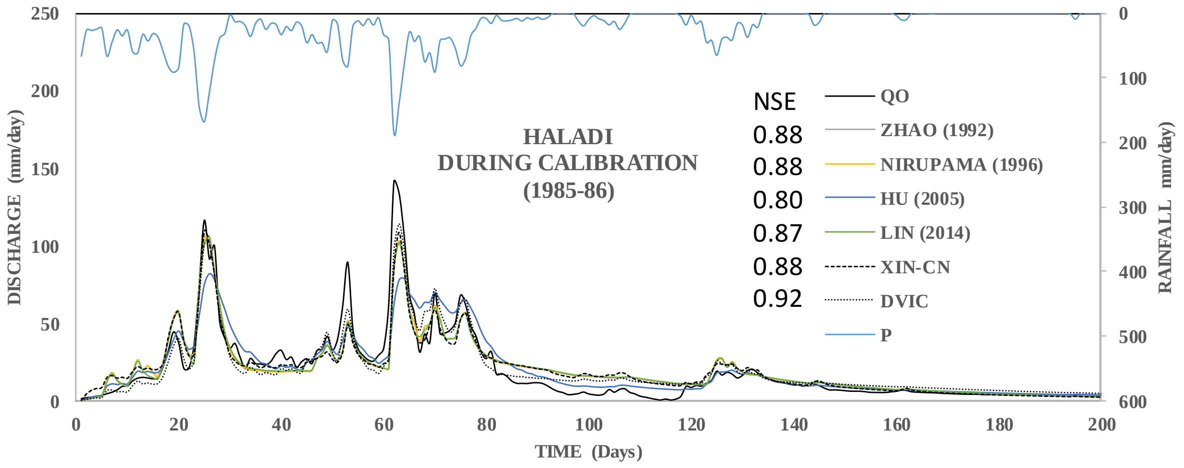
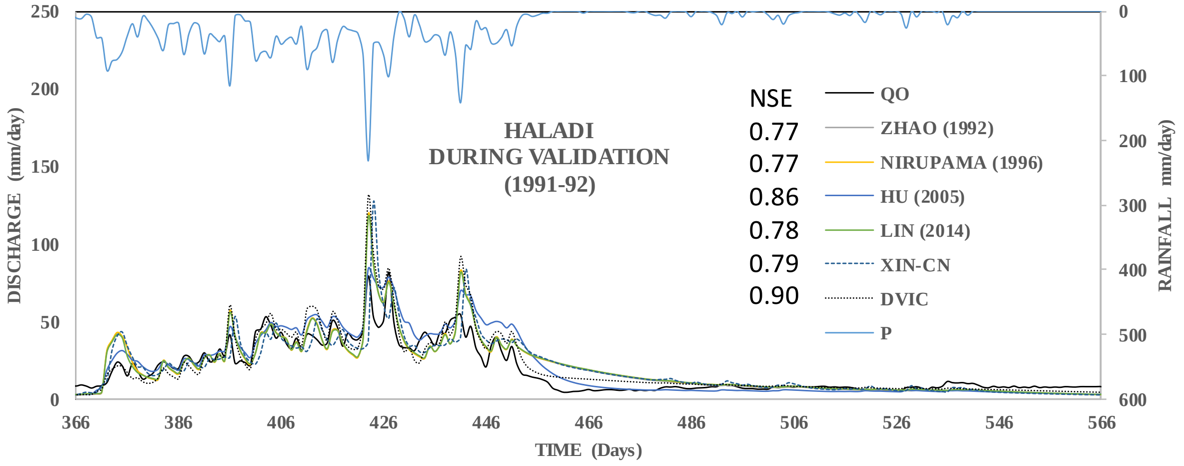
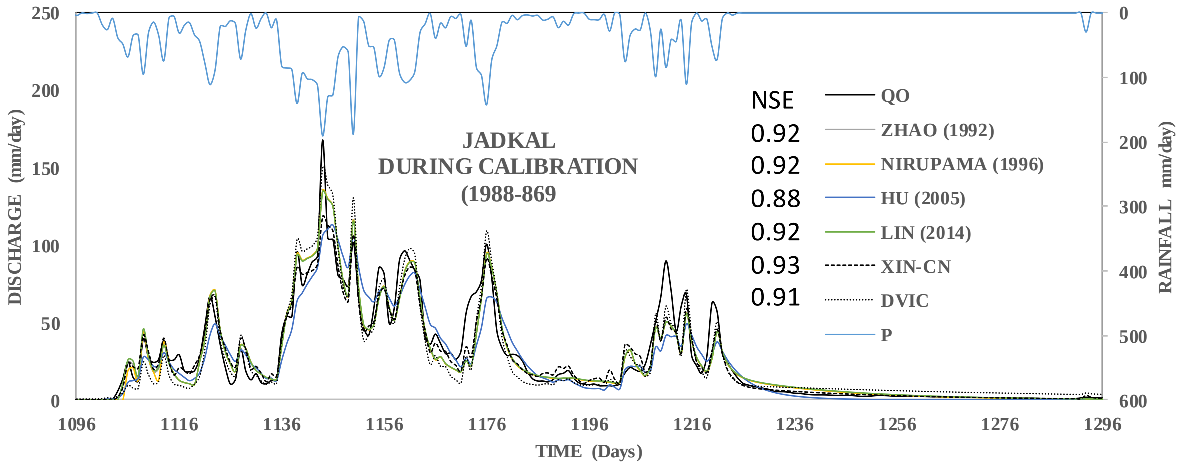
APPENDICES

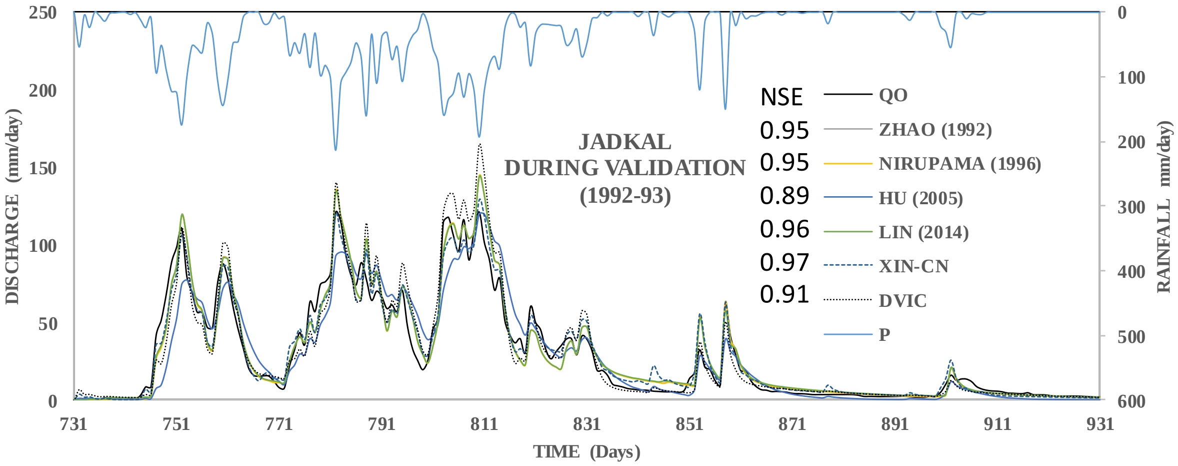
APPENDIX-I

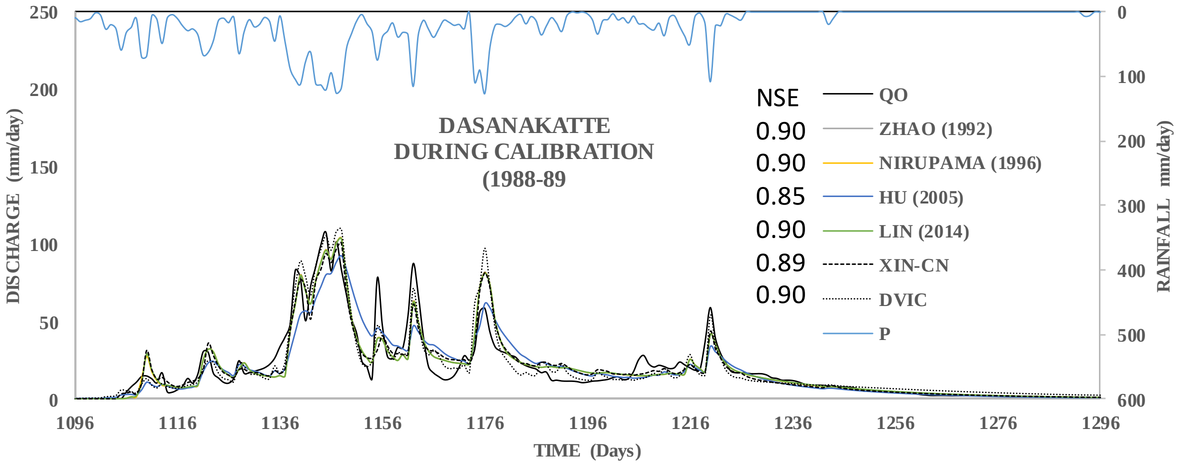
COMPARATIVE PLOTS OF OBSERVED RAINFALL-RUNOFF WITH SIMULATED RUNOFF FOR SELECTED YEARS

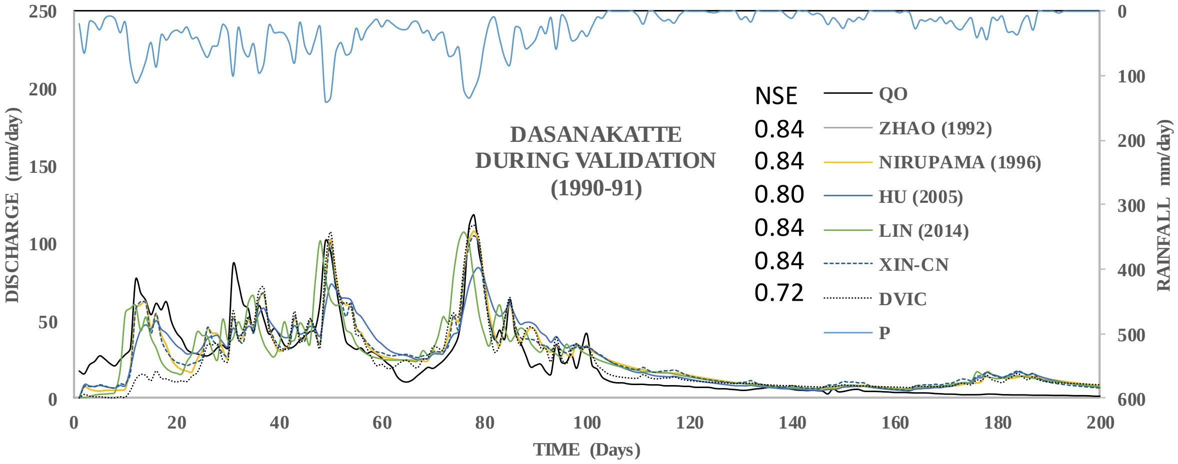


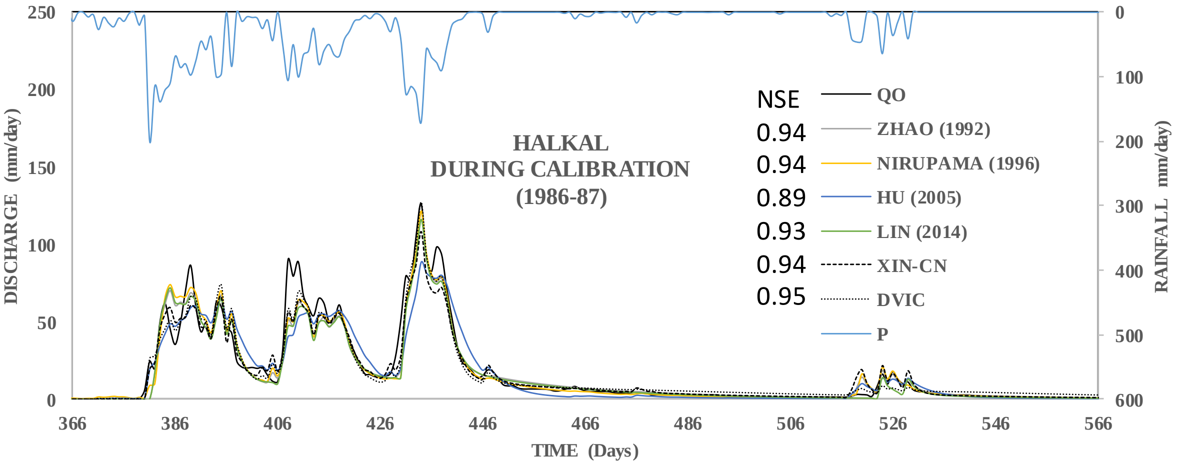


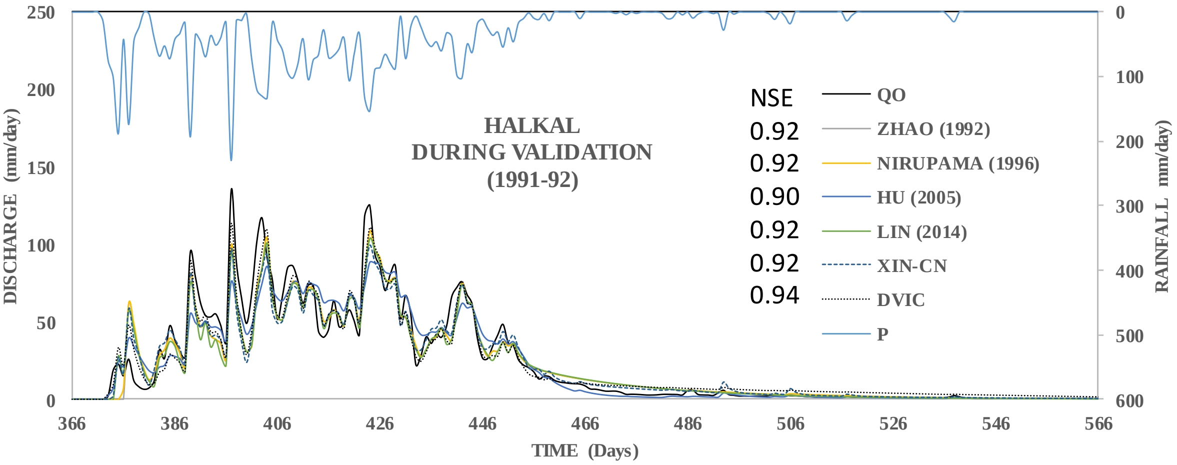


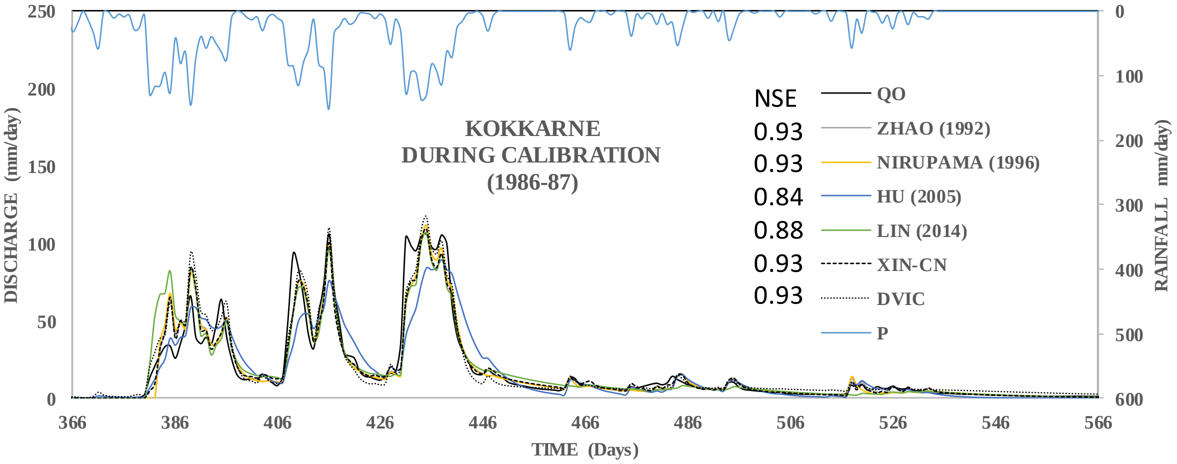

JADKAL
DURING VALIDATION
(1992-93)
NSE
0.95
0.95
0.89
0.96
0.97
0.91
QO
ZHAO (1992)
NIRUPAMA (1996)
HU (2005)
LIN (2014)
XIN-CN
DVIC
P
DISCHARGE (mm/day)
RAINFALL mm/day)
TIME (Days)
250
200
150
100
50
0
0
100
200
300
400
500
600
731
751
771
791
811
831
851
871
891
911
931

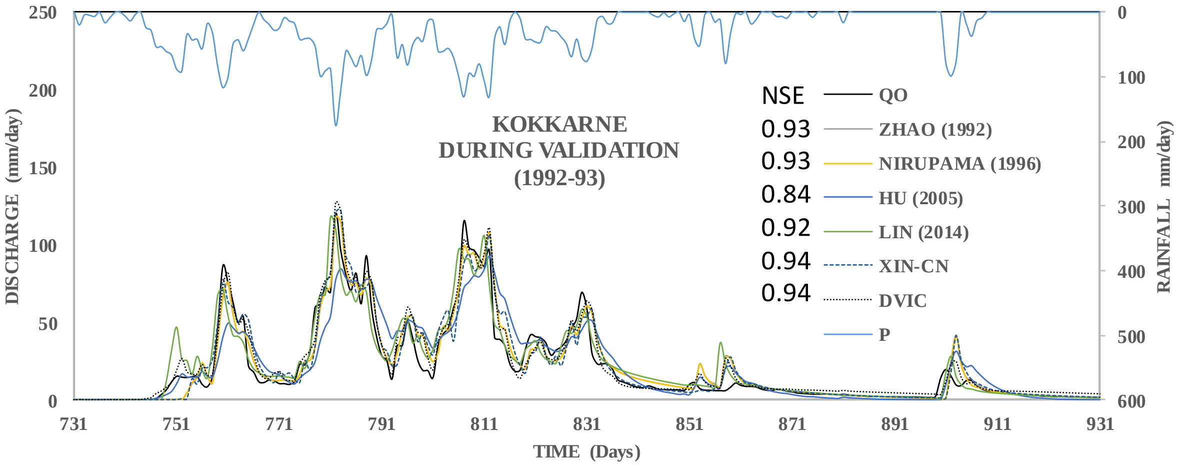

DASANAKATTE
DURING CALIBRATION
(1988-89
NSE
0.90
0.90
0.85
0.90
0.89
0.90
QO
ZHAO (1992)
NIRUPAMA (1996)
HU (2005)
LIN (2014)
XIN-CN
DVIC
P
DISCHARGE (mm/day)
RAINFALL mm/day)
TIME (Days)
250
200
150
100
50
0
0
100
200
300
400
500
600
1096
1116
1136
1156
1176
1196
1216
1236
1256
1276
1296

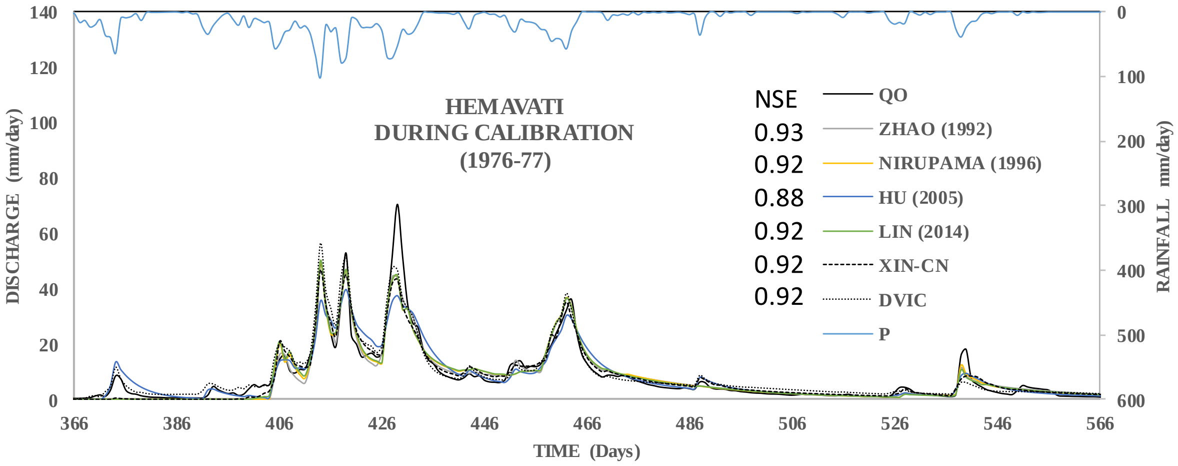

DASANAKATTE
DURING VALIDATION
(1990-91)
NSE
0.84
0.84
0.80
0.84
0.84
0.72
QO
ZHAO (1992)
NIRUPAMA (1996)
HU (2005)
LIN (2014)
XIN-CN
DVIC
P
DISCHARGE (mm/day)
RAINFALL mm/day)
TIME (Days)
250
200
150
100
50
0
0
100
200
300
400
500
600
0
20
40
60
80
100
120
140
160
180
200

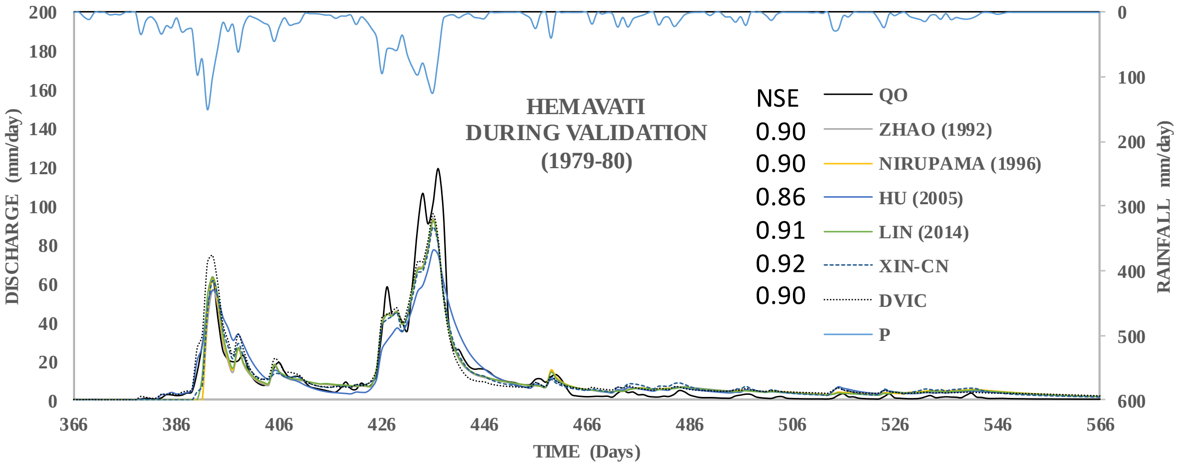

HALKAL
DURING CALIBRATION
(1986-87)
NSE
QO
0.94 ZHAO (1992)
0.94 NIRUPAMA (1996)
0.89 HU (2005)
0.93 LIN (2014)
0.94 XIN-CN
0.95 DVIC
P
DISCHARGE (mm/day)
RAINFALL mm/day)
TIME (Days)
250
200
150
100
50
0
0
100
200
300
400
500
600
366
386
406
426
446
466
486
506
526
546
566

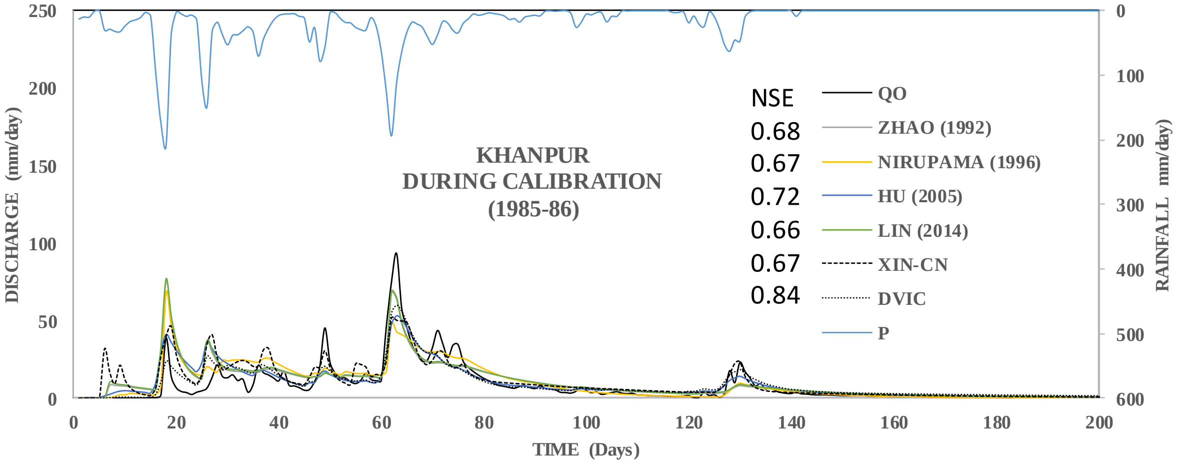

HALKAL
DURING VALIDATION
(1991-92)
NSE
QO
0.92 ZHAO (1992)
0.92 NIRUPAMA (1996)
0.90 HU (2005)
0.92 LIN (2014)
0.92 XIN-CN
0.94 DVIC
P
DISCHARGE (mm/day)
RAINFALL mm/day)
TIME (Days)
250
200
150
100
50
0
0
100
200
300
400
500
600
366
386
406
426
446
466
486
506
526
546
566

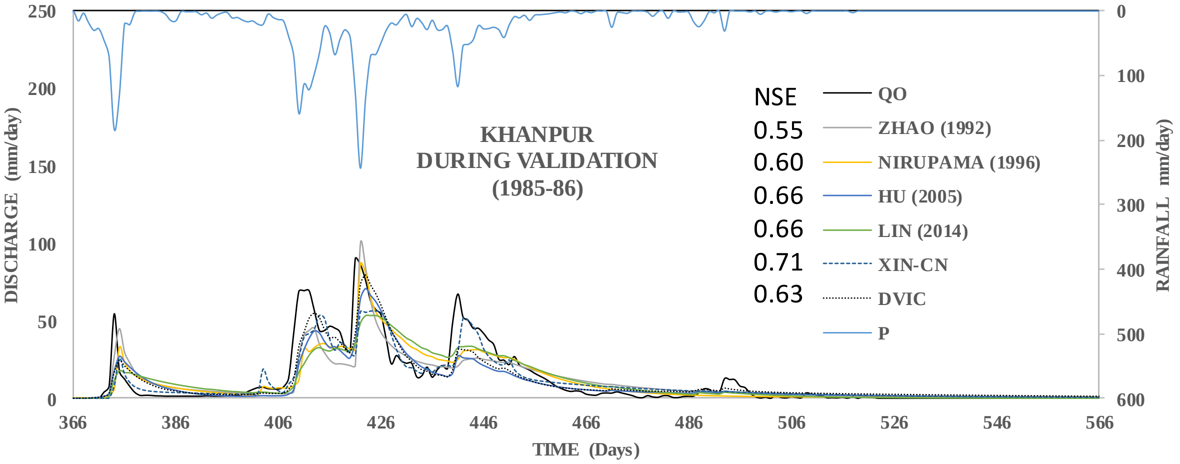

KOKKARNE
DURING CALIBRATION
(1986-87)
NSE
QO
0.93 ZHAO (1992)
0.93 NIRUPAMA (1996)
0.84 HU (2005)
0.88 LIN (2014)
0.93 XIN-CN
0.93 DVIC
P
DISCHARGE (mm/day)
RAINFALL mm/day)
TIME (Days)
250
200
150
100
50
0
0
100
200
300
400
500
600
366
386
406
426
446
466
486
506
526
546
566

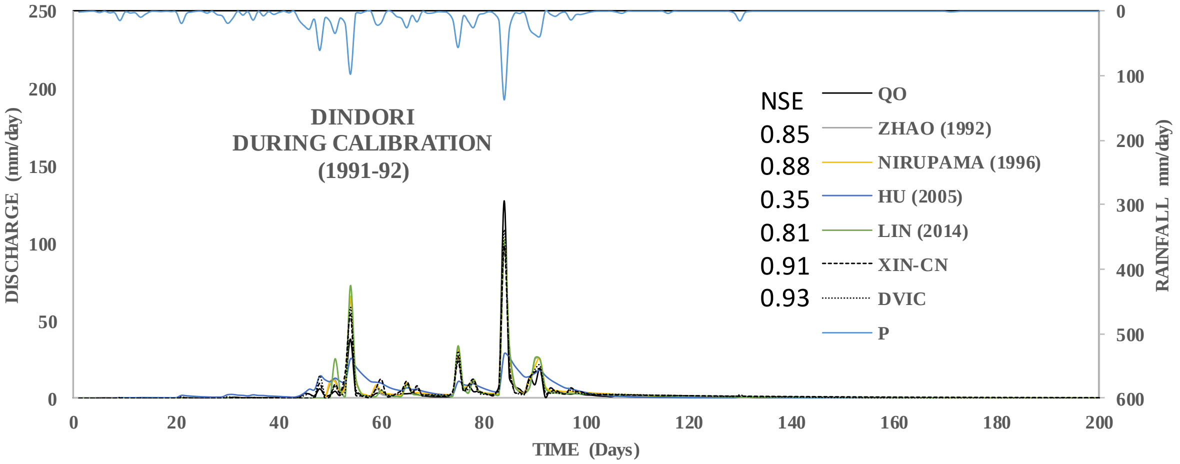

KOKKARNE
DURING VALIDATION
(1992-93)
NSE
0.93
0.93
0.84
0.92
0.94
0.94
QO
ZHAO (1992)
NIRUPAMA (1996)
HU (2005)
LIN (2014)
XIN-CN
DVIC
P
DISCHARGE (mm/day)
RAINFALL mm/day)
TIME (Days)
250
200
150
100
50
0
0
100
200
300
400
500
600
731
751
771
791
811
831
851
871
891
911
931

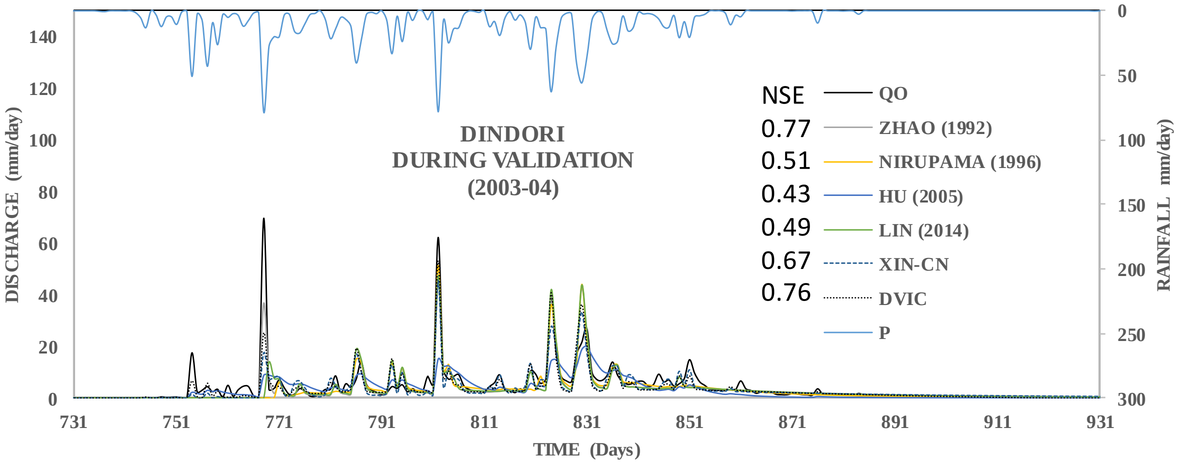

HEMAVATI
DURING CALIBRATION
(1976-77)
NSE
0.93
0.92
0.88
0.92
0.92
0.92
QO
ZHAO (1992)
NIRUPAMA (1996)
HU (2005)
LIN (2014)
XIN-CN
DVIC
P
DISCHARGE (mm/day)
RAINFALL mm/day)
TIME (Days)
140
120
100
80
60
40
20
0
0
100
200
300
400
500
600
366
386
406
426
446
466
486
506
526
546
566

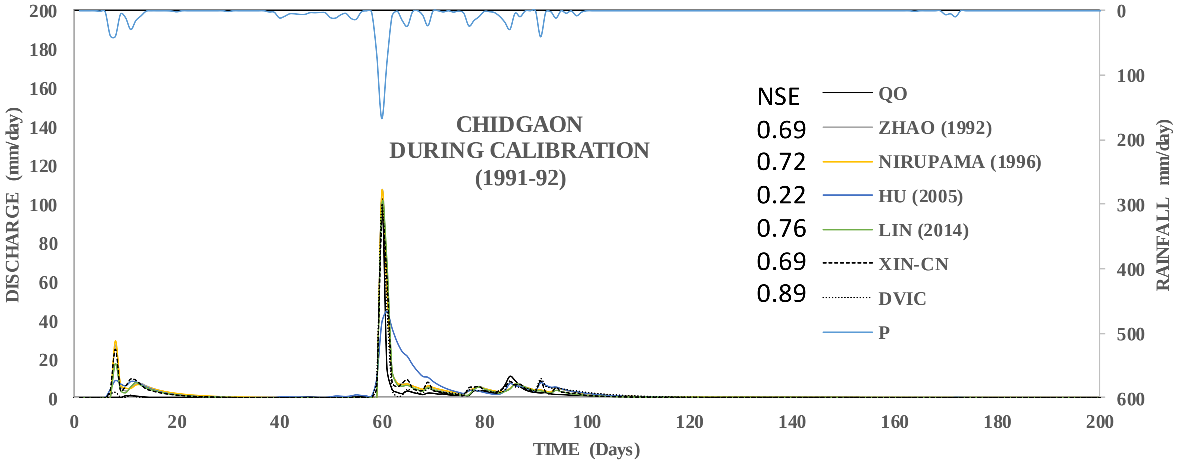

HEMAVATI
DURING VALIDATION
(1979-80)
NSE
0.90
0.90
0.86
0.91
0.92
0.90
QO
ZHAO (1992)
NIRUPAMA (1996)
HU (2005)
LIN (2014)
XIN-CN
DVIC
P
DISCHARGE (mm/day)
RAINFALL mm/day)
TIME (Days)
200
180
160
140
120
100
80
60
40
20
0
0
100
200
300
400
500
600
366
386
406
426
446
466
486
506
526
546
566

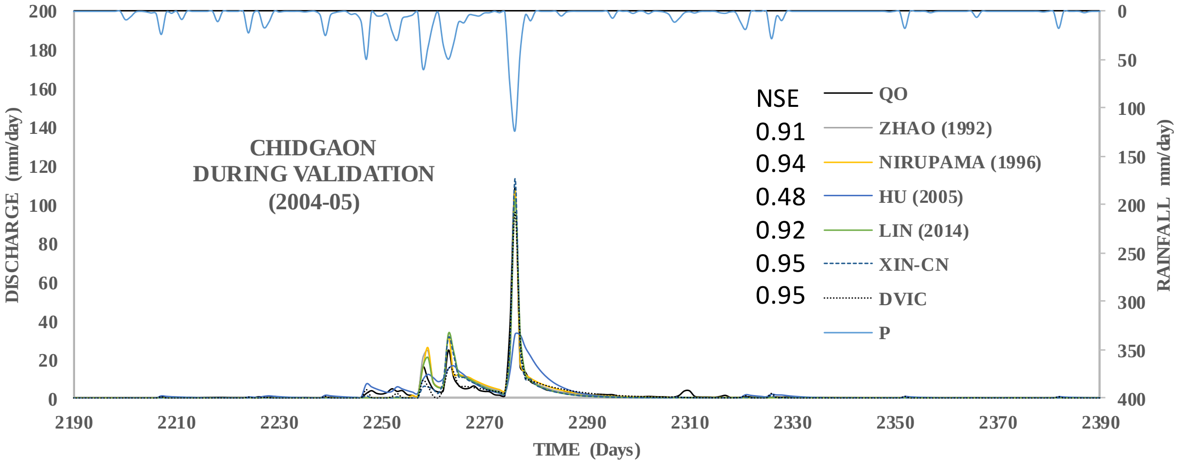

KHANPUR
DURING CALIBRATION
(1985-86)
NSE
0.68
0.67
0.72
0.66
0.67
0.84
QO
ZHAO (1992)
NIRUPAMA (1996)
HU (2005)
LIN (2014)
XIN-CN
DVIC
P
DISCHARGE (mm/day)
250
200
150
100
50
0
RAINFALL mm/day)
0
100
200
300
400
500
600
0
20
40
60
80
100
120
140
160
180
200
TIME (Days)

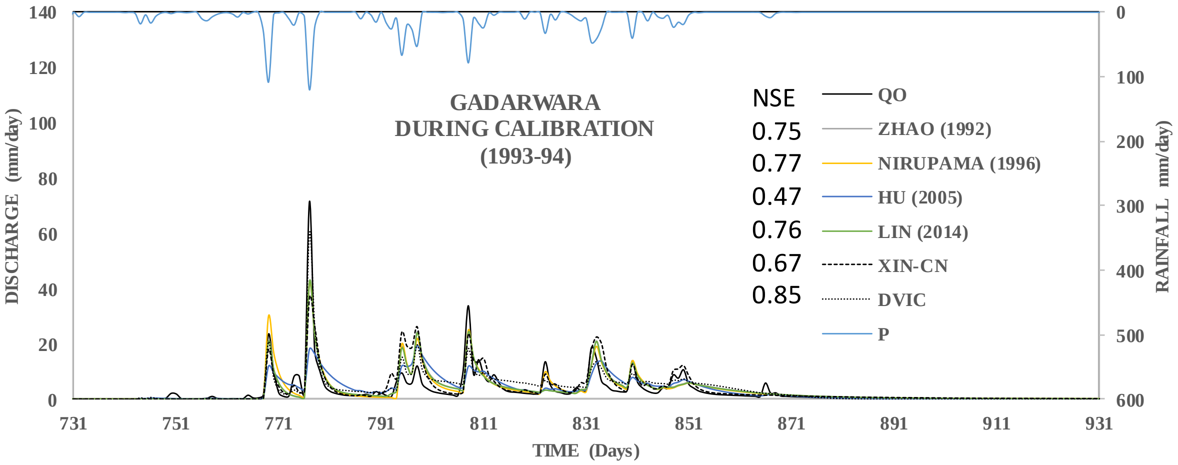

KHANPUR
DURING VALIDATION
(1985-86)
NSE
0.55
0.60
0.66
0.66
0.71
0.63
QO
ZHAO (1992)
NIRUPAMA (1996)
HU (2005)
LIN (2014)
XIN-CN
DVIC
P
DISCHARGE (mm/day)
250
200
150
100
50
0
RAINFALL mm/day)
0
100
200
300
400
500
600
366
386
406
426
446
466
486
506
526
546
566
TIME (Days)

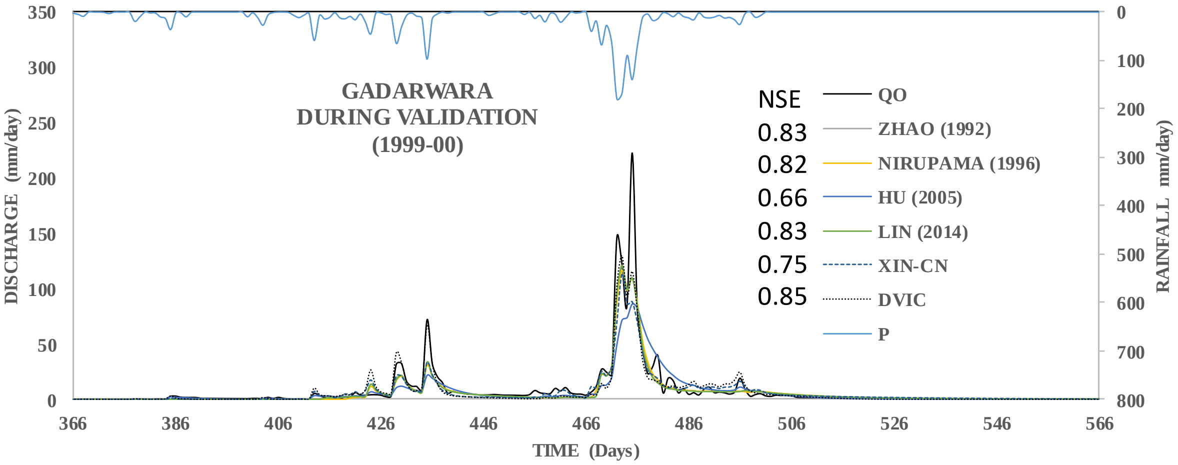

DINDORI
DURING CALIBRATION
(1991-92)
NSE
0.85
0.88
0.35
0.81
0.91
0.93
QO
ZHAO (1992)
NIRUPAMA (1996)
HU (2005)
LIN (2014)
XIN-CN
DVIC
P
DISCHARGE (mm/day)
250
200
150
100
50
0
RAINFALL mm/day)
0
100
200
300
400
500
600
0
20
40
60
80
100
120
140
160
180
200
TIME (Days)

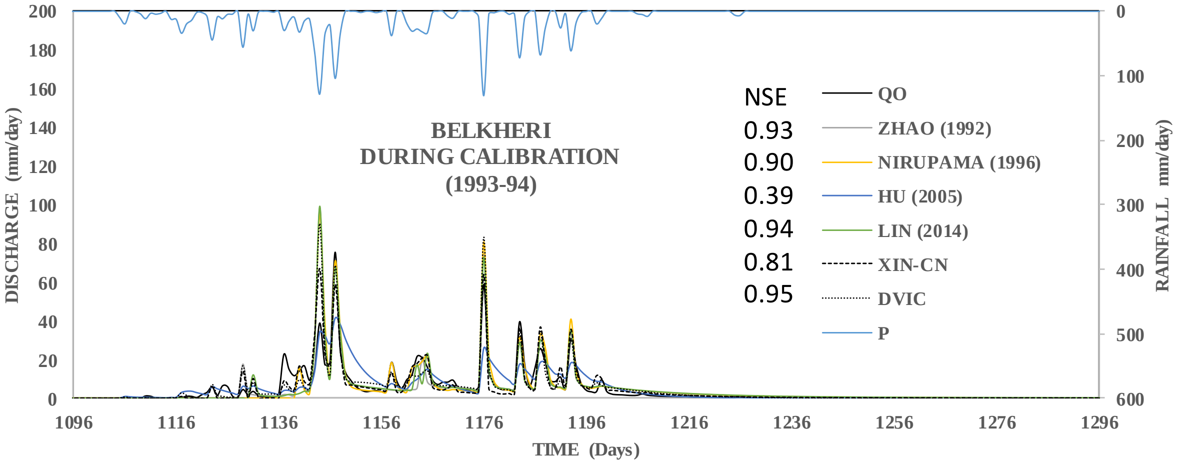

DINDORI
DURING VALIDATION
(2003-04)
NSE
0.77
0.51
0.43
0.49
0.67
0.76
QO
ZHAO (1992)
NIRUPAMA (1996)
HU (2005)
LIN (2014)
XIN-CN
DVIC
P
DISCHARGE (mm/day)
RAINFALL mm/day)
TIME (Days)
0
20
40
60
80
100
120
140
0
50
100
150
200
250
300
731
751
771
791
811
831
851
871
891
911
931

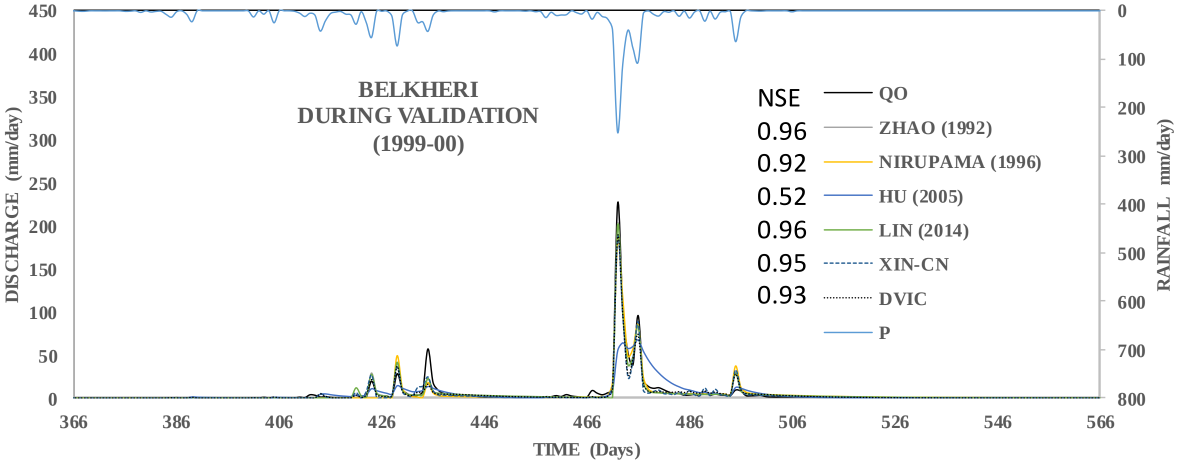

CHIDGAON
DURING CALIBRATION
(1991-92)
NSE
0.69
0.72
0.22
0.76
0.69
0.89
QO
ZHAO (1992)
NIRUPAMA (1996)
HU (2005)
LIN (2014)
XIN-CN
DVIC
P
DISCHARGE (mm/day)
RAINFALL mm/day)
TIME (Days)
0
20
40
60
80
100
120
140
160
180
200
0
100
200
300
400
500
600
0
20
40
60
80
100
120
140
160
180
200

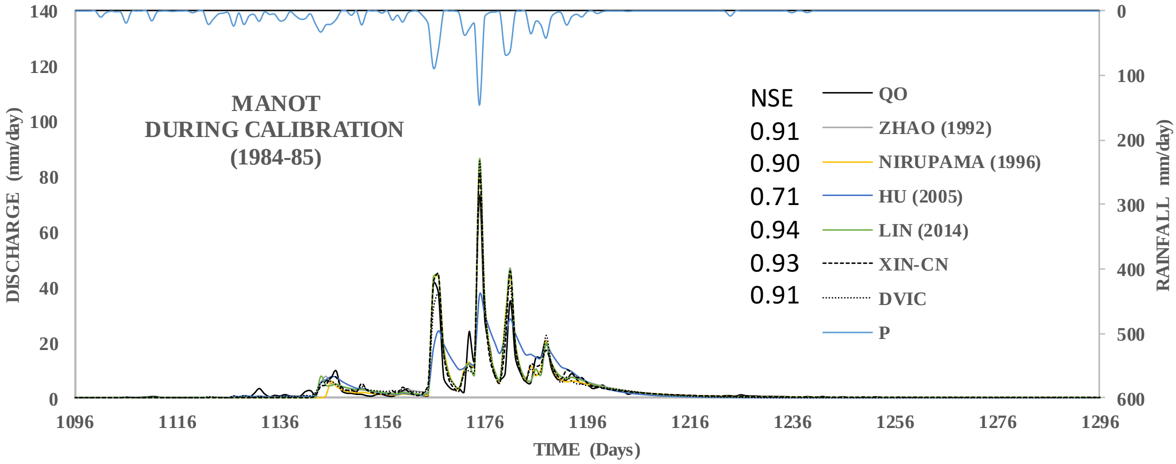

CHIDGAON
DURING VALIDATION
(2004-05)
NSE
0.91
0.94
0.48
0.92
0.95
0.95
QO
ZHAO (1992)
NIRUPAMA (1996)
HU (2005)
LIN (2014)
XIN-CN
DVIC
P
DISCHARGE (mm/day)
RAINFALL mm/day)
TIME (Days)
0
20
40
60
80
100
120
140
160
180
200
0
50
100
150
200
250
300
350
400
2190
2210
2230
2250
2270
2290
2310
2330
2350
2370
2390

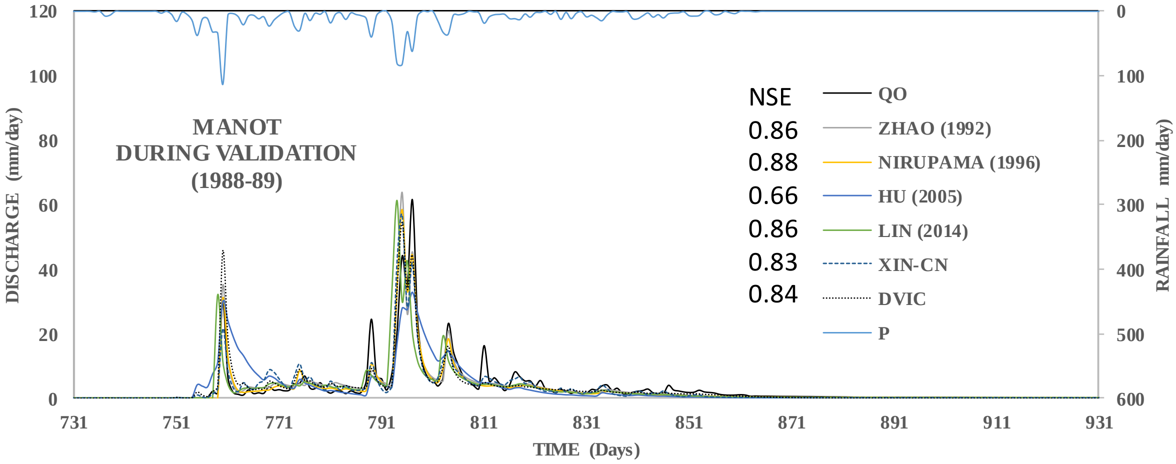

GADARWARA
DURING CALIBRATION
(1993-94)
NSE
0.75
0.77
0.47
0.76
0.67
0.85
QO
ZHAO (1992)
NIRUPAMA (1996)
HU (2005)
LIN (2014)
XIN-CN
DVIC
P
DISCHARGE (mm/day)
140
120
100
80
60
40
20
0
RAINFALL mm/day)
0
100
200
300
400
500
600
731
751
771
791
811
831
851
871
891
911
931
TIME (Days)

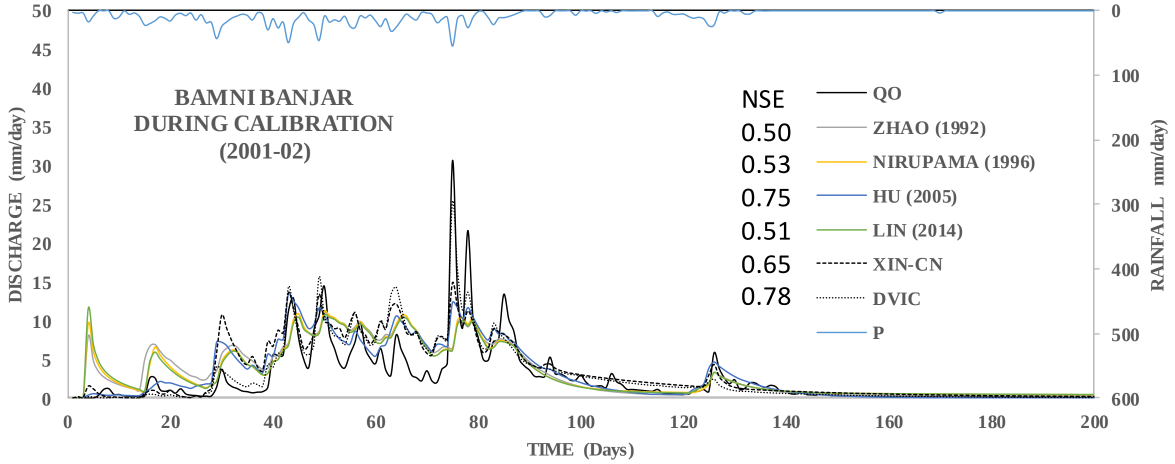

GADARWARA
DURING VALIDATION
(1999-00)
NSE
0.83
0.82
0.66
0.83
0.75
0.85
QO
ZHAO (1992)
NIRUPAMA (1996)
HU (2005)
LIN (2014)
XIN-CN
DVIC
P
DISCHARGE (mm/day)
350
300
250
200
150
100
50
0
RAINFALL mm/day)
0
100
200
300
400
500
600
700
800
366
386
406
426
446
466
486
506
526
546
566
TIME (Days)

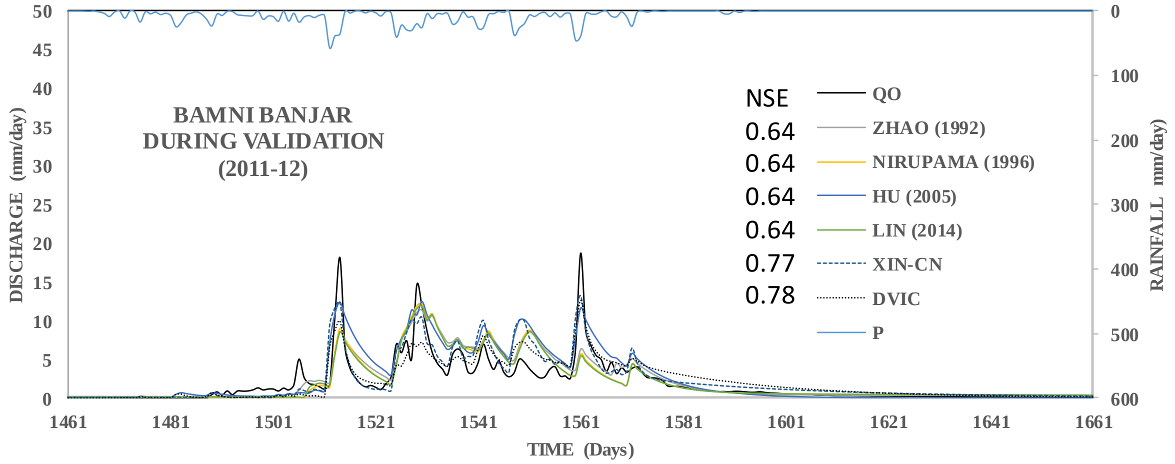

BELKHERI
DURING CALIBRATION
(1993-94)
NSE
0.93
0.90
0.39
0.94
0.81
0.95
QO
ZHAO (1992)
NIRUPAMA (1996)
HU (2005)
LIN (2014)
XIN-CN
DVIC
P
DISCHARGE (mm/day)
200
180
160
140
120
100
80
60
40
20
0
RAINFALL mm/day)
0
100
200
300
400
500
600
1096
1116
1136
1156
1176
1196
1216
1236
1256
1276
1296
TIME (Days)

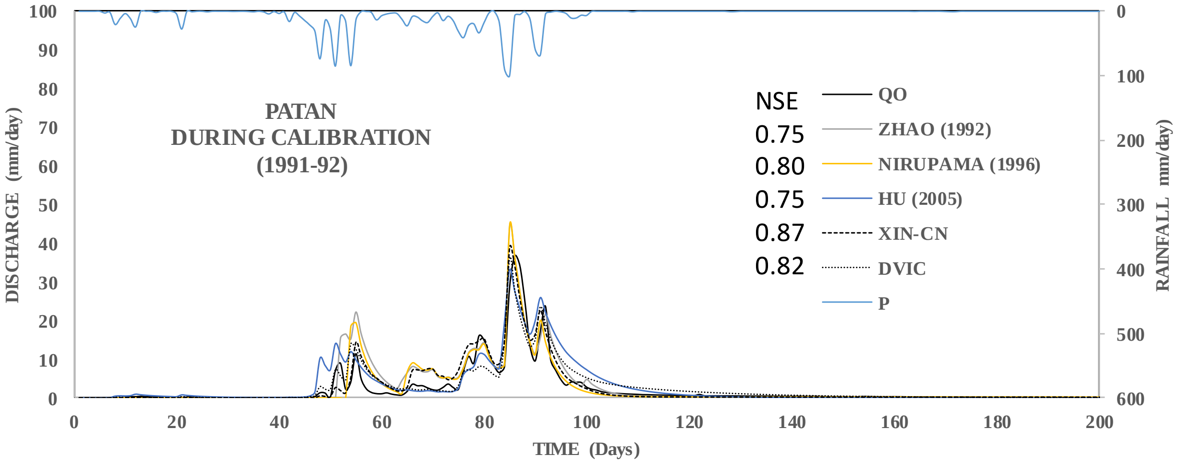

BELKHERI
DURING VALIDATION
(1999-00)
NSE
QO
0.96 ZHAO (1992)
0.92 NIRUPAMA (1996)
0.52 HU (2005)
0.96 LIN (2014)
0.95 XIN-CN
0.93 DVIC
P
DISCHARGE (mm/day)
0
50
100
150
200
250
300
350
400
450
RAINFALL mm/day)
0
100
200
300
400
500
600
700
800
TIME (Days)
366
386
406
426
446
466
486
506
526
546
566

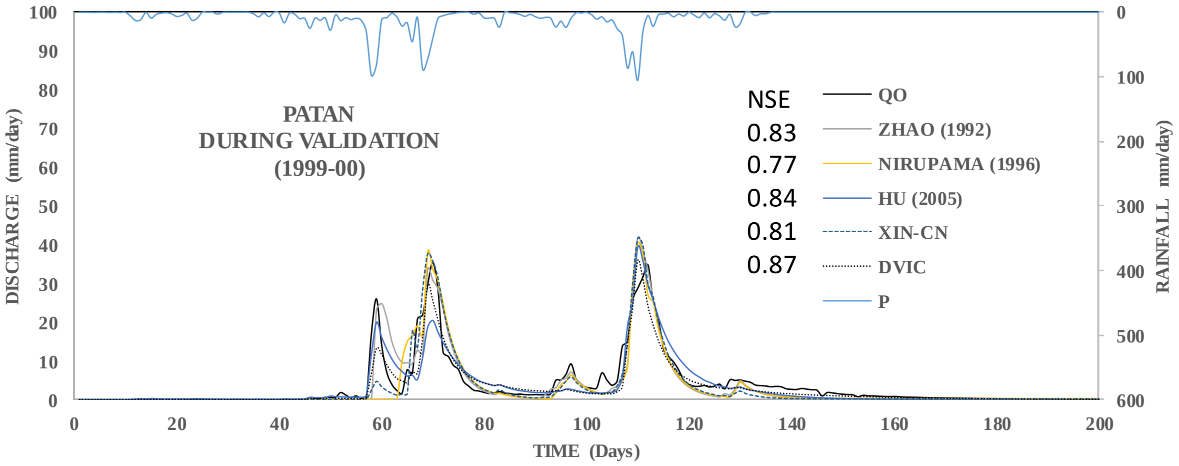

MANOT
DURING CALIBRATION
(1984-85)
NSE
QO
0.91 ZHAO (1992)
0.90 NIRUPAMA (1996)
0.71 HU (2005)
0.94 LIN (2014)
0.93 XIN-CN
0.91 DVIC
P
DISCHARGE (mm/day)
0
20
40
60
80
100
120
140
RAINFALL mm/day)
0
100
200
300
400
500
600
TIME (Days)
1096
1116
1136
1156
1176
1196
1216
1236
1256
1276
1296

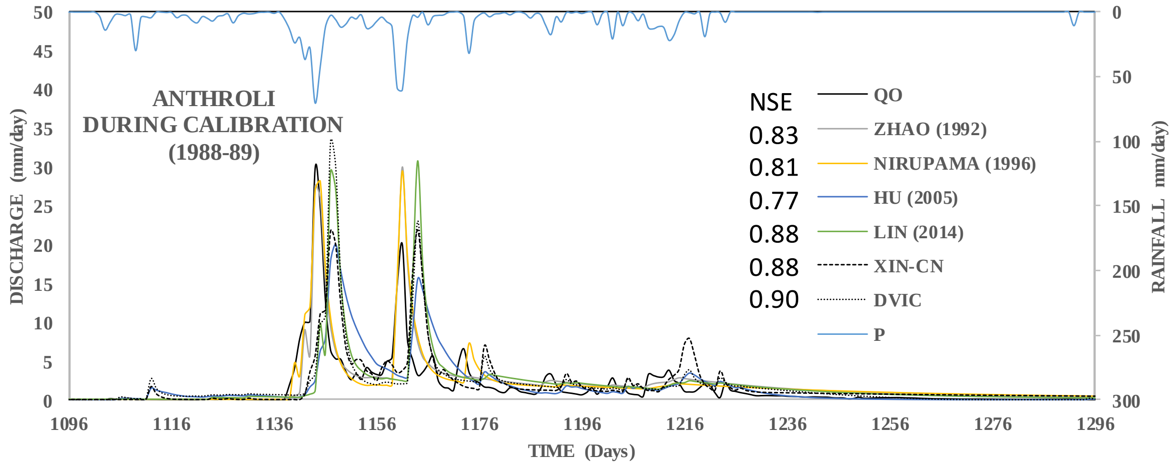

MANOT
DURING VALIDATION
(1988-89)
NSE
QO
0.86 ZHAO (1992)
0.88 NIRUPAMA (1996)
0.66 HU (2005)
0.86 LIN (2014)
0.83 XIN-CN
0.84 DVIC
P
DISCHARGE (mm/day)
0
20
40
60
80
100
120
RAINFALL mm/day)
0
100
200
300
400
500
600
TIME (Days)
731
751
771
791
811
831
851
871
891
911
931

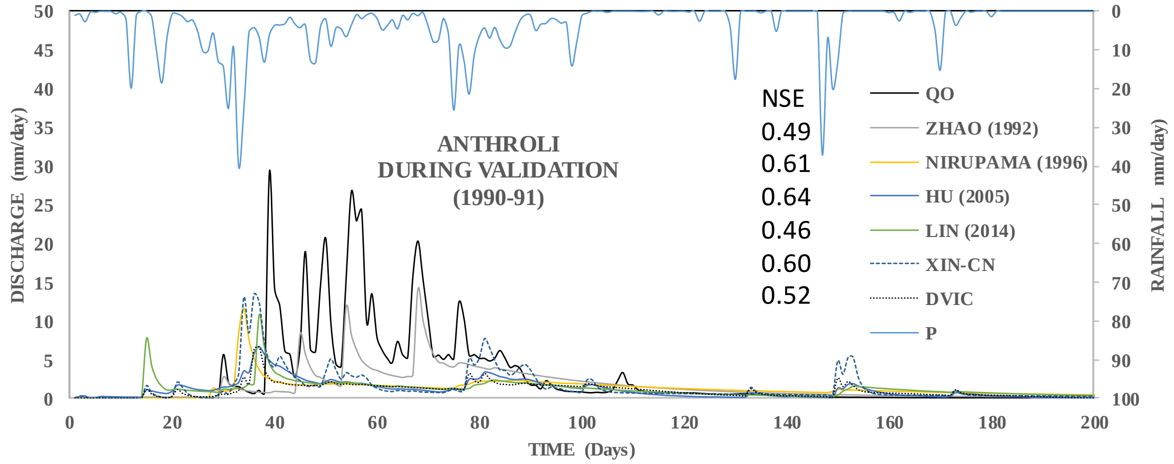

BAMNI BANJAR
DURING CALIBRATION
(2001-02)
NSE
0.50
0.53
0.75
0.51
0.65
0.78
QO
ZHAO (1992)
NIRUPAMA (1996)
HU (2005)
LIN (2014)
XIN-CN
DVIC
P
DISCHARGE (mm/day)
50
45
40
35
30
25
20
15
10
5
0
RAINFALL mm/day)
0
100
200
300
400
500
600
0
20
40
60
80
100
120
140
160
180
200
TIME (Days)

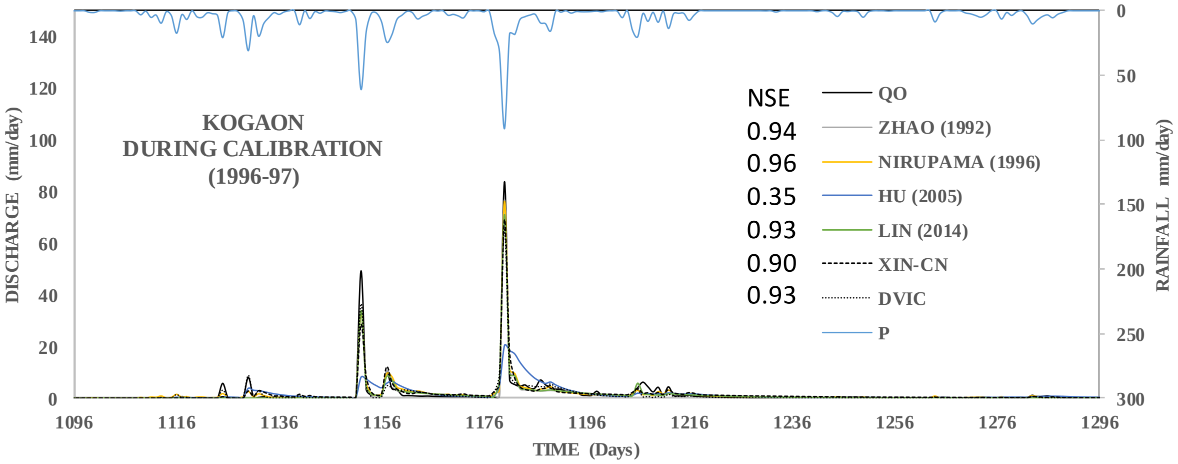

BAMNI BANJAR
DURING VALIDATION
(2011-12)
NSE
0.64
0.64
0.64
0.64
0.77
0.78
QO
ZHAO (1992)
NIRUPAMA (1996)
HU (2005)
LIN (2014)
XIN-CN
DVIC
P
DISCHARGE (mm/day)
50
45
40
35
30
25
20
15
10
5
0
RAINFALL mm/day)
0
100
200
300
400
500
600
1461
1481
1501
1521
1541
1561
1581
1601
1621
1641
1661
TIME (Days)

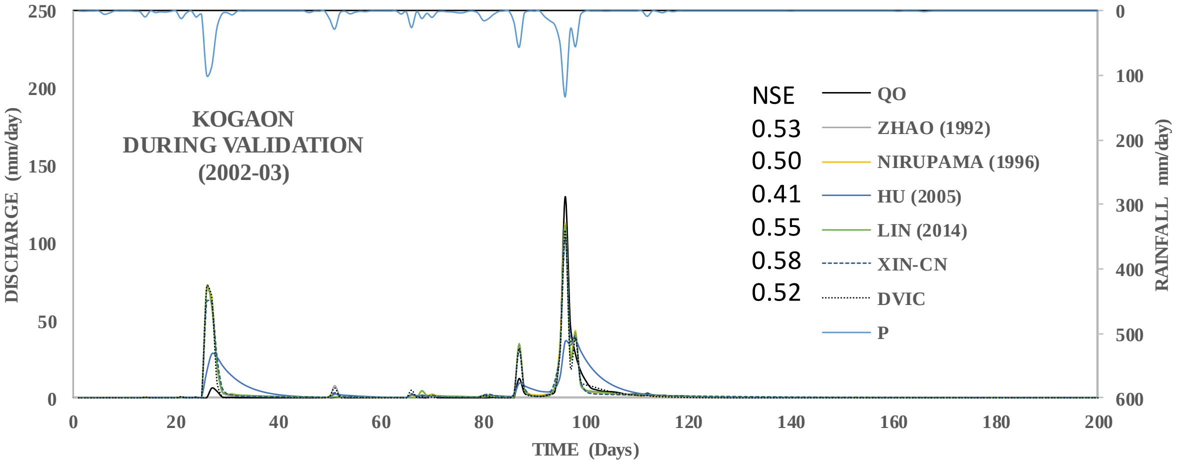

PATAN
DURING CALIBRATION
(1991-92)
NSE
0.75
0.80
0.75
0.87
0.82
QO
ZHAO (1992)
NIRUPAMA (1996)
HU (2005)
XIN-CN
DVIC
P
DISCHARGE (mm/day)
100
90
80
70
60
50
40
30
20
10
0
RAINFALL mm/day)
0
100
200
300
400
500
600
0
20
40
60
80
100
120
140
160
180
200
TIME (Days)

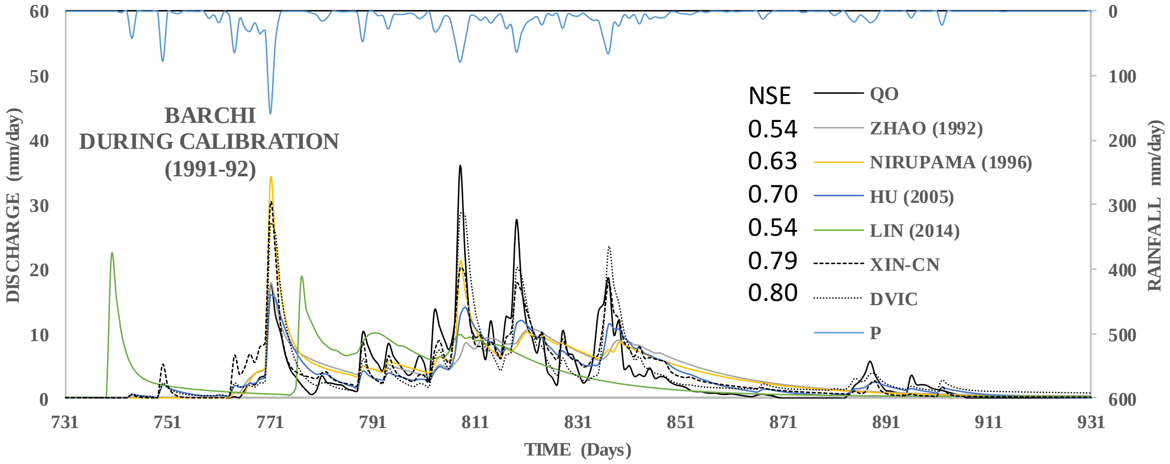

PATAN
DURING VALIDATION
(1999-00)
NSE
0.83
0.77
0.84
0.81
0.87
QO
ZHAO (1992)
NIRUPAMA (1996)
HU (2005)
XIN-CN
DVIC
P
DISCHARGE (mm/day)
RAINFALL mm/day)
TIME (Days)
100
90
80
70
60
50
40
30
20
10
0
0
100
200
300
400
500
600
0
20
40
60
80
100
120
140
160
180
200

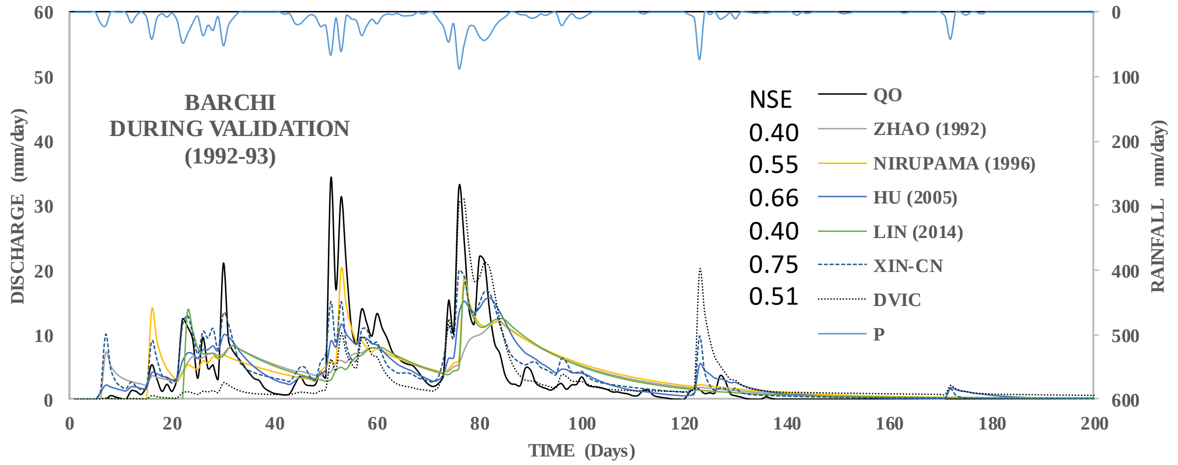

ANTHROLI
DURING CALIBRATION
(1988-89)
NSE
0.83
0.81
0.77
0.88
0.88
0.90
QO
ZHAO (1992)
NIRUPAMA (1996)
HU (2005)
LIN (2014)
XIN-CN
DVIC
P
DISCHARGE (mm/day)
RAINFALL mm/day)
TIME (Days)
50
45
40
35
30
25
20
15
10
5
0
0
50
100
150
200
250
300
1096
1116
1136
1156
1176
1196
1216
1236
1256
1276
1296

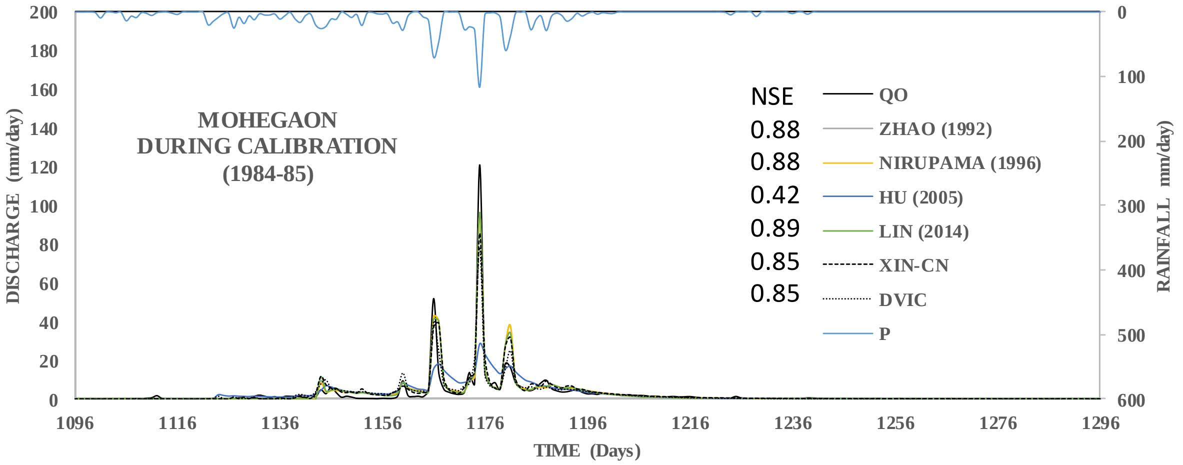

ANTHROLI
DURING VALIDATION
(1990-91)
NSE
0.49
0.61
0.64
0.46
0.60
0.52
QO
ZHAO (1992)
NIRUPAMA (1996)
HU (2005)
LIN (2014)
XIN-CN
DVIC
P
DISCHARGE (mm/day)
RAINFALL mm/day)
TIME (Days)
50
45
40
35
30
25
20
15
10
5
0
0
10
20
30
40
50
60
70
80
90
100
0
20
40
60
80
100
120
140
160
180
200

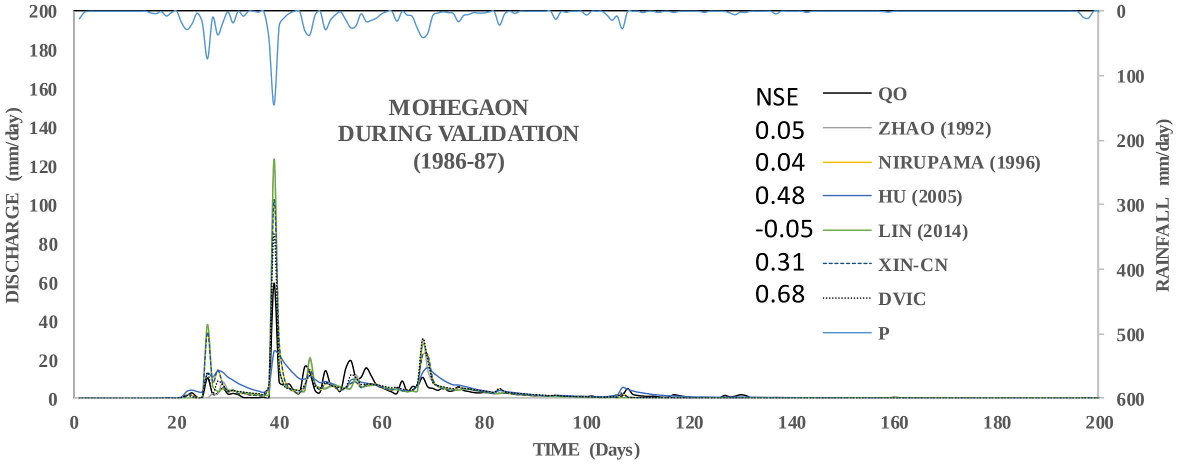

KOGAON
DURING CALIBRATION
(1996-97)
NSE
0.94
0.96
0.35
0.93
0.90
0.93
QO
ZHAO (1992)
NIRUPAMA (1996)
HU (2005)
LIN (2014)
XIN-CN
DVIC
P
DISCHARGE (mm/day)
RAINFALL mm/day)
TIME (Days)
0
20
40
60
80
100
120
140
0
50
100
150
200
250
300
1096
1116
1136
1156
1176
1196
1216
1236
1256
1276
1296

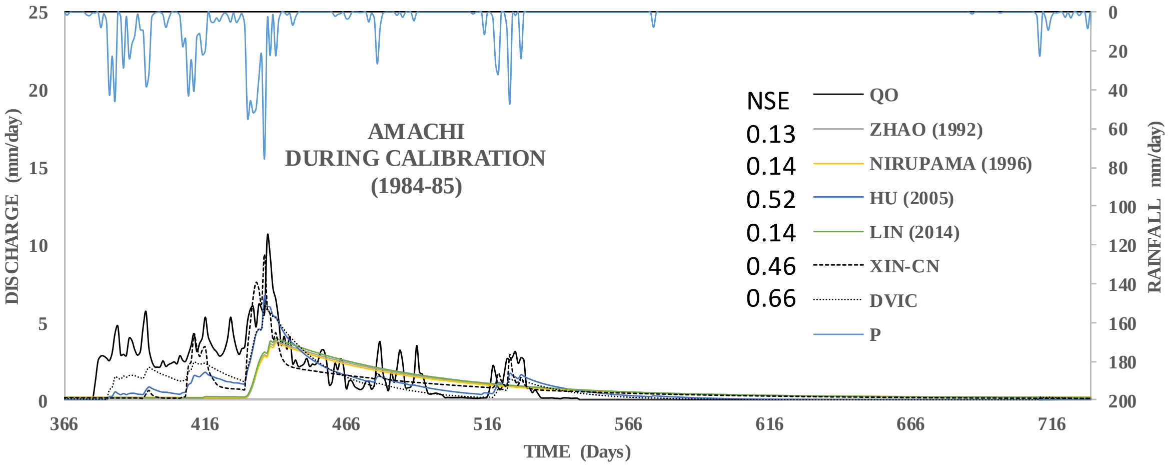

KOGAON
DURING VALIDATION
(2002-03)
NSE
0.53
0.50
0.41
0.55
0.58
0.52
QO
ZHAO (1992)
NIRUPAMA (1996)
HU (2005)
LIN (2014)
XIN-CN
DVIC
P
DISCHARGE (mm/day)
RAINFALL mm/day)
TIME (Days)
0
50
100
150
200
250
0
100
200
300
400
500
600
0
20
40
60
80
100
120
140
160
180
200

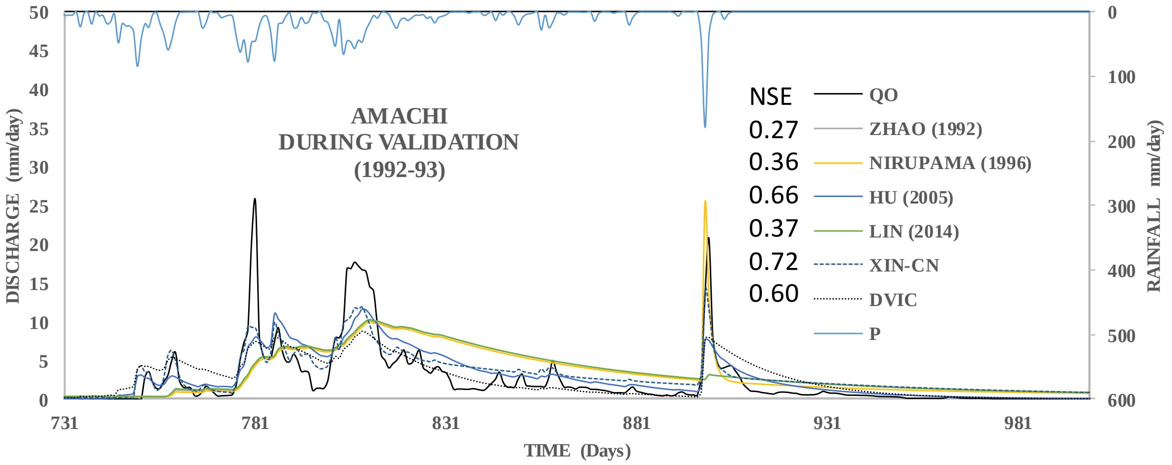

BARCHI
DURING CALIBRATION
(1991-92)
NSE
0.54
0.63
0.70
0.54
0.79
0.80
QO
ZHAO (1992)
NIRUPAMA (1996)
HU (2005)
LIN (2014)
XIN-CN
DVIC
P
DISCHARGE (mm/day)
RAINFALL mm/day)
TIME (Days)
0
10
20
30
40
50
60
0
100
200
300
400
500
600
731
751
771
791
811
831
851
871
891
911
931

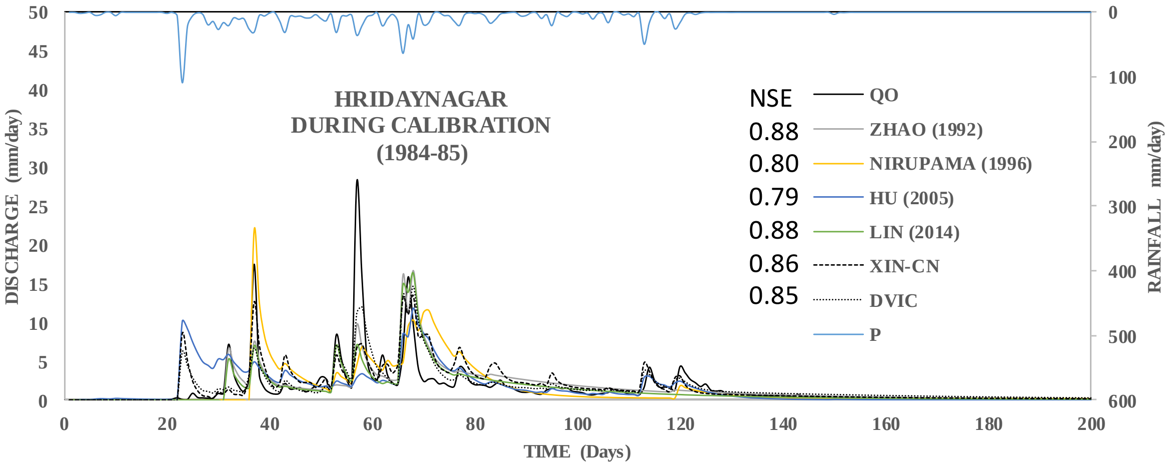

BARCHI
DURING VALIDATION
(1992-93)
NSE
QO
0.40 ZHAO (1992)
0.55 NIRUPAMA (1996)
0.66 HU (2005)
0.40 LIN (2014)
0.75 XIN-CN
0.51 DVIC
P
DISCHARGE (mm/day)
RAINFALL mm/day)
TIME (Days)
0
10
20
30
40
50
60
0
20
40
60
80
100
120
140
160
180
200
0
100
200
300
400
500
600

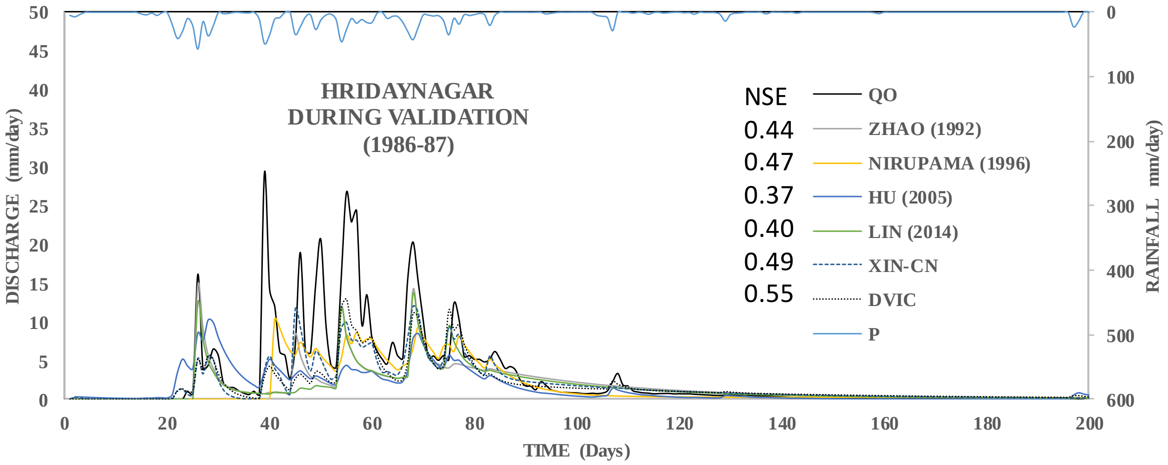

MOHEGAON
DURING CALIBRATION
(1984-85)
NSE
QO
0.88 ZHAO (1992)
0.88 NIRUPAMA (1996)
0.42 HU (2005)
0.89 LIN (2014)
0.85 XIN-CN
0.85 DVIC
P
DISCHARGE (mm/day)
RAINFALL mm/day)
TIME (Days)
0
20
40
60
80
100
120
140
160
180
200
1096
1116
1136
1156
1176
1196
1216
1236
1256
1276
1296
0
100
200
300
400
500
600


MOHEGAON
DURING VALIDATION
(1986-87)
NSE
QO
0.05 ZHAO (1992)
0.04 NIRUPAMA (1996)
0.48 HU (2005)
-0.05 LIN (2014)
0.31 XIN-CN
0.68 DVIC
P
DISCHARGE (mm/day)
RAINFALL mm/day)
TIME (Days)
0
20
40
60
80
100
120
140
160
180
200
0
20
40
60
80
100
120
140
160
180
200
0
100
200
300
400
500
600

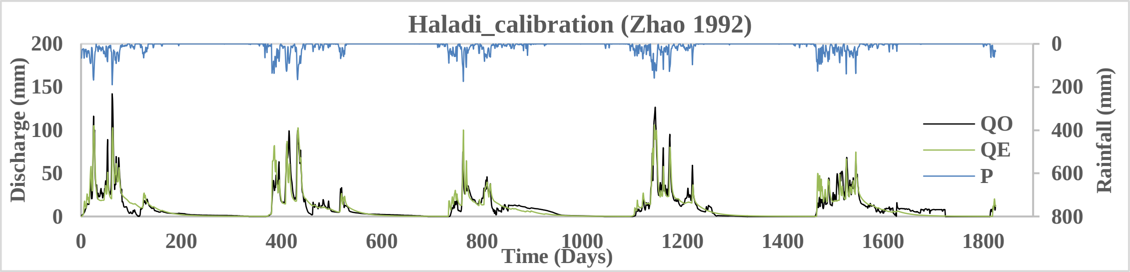

AMACHI
DURING CALIBRATION
(1984-85)
NSE
0.13
0.14
0.52
0.14
0.46
0.66
QO
ZHAO (1992)
NIRUPAMA (1996)
HU (2005)
LIN (2014)
XIN-CN
DVIC
P
DISCHARGE (mm/day)
RAINFALL mm/day)
TIME (Days)
25
20
15
10
5
0
0
20
40
60
80
100
120
140
160
180
200
366
416
466
516
566
616
666
716

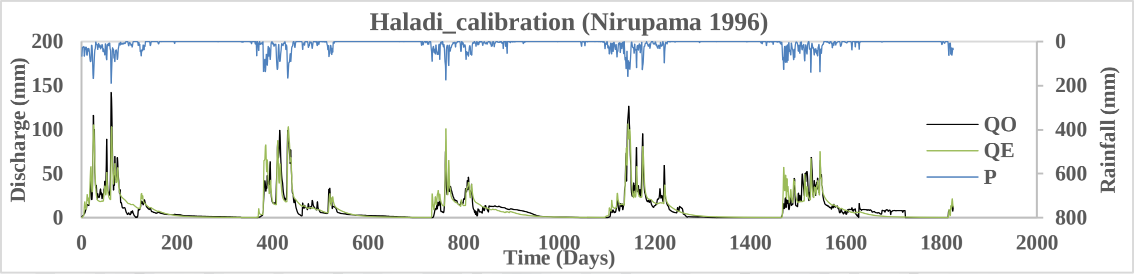

AMACHI
DURING VALIDATION
(1992-93)
NSE
0.27
0.36
0.66
0.37
0.72
0.60
QO
ZHAO (1992)
NIRUPAMA (1996)
HU (2005)
LIN (2014)
XIN-CN
DVIC
P
DISCHARGE (mm/day)
RAINFALL mm/day)
TIME (Days)
50
45
40
35
30
25
20
15
10
5
0
0
100
200
300
400
500
600
731
781
831
881
931
981

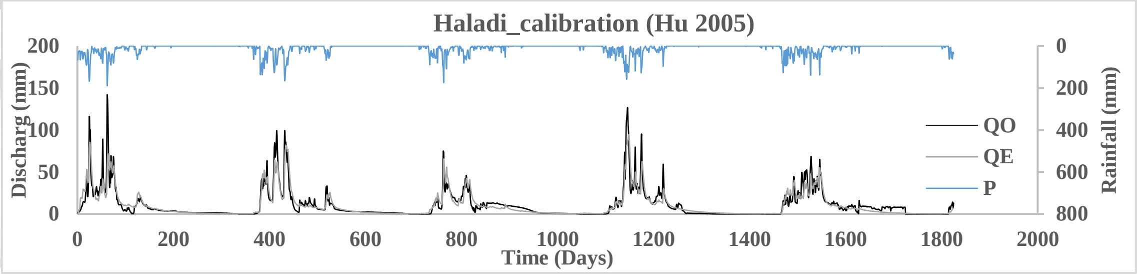

HRIDAYNAGAR
DURING CALIBRATION
(1984-85)
NSE
0.88
0.80
0.79
0.88
0.86
0.85
QO
ZHAO (1992)
NIRUPAMA (1996)
HU (2005)
LIN (2014)
XIN-CN
DVIC
P
DISCHARGE (mm/day)
RAINFALL mm/day)
TIME (Days)
50
45
40
35
30
25
20
15
10
5
0
0
100
200
300
400
500
600
0
20
40
60
80
100
120
140
160
180
200

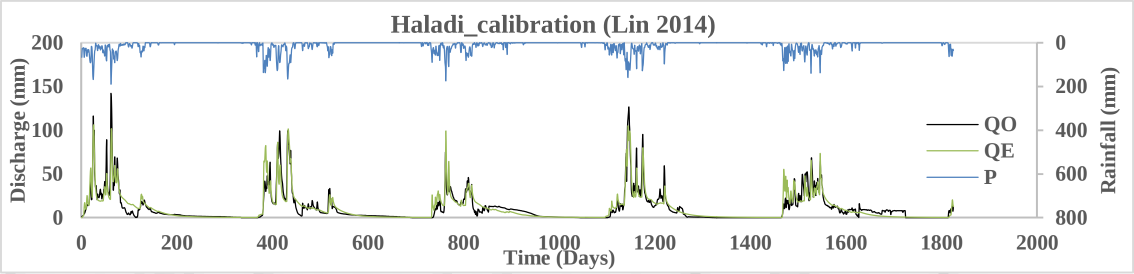

HRIDAYNAGAR
DURING VALIDATION
(1986-87)
NSE
0.44
0.47
0.37
0.40
0.49
0.55
QO
ZHAO (1992)
NIRUPAMA (1996)
HU (2005)
LIN (2014)
XIN-CN
DVIC
P
DISCHARGE (mm/day)
0
5
10
15
20
25
30
35
40
45
50
RAINFALL mm/day)
0
100
200
300
400
500
600
TIME (Days)
0
20
40
60
80
100
120
140
160
180
200

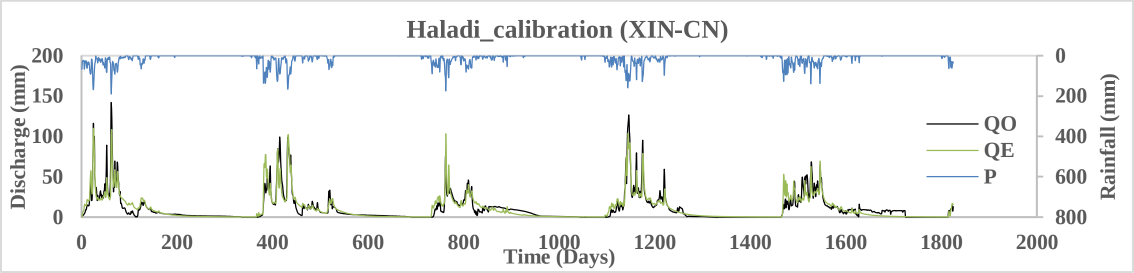
APPENDIX-II PLOTS OF OBSERVED RAINFALL-RUNOFF WITH SIMULATED RUNOFF

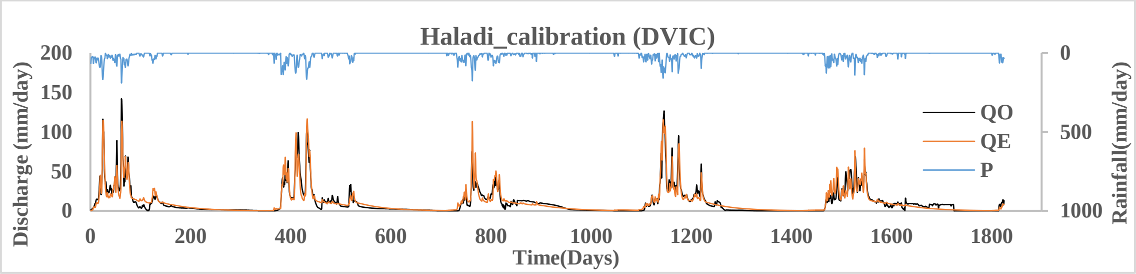


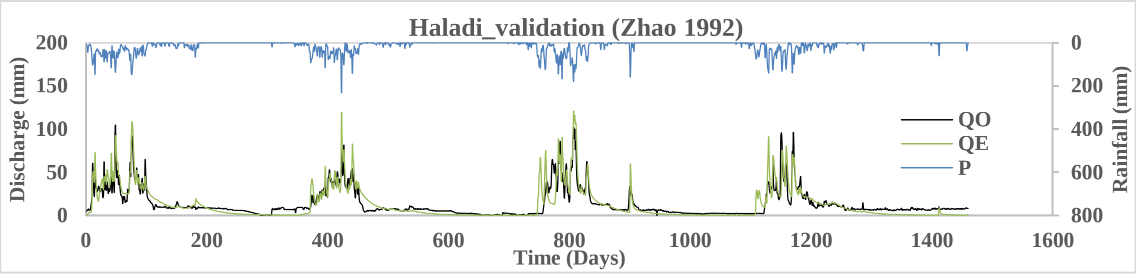


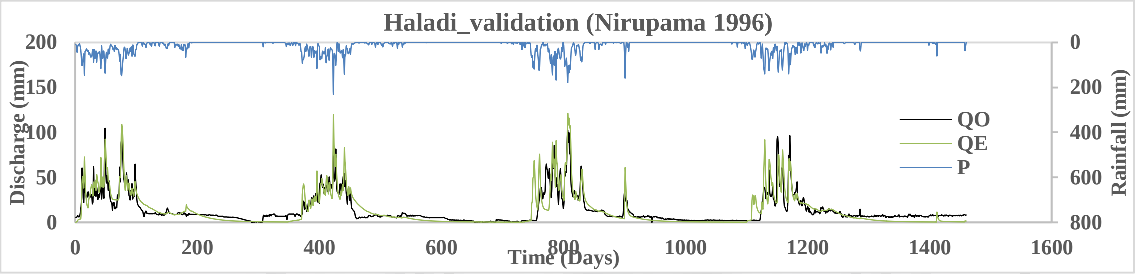


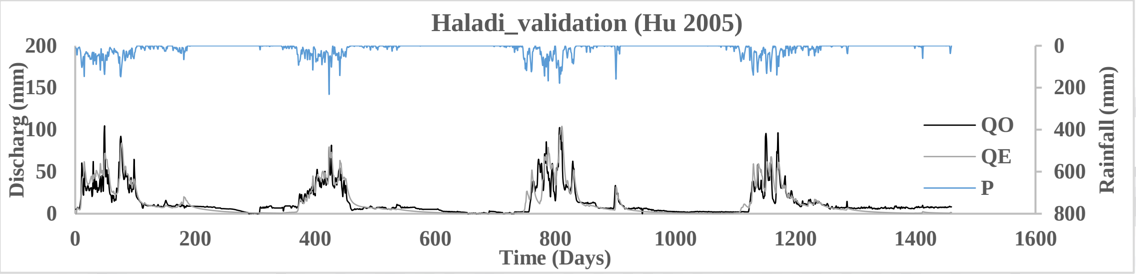


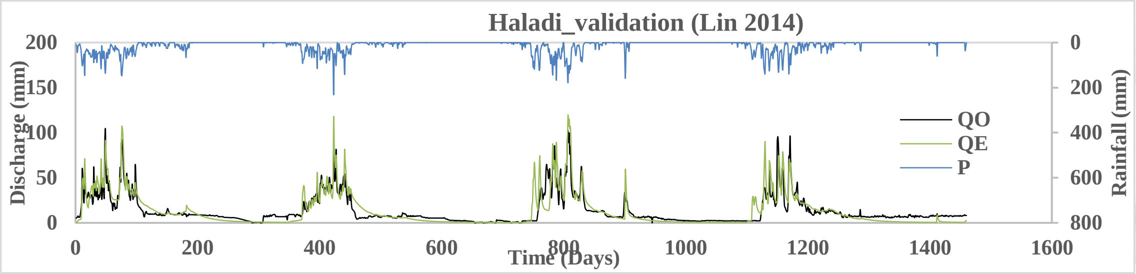


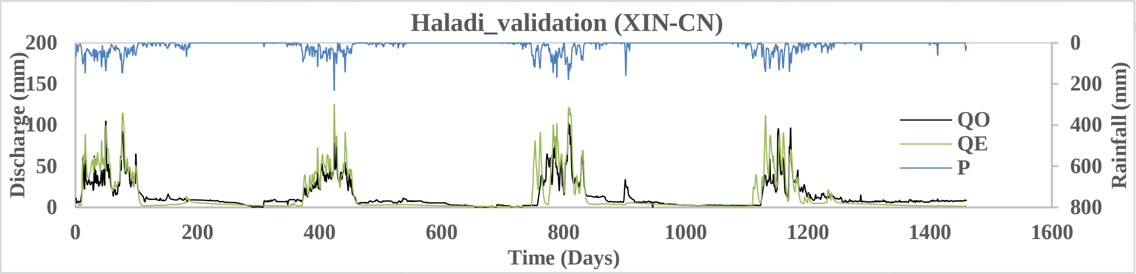


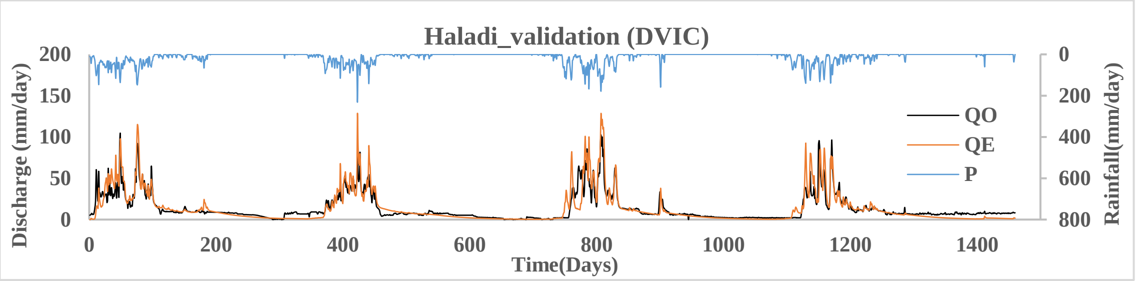

Haladi_validation (Zhao 1992)
Discharge (mm)
200
150
100
50
0
0
200
400
600
800
1000
1200
1400
1600
Time (Days)
Rainfall (mm)
0
200
400
600
800
QO
QE
P

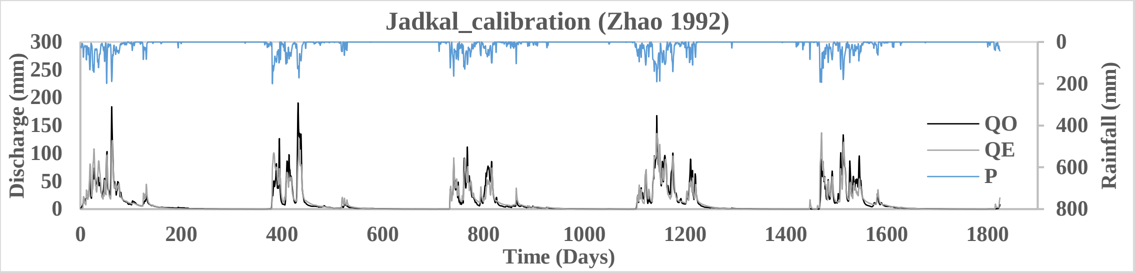

Haladi_validation (Nirupama 1996)
Discharge (mm)
200
150
100
50
0
0
200
400
600
800
1000
1200
1400
1600
Time (Days)
Rainfall (mm)
0
200
400
600
800
QO
QE
P

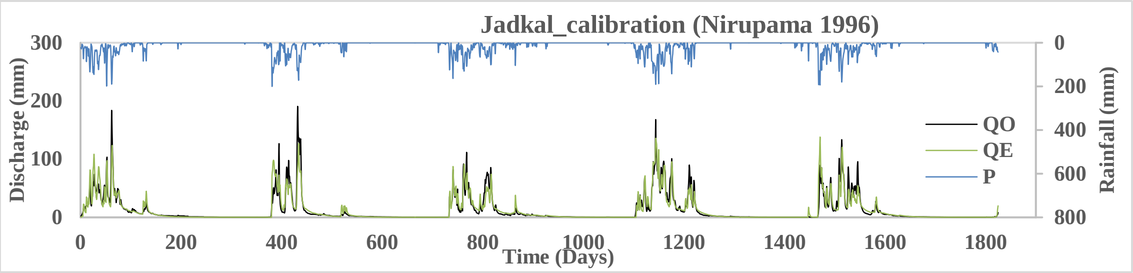

Haladi_validation (Hu 2005)
Discharg (mm)
200
150
100
50
0
0
200
400
600
800
1000
1200
1400
1600
Time (Days)
Rainfall (mm)
0
200
400
600
800
QO
QE
P

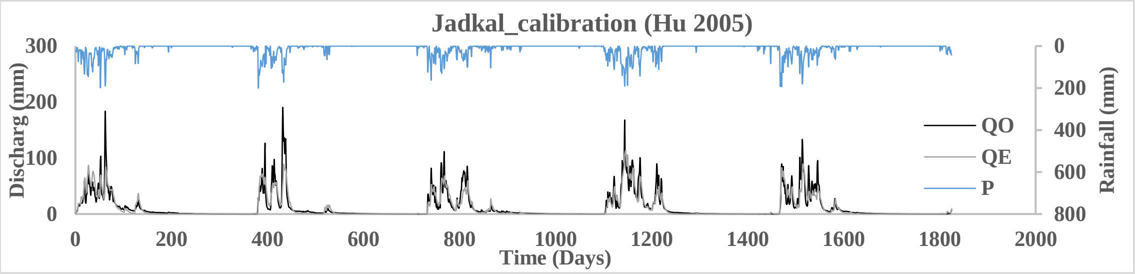

Haladi_validation (Lin 2014)
Discharge (mm)
200
150
100
50
0
0
200
400
600
800
1000
1200
1400
1600
Time (Days)
Rainfall (mm)
0
200
400
600
800
QO
QE
P

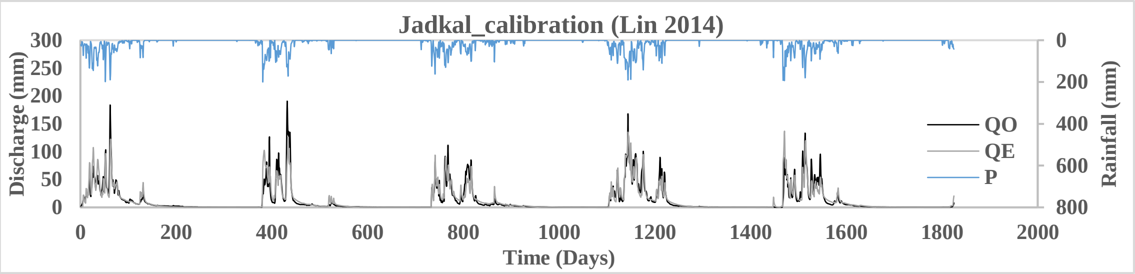

Haladi_validation (XIN-CN)
Discharge (mm)
200
150
100
50
0
0
200
400
600
800
1000
1200
1400
1600
Time (Days)
Rainfall (mm)
0
200
400
600
800
QO
QE
P

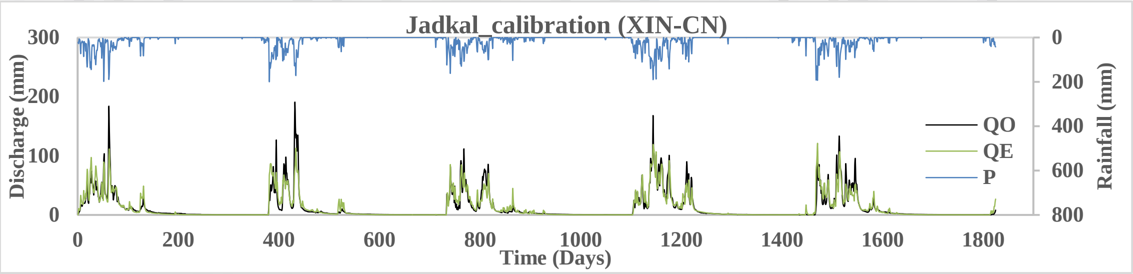

Haladi_validation (DVIC)
Discharge (mm/day)
200
150
100
50
0
0
200
400
600
800
1000
1200
1400
Time(Days)
Rainfall(mm/day)
0
200
400
600
800
QO
QE
P

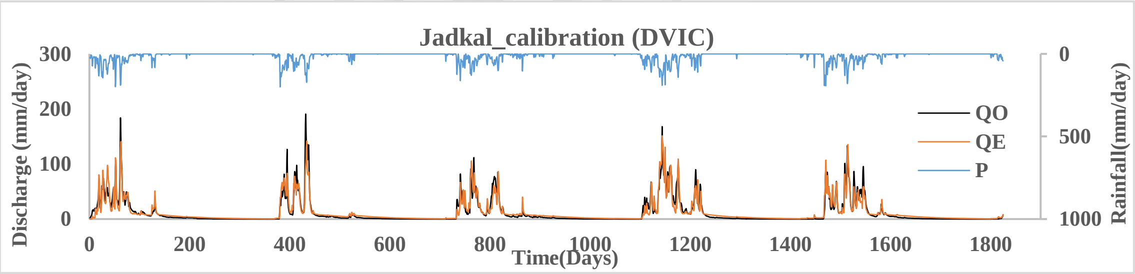

Jadkal_calibration (Zhao 1992)
Discharge (mm)
300
250
200
150
100
50
0
0
200
400
600
800
1000
1200
1400
1600
1800
Time (Days)
Rainfall (mm)
0
200
400
600
800
QO
QE
P

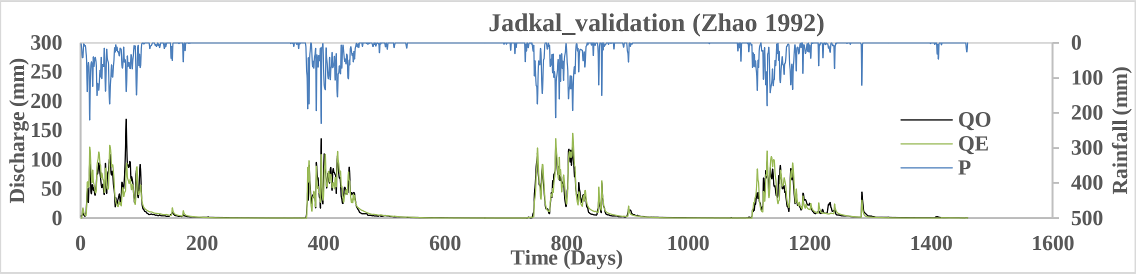

Jadkal_calibration (Nirupama 1996)
Discharge (mm)
300
200
100
0
0
200
400
600
800
1000
1200
1400
1600
1800
Time (Days)
Rainfall (mm)
0
200
400
600
800
QO
QE
P

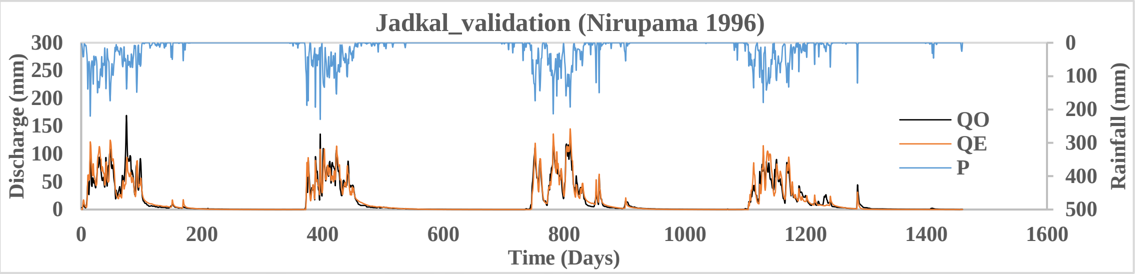

Jadkal_calibration (Hu 2005)
Discharg (mm)
300
200
100
0
0
200
400
600
800
1000
1200
1400
1600
1800
2000
Time (Days)
Rainfall (mm)
0
200
400
600
800
QO
QE
P

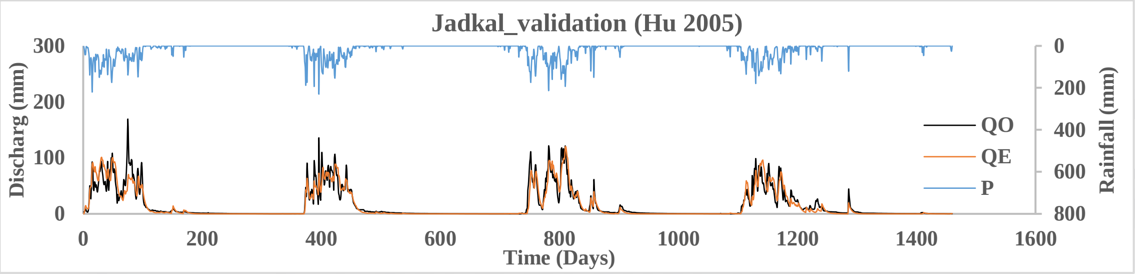

Jadkal_calibration (Lin 2014)
Discharge (mm)
300
250
200
150
100
50
0
0
200
400
600
800
1000
1200
1400
1600
1800
2000
Time (Days)
Rainfall (mm)
0
200
400
600
800
QO
QE
P

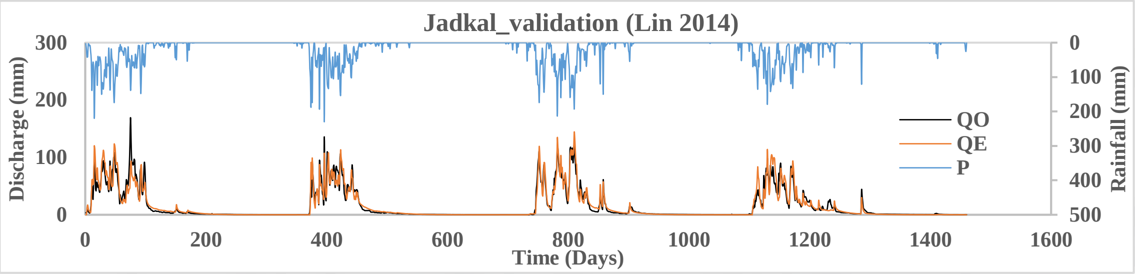

Jadkal_calibration (XIN-CN)
Discharge (mm)
300
200
100
0
0
200
400
600
800
1000
1200
1400
1600
1800
Time (Days)
Rainfall (mm)
0
200
400
600
800
QO
QE
P

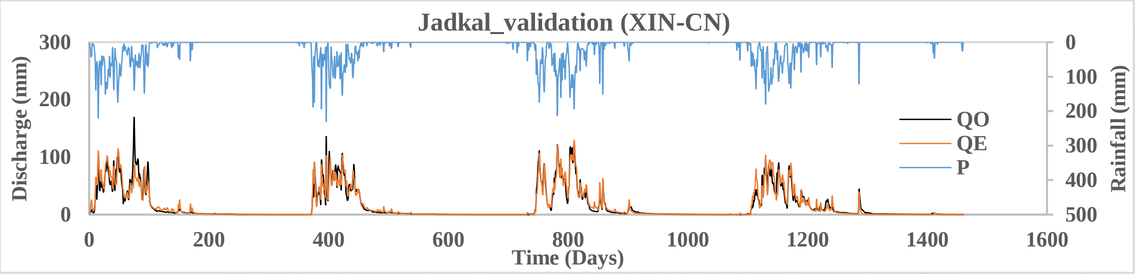

Jadkal_calibration (DVIC)
Discharge (mm/day)
300
200
100
0
0
200
400
600
800
1000
1200
1400
1600
1800
Time(Days)
Rainfall(mm/day)
0
500
1000
QO
QE
P

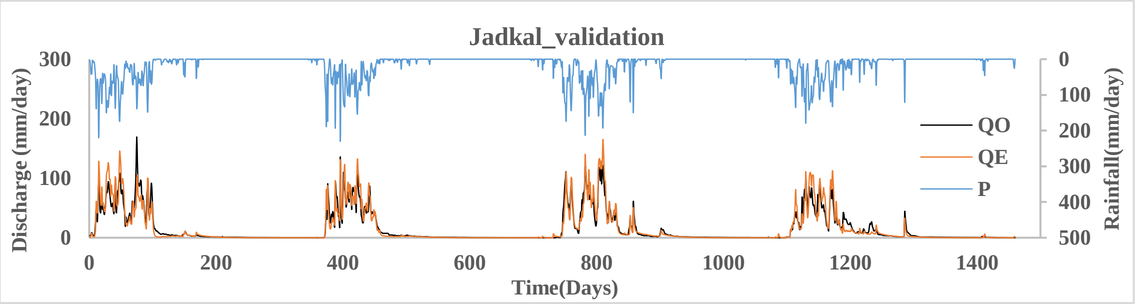

Jadkal_validation (Zhao 1992)
Discharge (mm)
300
250
200
150
100
50
0
0
200
400
600
800
1000
1200
1400
1600
Time (Days)
Rainfall (mm)
0
100
200
300
400
500
QO
QE
P

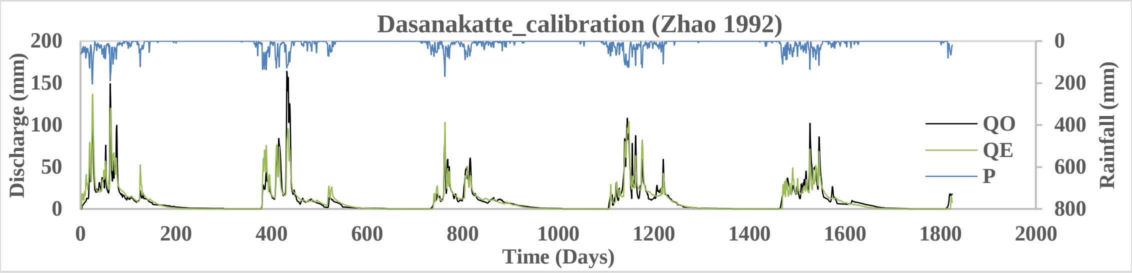

Jadkal_validation (Nirupama 1996)
Discharge (mm)
300
250
200
150
100
50
0
0
200
400
600
800
1000
1200
1400
1600
Time (Days)
Rainfall (mm)
0
100
200
300
400
500
QO
QE
P

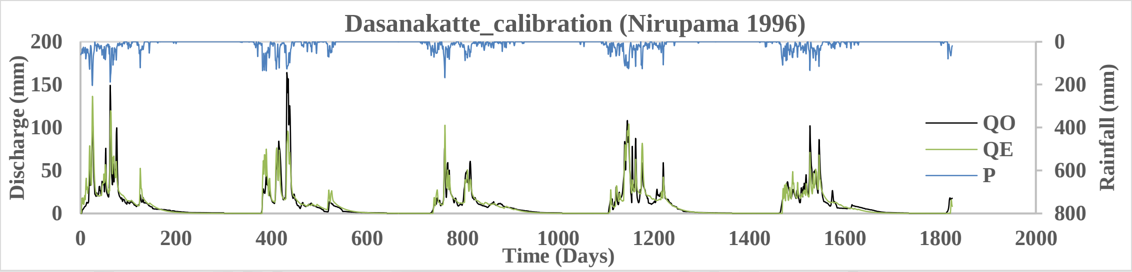

Jadkal_validation (Hu 2005)
Discharg (mm)
300
200
100
0
0
200
400
600
800
1000
1200
1400
1600
Time (Days)
Rainfall (mm)
0
200
400
600
800
QO
QE
P

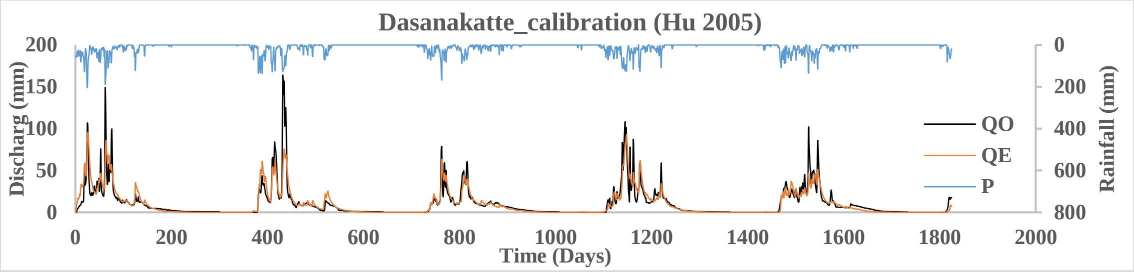

Jadkal_validation (Lin 2014)
Discharge (mm)
300
200
100
0
0
200
400
600
800
1000
1200
1400
1600
Time (Days)
Rainfall (mm)
0
100
200
300
400
500
QO
QE
P

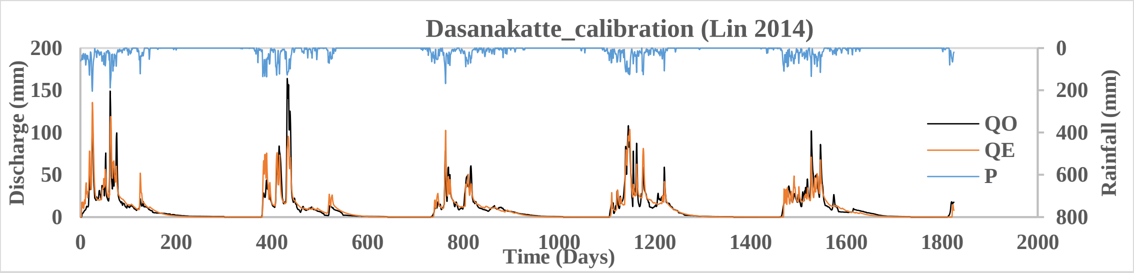

Jadkal_validation (XIN-CN)
Discharge (mm)
300
200
100
0
0
200
400
600
800
1000
1200
1400
1600
Time (Days)
Rainfall (mm)
0
100
200
300
400
500
QO
QE
P

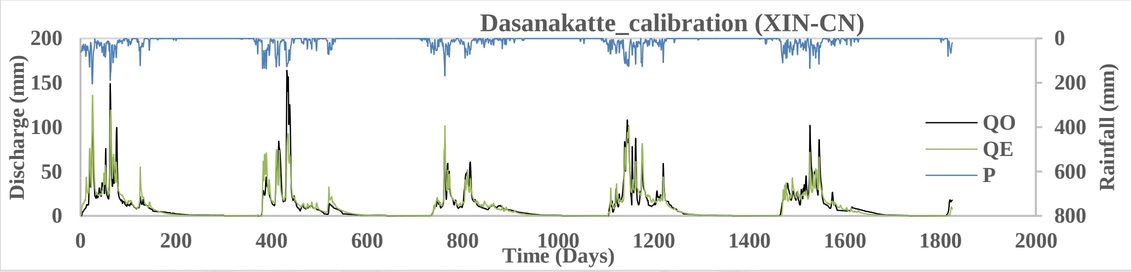

Jadkal_validation
Discharge (mm/day)
300
200
100
0
0
200
400
600
800
1000
1200
1400
Time(Days)
Rainfall(mm/day)
0
100
200
300
400
500
QO
QE
P

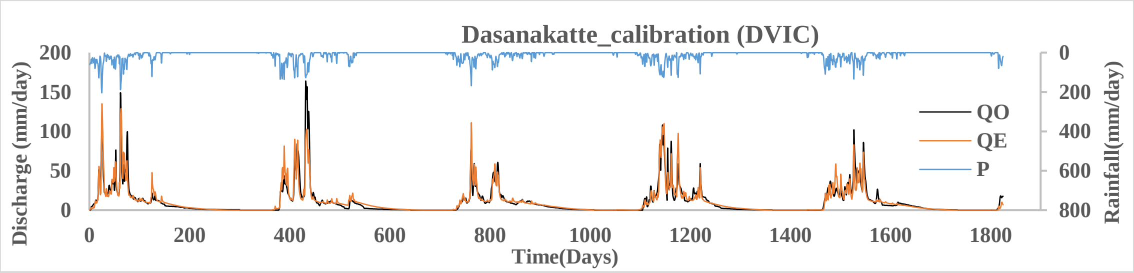

Dasanakatte_calibration (Zhao 1992)
Discharge (mm)
200
150
100
50
0
0
200
400
600
800
1000
1200
1400
1600
1800
2000
Time (Days)
Rainfall (mm)
0
200
400
600
800
QO
QE
P

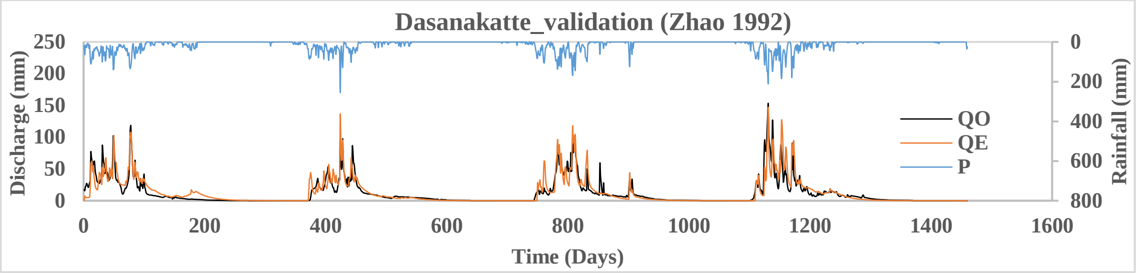

Dasanakatte_calibration (Nirupama 1996)
Discharge (mm)
200
150
100
50
0
0
200
400
600
800
1000
1200
1400
1600
1800
2000
Time (Days)
Rainfall (mm)
0
200
400
600
800
QO
QE
P

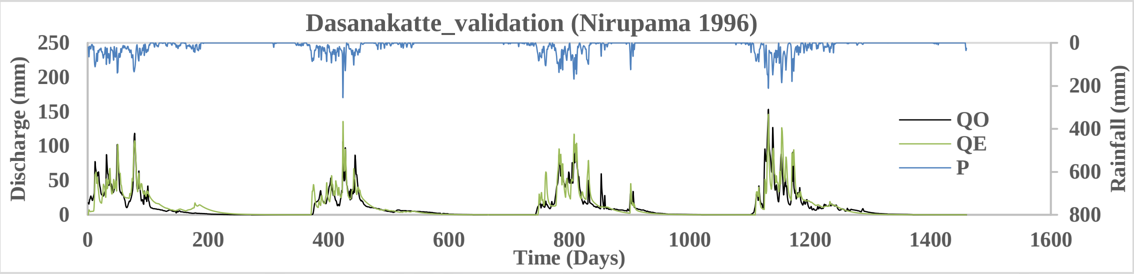

Dasanakatte_calibration (Hu 2005)
Discharg (mm)
200
150
100
50
0
0
200
400
600
800
1000
1200
1400
1600
1800
2000
Time (Days)
Rainfall (mm)
0
200
400
600
800
QO
QE
P

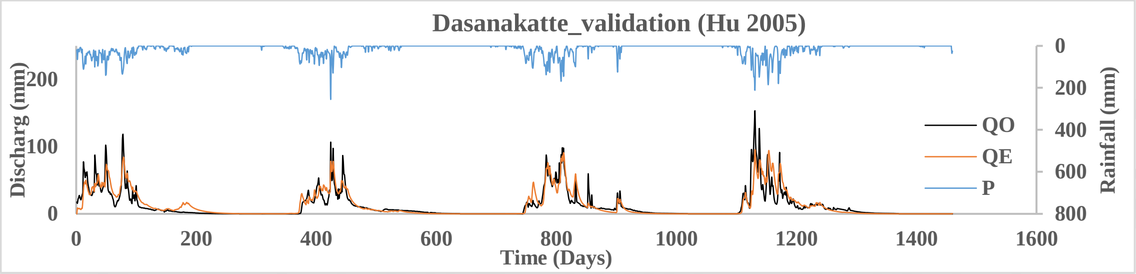

Dasanakatte_calibration (Lin 2014)
Discharge (mm)
200
150
100
50
0
0
200
400
600
800
1000
1200
1400
1600
1800
2000
Time (Days)
Rainfall (mm)
0
200
400
600
800
QO
QE
P

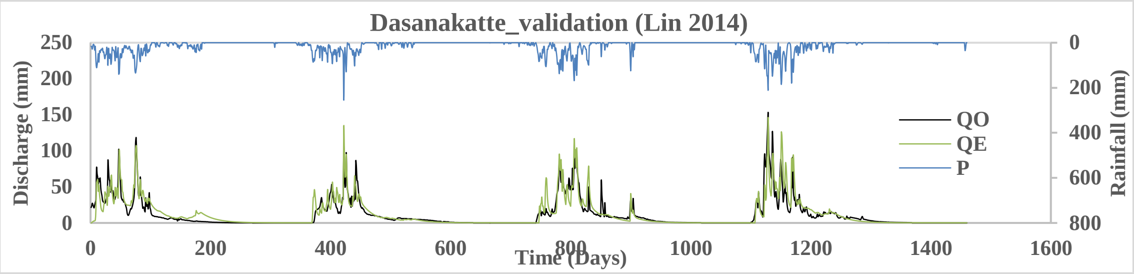

Dasanakatte_calibration (XIN-CN)
Discharge (mm)
200
150
100
50
0
0
200
400
600
800
1000
1200
1400
1600
1800
2000
Time (Days)
Rainfall (mm)
0
200
400
600
800
QO
QE
P

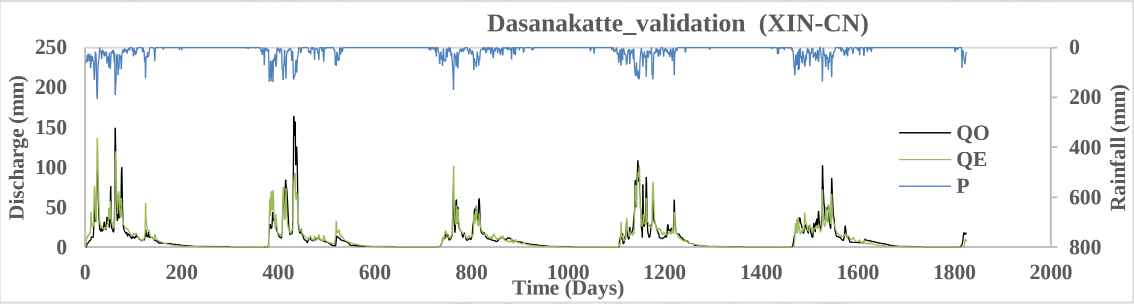

Dasanakatte_calibration (DVIC)
Discharge (mm/day)
200
150
100
50
0
0
200
400
600
800
1000
1200
1400
1600
1800
Time(Days)
Rainfall(mm/day)
0
200
400
600
800
QO
QE
P

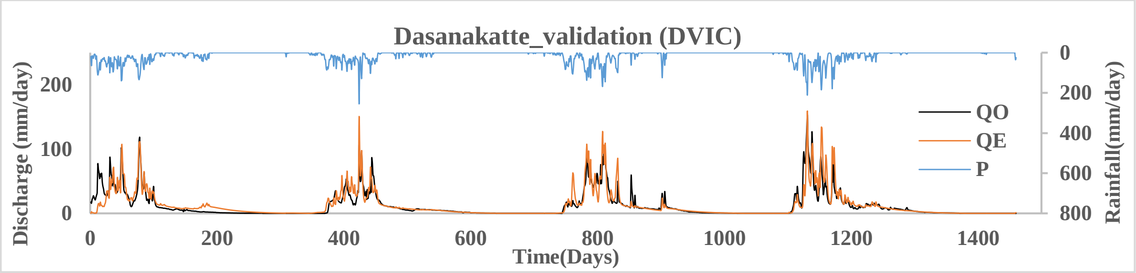

Dasanakatte_validation (Zhao 1992)
Discharge (mm)
250
200
150
100
50
0
0
200
400
600
800
1000
1200
1400
1600
Time (Days)
Rainfall (mm)
0
200
400
600
800
QO
QE
P

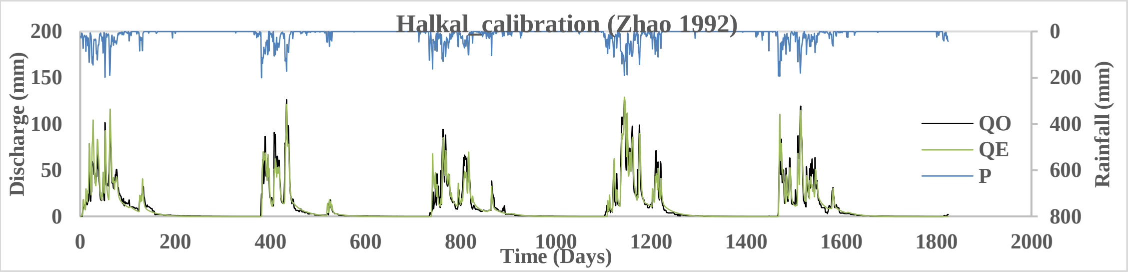

Dasanakatte_validation (Nirupama 1996)
Discharge (mm)
250
200
150
100
50
0
0
200
400
600
800
1000
1200
1400
1600
Time (Days)
Rainfall (mm)
0
200
400
600
800
QO
QE
P

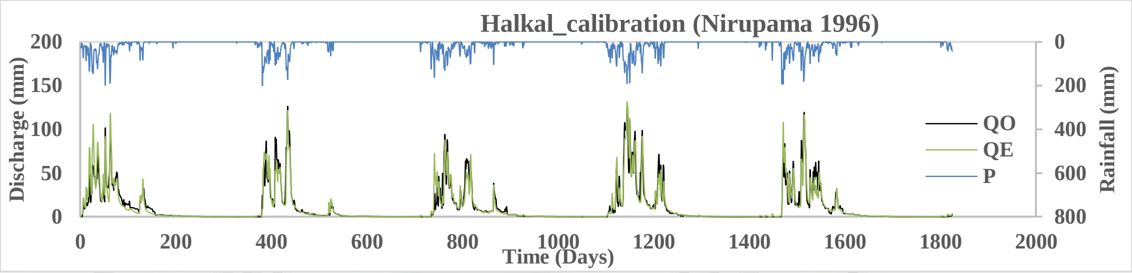

Dasanakatte_validation (Hu 2005)
Discharg (mm)
200
100
0
0
200
400
600
800
1000
1200
1400
1600
Time (Days)
Rainfall (mm)
0
200
400
600
800
QO
QE
P


Dasanakatte_validation (Lin 2014)
Discharge (mm)
250
200
150
100
50
0
0
200
400
600
800
1000
1200
1400
1600
Time (Days)
Rainfall (mm)
0
200
400
600
800
QO
QE
P


Dasanakatte_validation (XIN-CN)
Discharge (mm)
250
200
150
100
50
0
0
200
400
600
800
1000
1200
1400
1600
1800
2000
Time (Days)
Rainfall (mm)
0
200
400
600
800
QO
QE
P


Dasanakatte_validation (DVIC)
Discharge (mm/day)
200
100
0
0
200
400
600
800
1000
1200
1400
Time(Days)
Rainfall(mm/day)
0
200
400
600
800
QO
QE
P


Halkal_calibration (Zhao 1992)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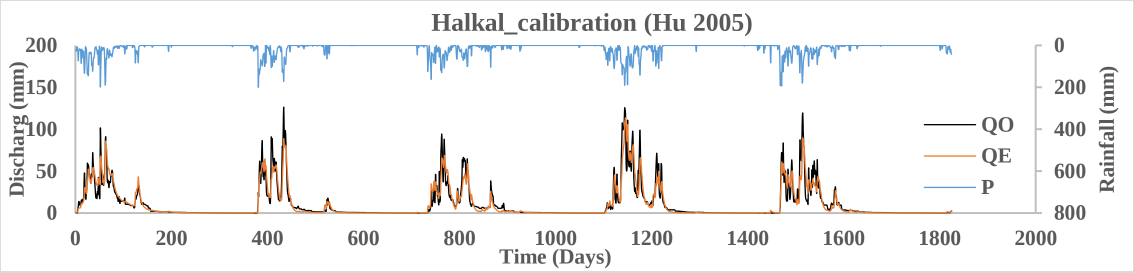
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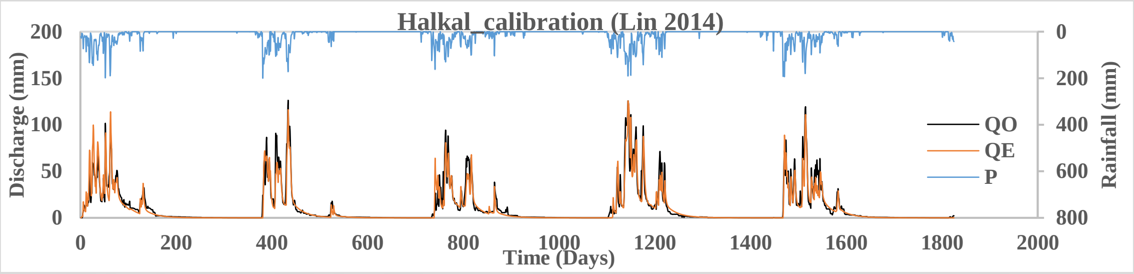
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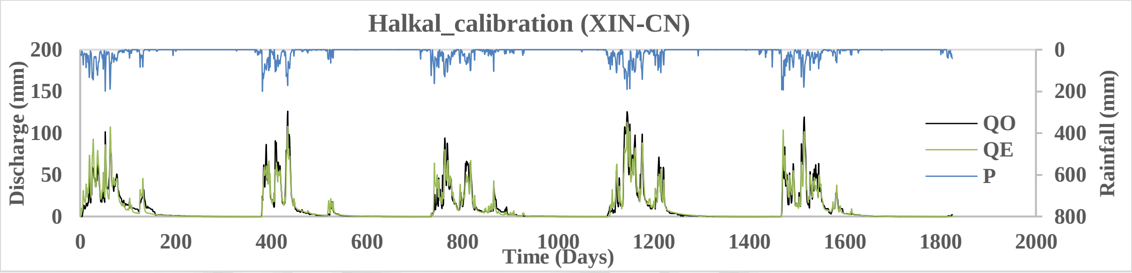
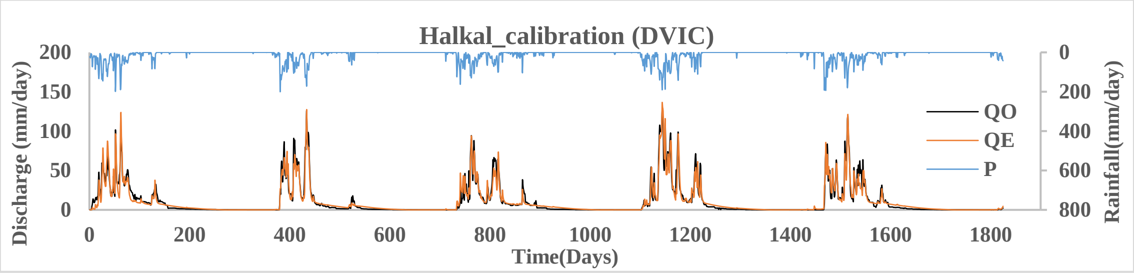
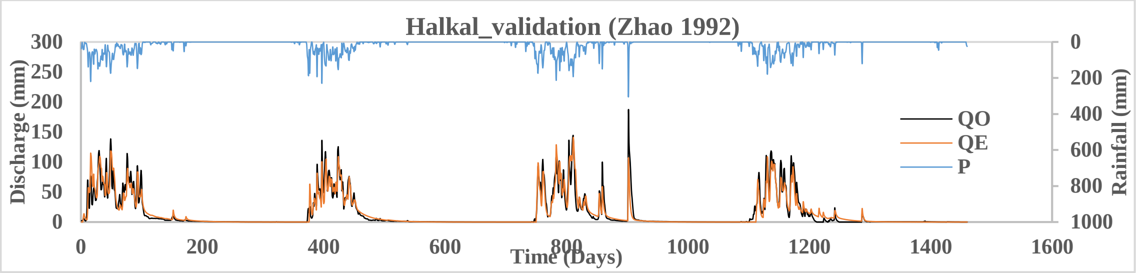

Halkal_calibration (XIN-CN)


Halkal_calibration (DVIC)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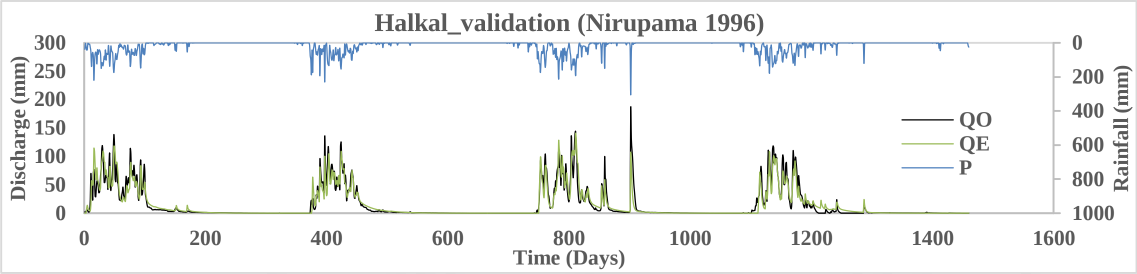
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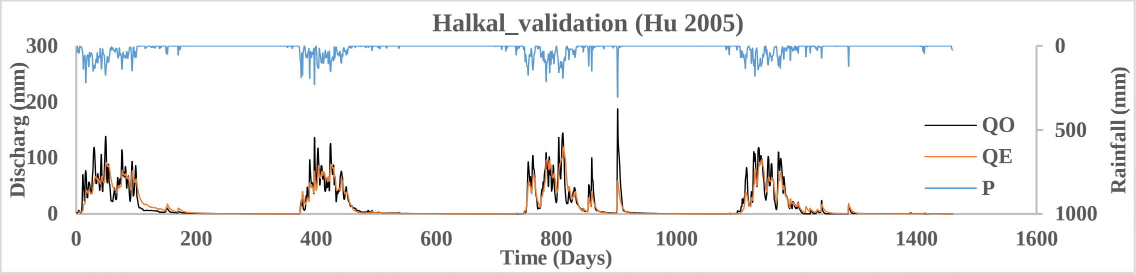
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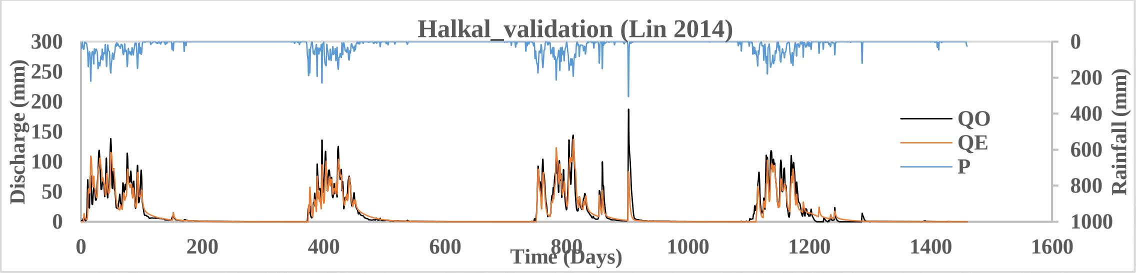
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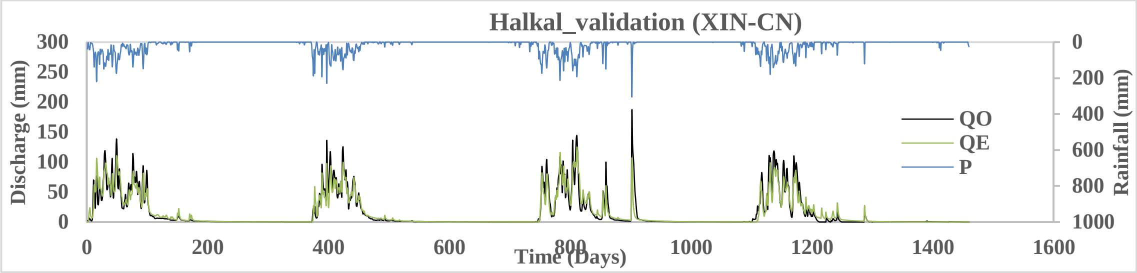
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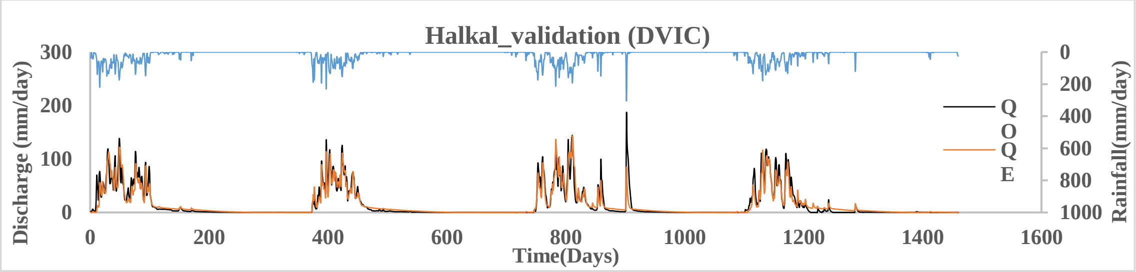
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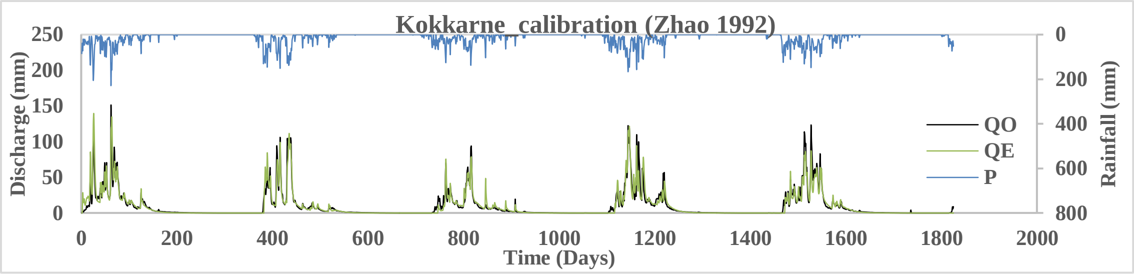
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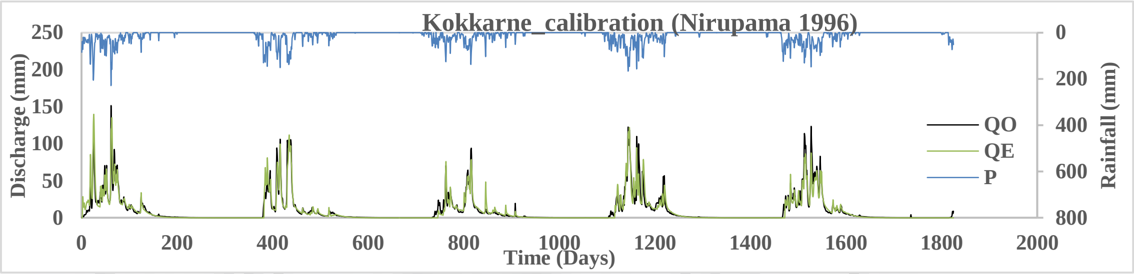
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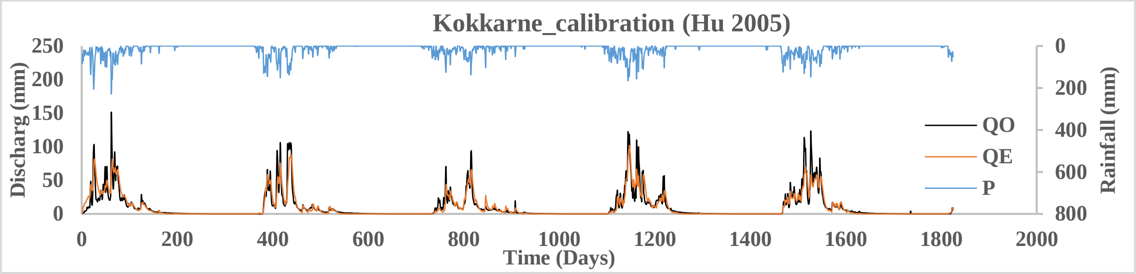
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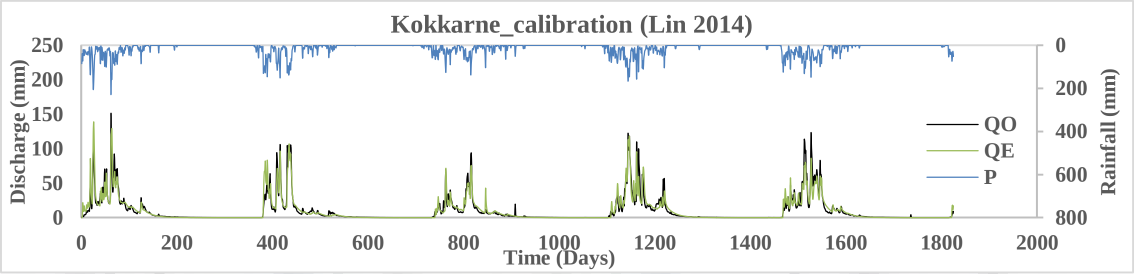
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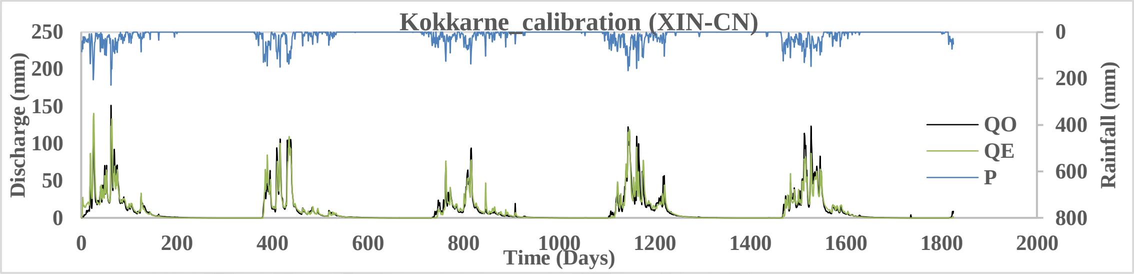
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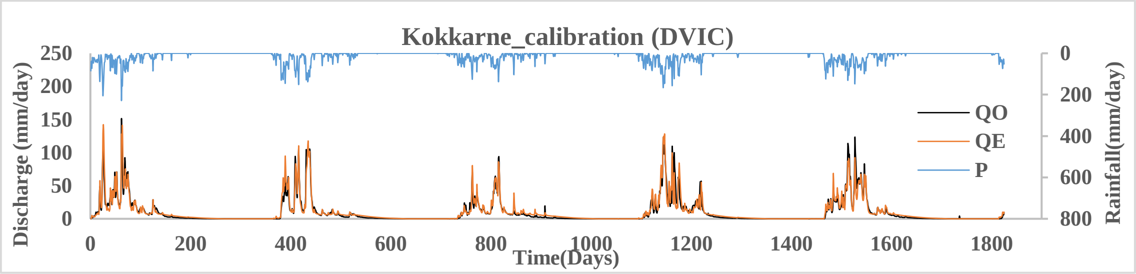
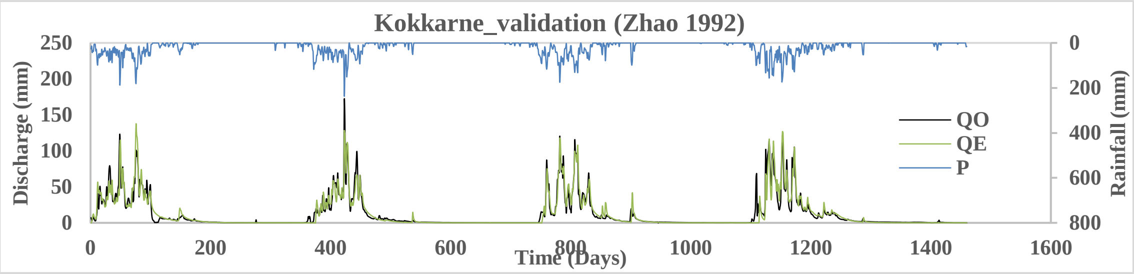
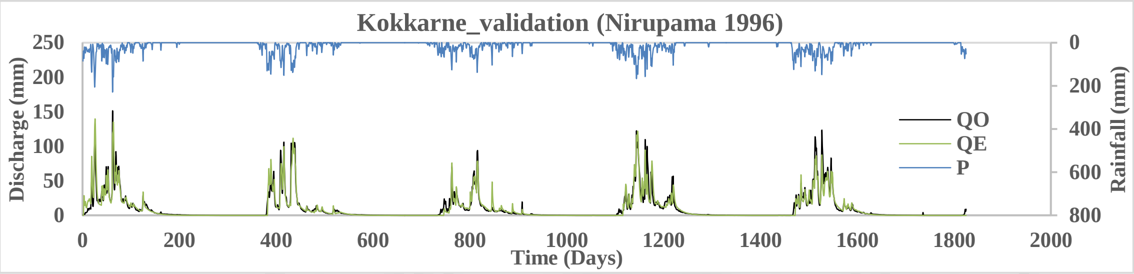
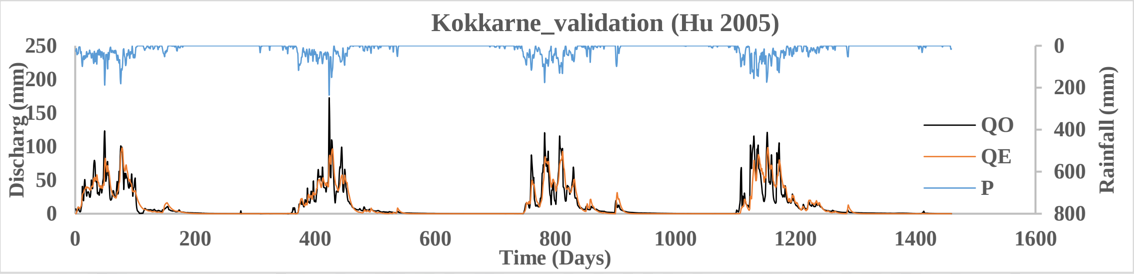
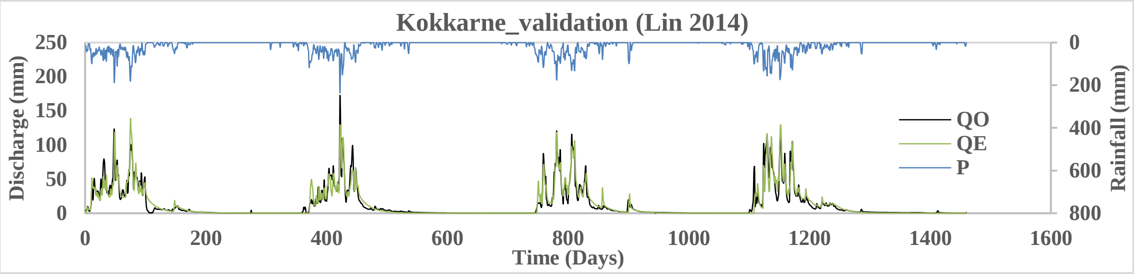

Kokkarne_calibration (DVIC)


Kokkarne_validation (Zhao 1992)
Discharge (mm)
Rainfall (mm)
Time (Days)
250
200
150
100
50
0
0
200
400
600
800
0
200
400
600
800
1000
1200
1400
1600
QO
QE
P


Kokkarne_validation (Nirupama 1996)
Discharge (mm)
Rainfall (mm)
Time (Days)
250
200
150
100
50
0
0
200
400
600
800
0
200
400
600
800
1000
1200
1400
1600
1800
2000
QO
QE
P


Kokkarne_validation (Hu 2005)
Discharg (mm)
Rainfall (mm)
Time (Days)
250
200
150
100
50
0
0
200
400
600
800
0
200
400
600
800
1000
1200
1400
1600
QO
QE
P


Kokkarne_validation (Lin 2014)
Discharge (mm)
Rainfall (mm)
Time (Days)
250
200
150
100
50
0
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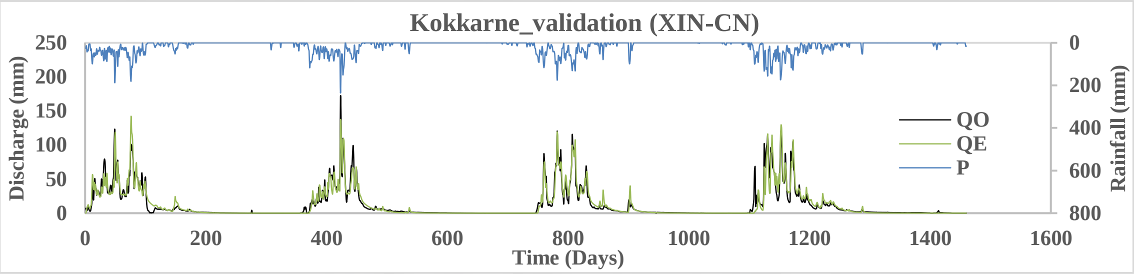
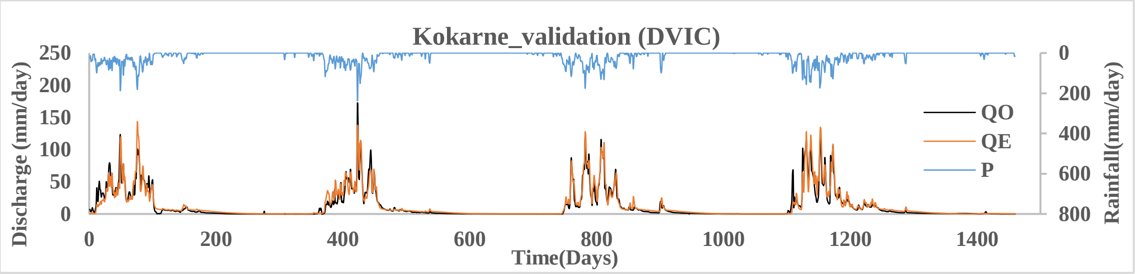
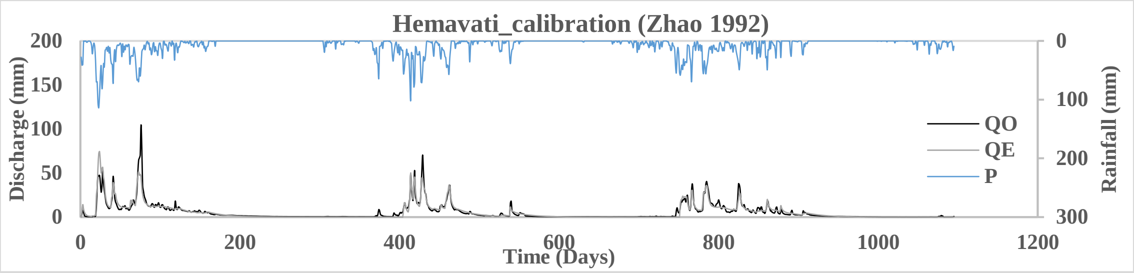
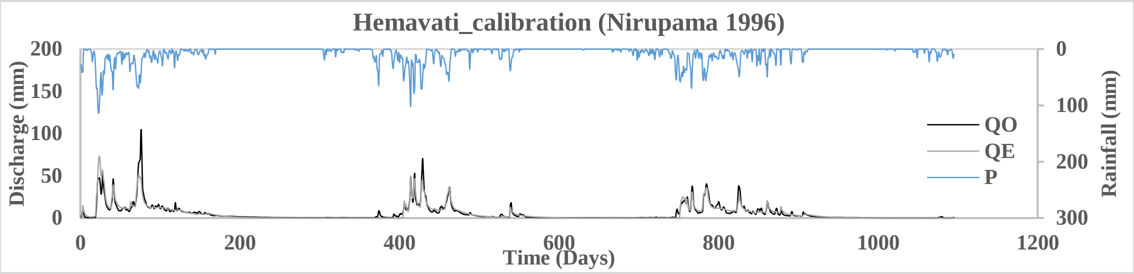
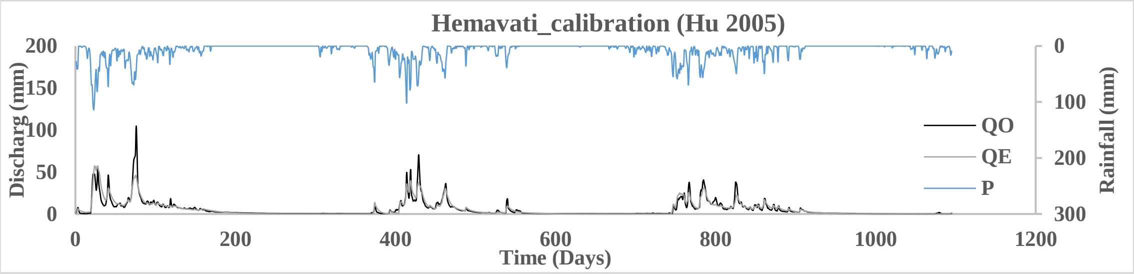
400
600
800
0
200
400
600
800
1000
1200
1400
1600
QO
QE
P

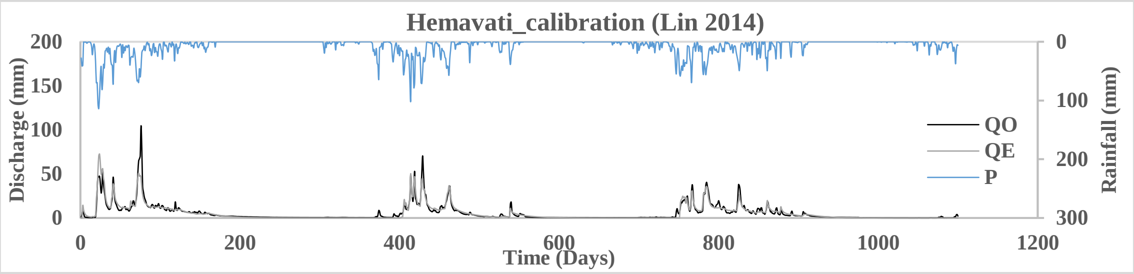

Kokkarne_validation (XIN-CN)
Discharge (mm)
Rainfall (mm)
Time (Days)
250
200
150
100
50
0
0
200
400
600
800
0
200
400
600
800
1000
1200
1400
1600
QO
QE
P

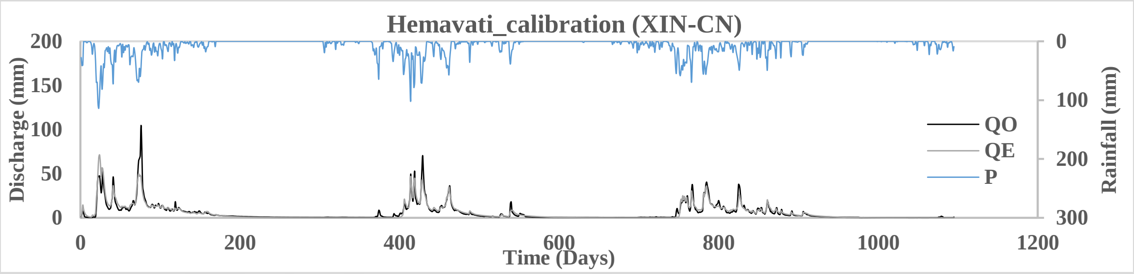

Kokarne_validation (DVIC)
Discharge (mm/day)
Rainfall(mm/day)
Time(Days)
250
200
150
100
50
0
0
200
400
600
800
0
200
400
600
800
1000
1200
1400
QO
QE
P

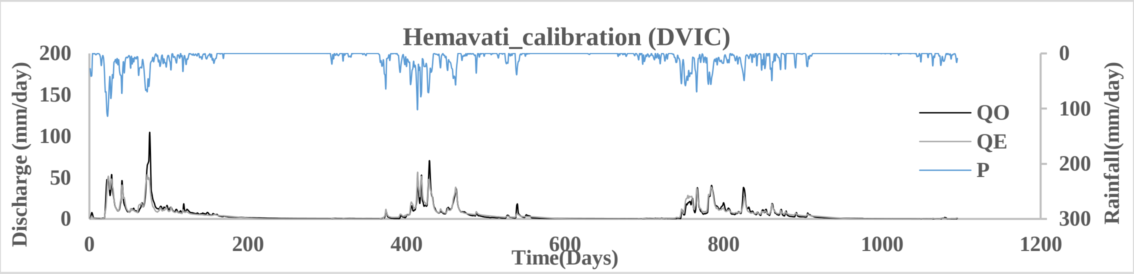

Hemavati_calibration (Zhao 1992)
Discharge (mm)
200
150
100
50
0
0
200
400
600
800
1000
1200
Time (Days)
0
100
200
300
Rainfall (mm)
QO
QE
P

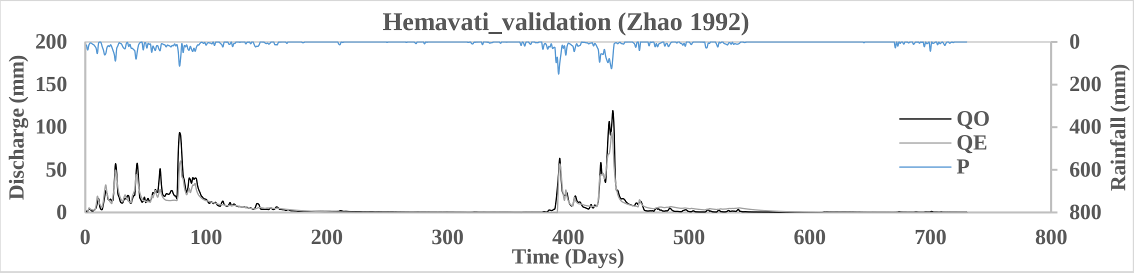

Hemavati_calibration (Nirupama 1996)
Discharge (mm)
200
150
100
50
0
0
200
400
600
800
1000
1200
Time (Days)
0
100
200
300
Rainfall (mm)
QO
QE
P


Hemavati_calibration (Hu 2005)
Discharg (mm)
200
150
100
50
0
0
200
400
600
800
1000
1200
Time (Days)
0
100
200
300
Rainfall (mm)
QO
QE
P


Hemavati_calibration (Lin 2014)
Discharge (mm)
200
150
100
50
0
0
200
400
600
800
1000
1200
Time (Days)
0
100
200
300
Rainfall (mm)
QO
QE
P


Hemavati_calibration (XIN-CN)
Discharge (mm)
200
150
100
50
0
0
200
400
600
800
1000
1200
Time (Days)
0
100
200
300
Rainfall (mm)
QO
QE
P


Hemavati_calibration (DVIC)
Discharge (mm/day)
200
150
100
50
0
0
200
400
600
800
1000
1200
Time(Days)
0
100
200
300
Rainfall(mm/day)
QO
QE
P


Hemavati_validation (Zhao 1992)
Discharge (mm)
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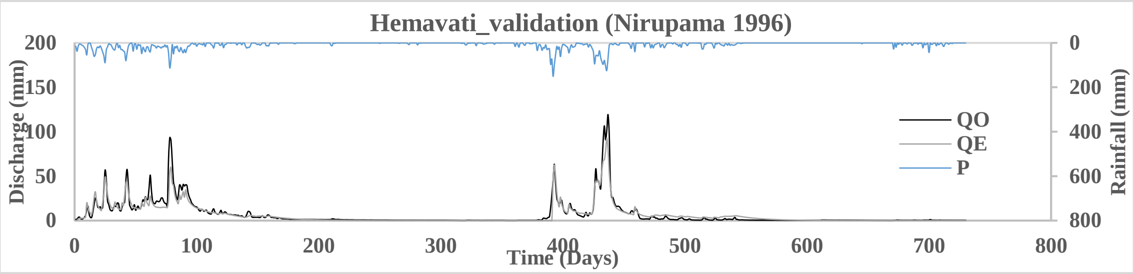
150
100
50
0
Rainfall (mm)
0
200
400
600
800
0
100
200
300
400
500
600
700
800
Time (Days)
QO
QE
P


Hemavati_validation (Nirupama 1996)
Discharge (mm)
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150
100
50
0
Rainfall (mm)
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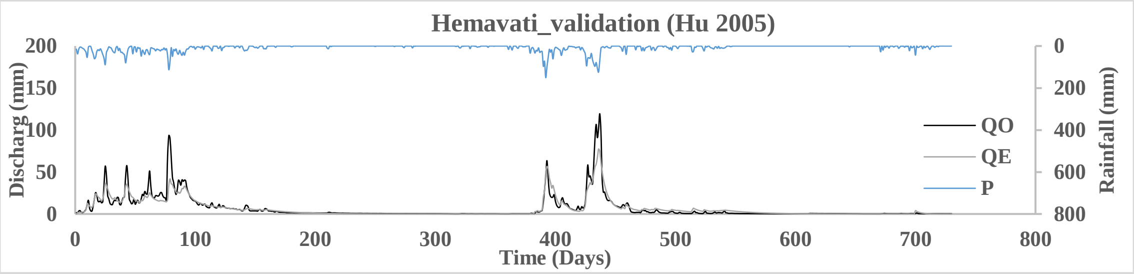
800
0
100
200
300
400
500
600
700
800
Time (Days)
QO
QE
P


Hemavati_validation (Hu 2005)
Discharg (mm)
200
150
100
50
0
Rainfall (mm)
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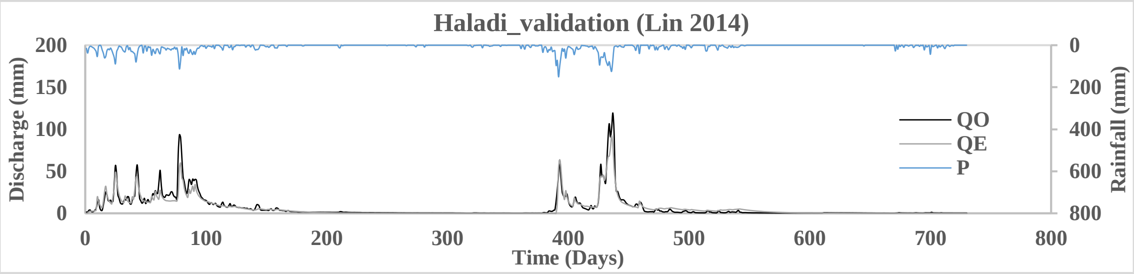
400
600
800
0
100
200
300
400
500
600
700
800
Time (Days)
QO
QE
P


Haladi_validation (Lin 2014)
Discharge (mm)
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150
100
50
0
Rainfall (mm)
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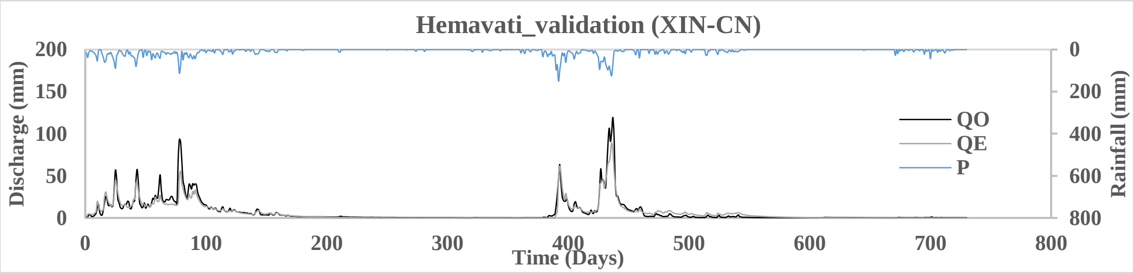
600
800
0
100
200
300
400
500
600
700
800
Time (Days)
QO
QE
P


Hemavati_validation (XIN-CN)
Discharge (mm)
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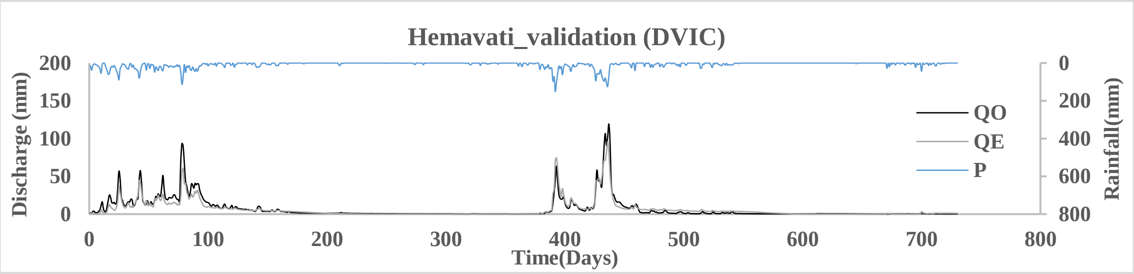
150
100
50
0
Rainfall (mm)
0
200
400
600
800
0
100
200
300
400
500
600
700
800
Time (Days)
QO
QE
P


Hemavati_validation (DVIC)
Discharge (mm)
200
150
100
50
0
Rainfall(mm)
0
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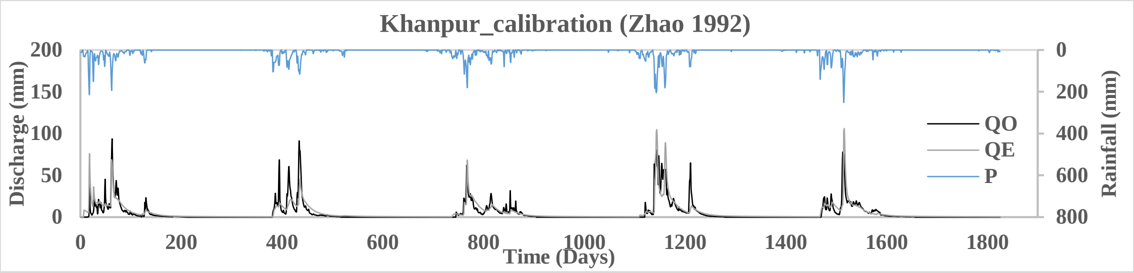
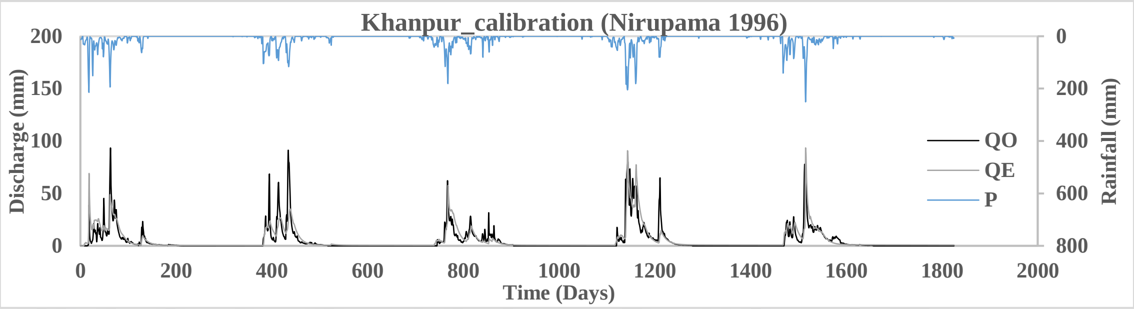
400
600
800
0
100
200
300
400
500
600
700
800
Time(Days)
QO
QE
P


Khanpur_calibration (Zhao 1992)
Discharge (mm)
200
150
100
50
0
0
200
400
600
800
1000
1200
1400
1600
1800
Time (Days)
Rainfall (mm)
0
200
400
600
800
QO
QE
P


Khanpur_calibration (Nirupama 1996)
Discharge (mm)
200
150
100
50
0
0
200
400
600
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1400
1600
1800
2000
Time (Days)
Rainfall (mm)
0
200
400
600
800
QO
QE
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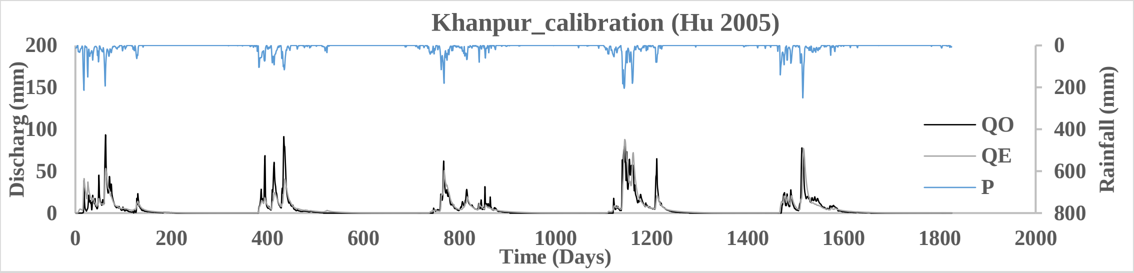
Khanpur_calibration (Hu 2005)
Discharg (mm)
200
150
100
50
0
0
200
400
600
800
1000
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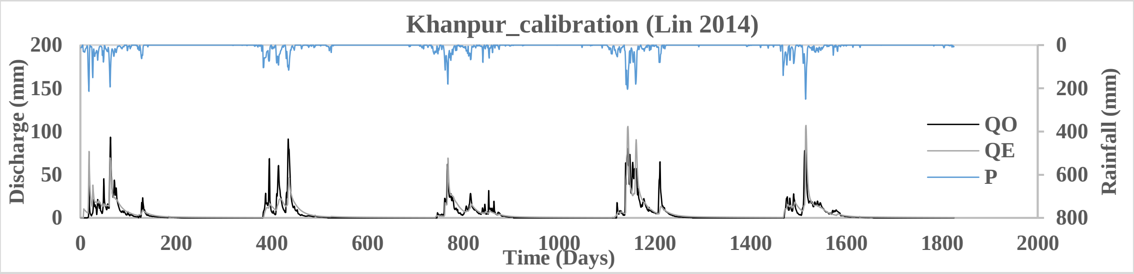
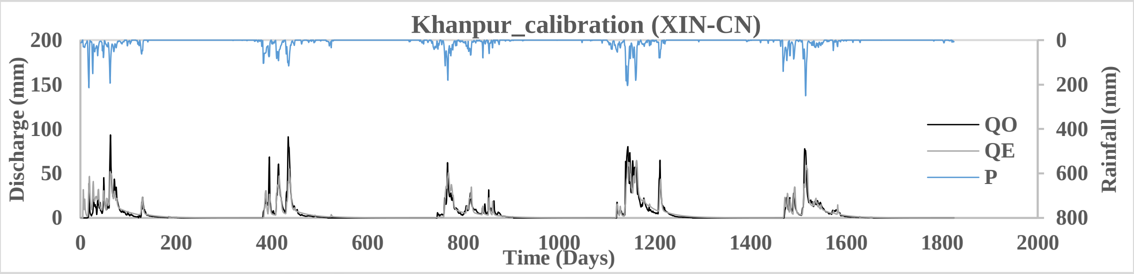
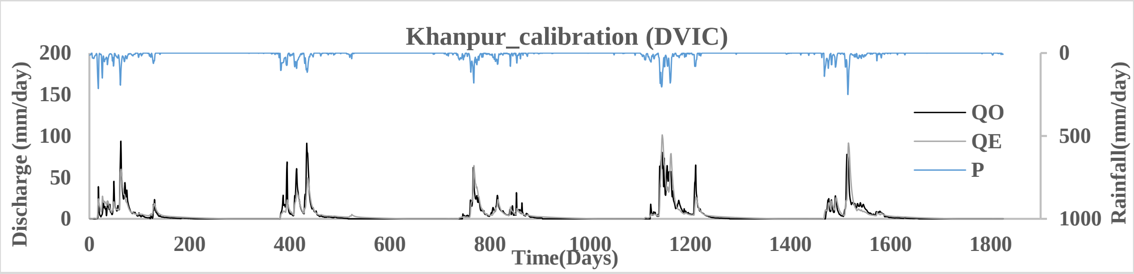
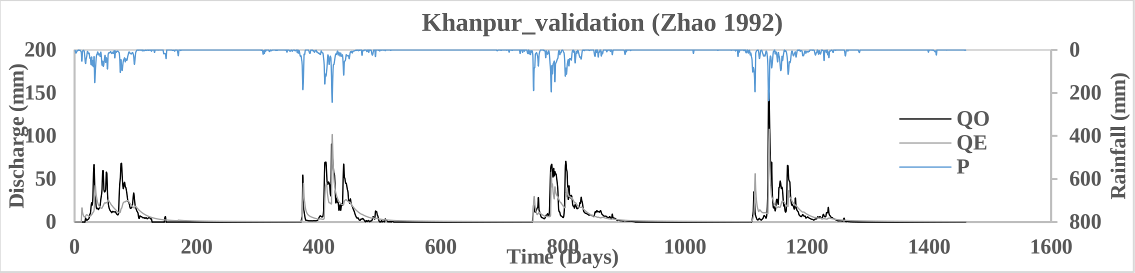
1400
1600
1800
2000
Time (Days)
Rainfall (mm)
0
200
400
600
800
QO
QE
P


Khanpur_calibration (Lin 2014)
Discharge (mm)
200
150
100
50
0
0
200
400
600
800
1000
1200
1400
1600
1800
2000
Time (Days)
Rainfall (mm)
0
200
400
600
800
QO
QE
P


Khanpur_calibration (XIN-CN)
Discharge (mm)
200
150
100
50
0
0
200
400
600
800
1000
1200
1400
1600
1800
2000
Time (Days)
Rainfall (mm)
0
200
400
600
800
QO
QE
P


Khanpur_calibration (DVIC)
Discharge (mm/day)
200
150
100
50
0
0
200
400
600
800
1000
1200
1400
1600
1800
Time(Days)
Rainfall(mm/day)
0
500
1000
QO
QE
P


Khanpur_validation (Zhao 1992)
Discharge (mm)
200
150
100
50
0
Rainfall (mm)
0
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400
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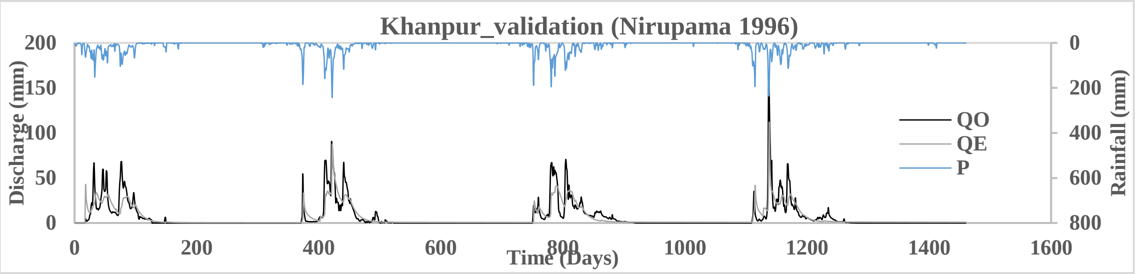
800
QO
QE
P
0
200
400
600
800
1000
1200
1400
1600
Time (Days)


Khanpur_validation (Nirupama 1996)
Discharge (mm)
200
150
100
50
0
Rainfall (mm)
0
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800
QO
QE
P
0
200
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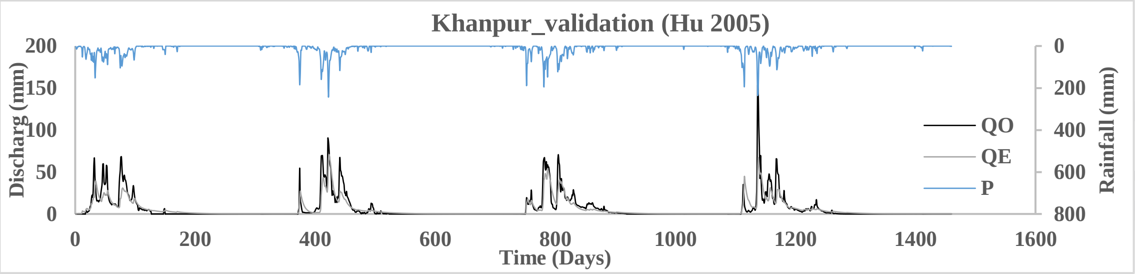
600
800
1000
1200
1400
1600
Time (Days)


Khanpur_validation (Hu 2005)
Discharg (mm)
200
150
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50
0
Rainfall (mm)
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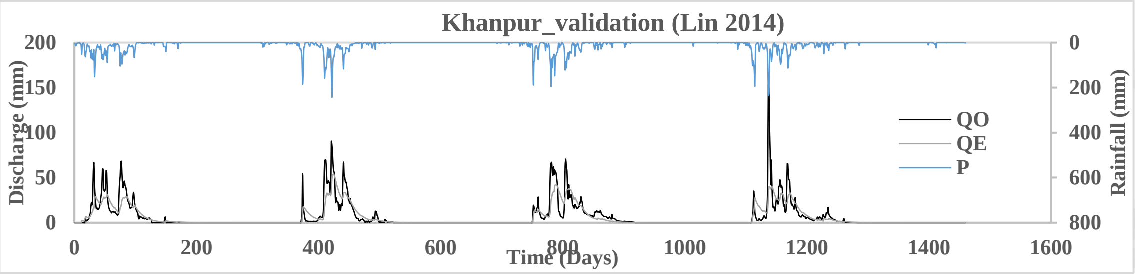
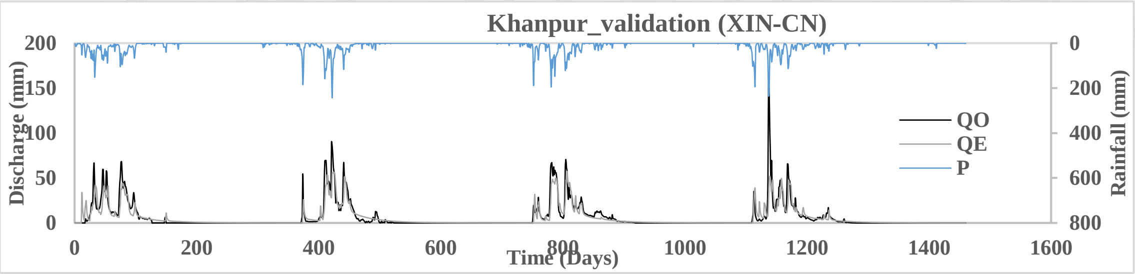
800
QO
QE
P
0
200
400
600
800
1000
1200
1400
1600
Time (Days)


Khanpur_validation (Lin 2014)
Discharge (mm)
200
150
100
50
0
Rainfall (mm)
0
200
400
600
800
QO
QE
P
0
200
400
600
800
1000
1200
1400
1600
Time (Days)


Khanpur_validation (XIN-CN)
Discharge (mm)
200
150
100
50
0
Rainfall (mm)
0
200
400
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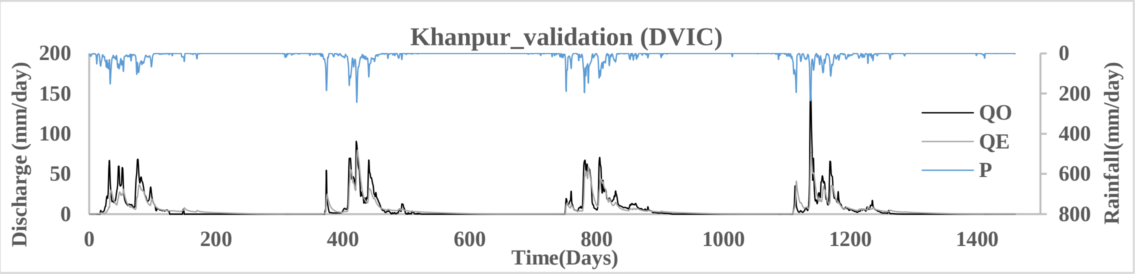
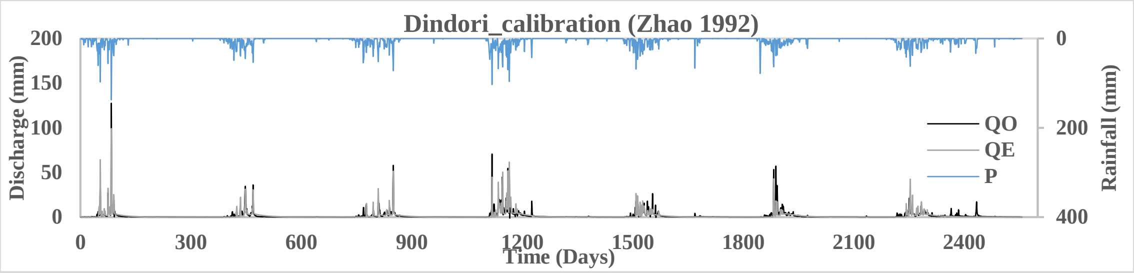
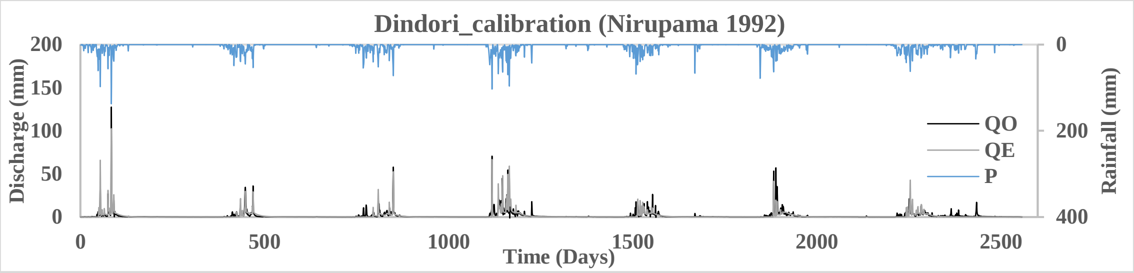
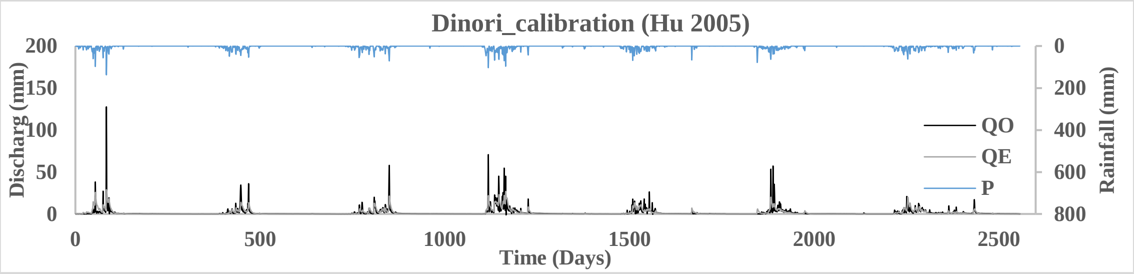
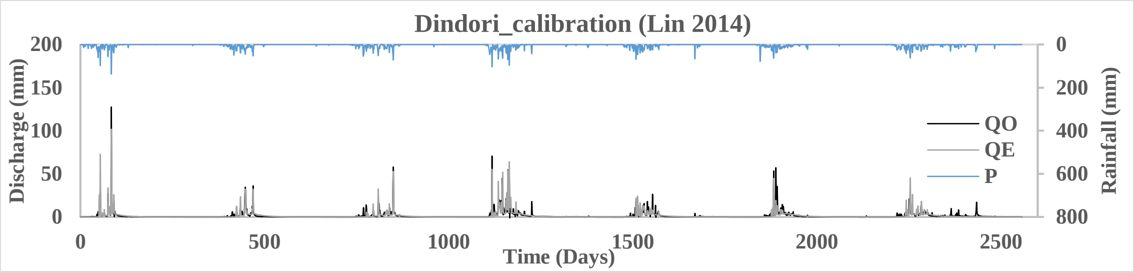
800
QO
QE
P
0
200
400
600
800
1000
1200
1400
1600
Time (Days)

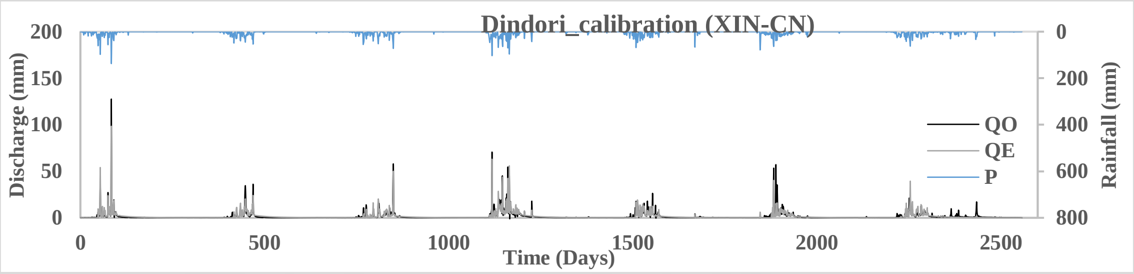

Khanpur_validation (DVIC)
Discharge (mm/day)
200
150
100
50
0
Rainfall(mm/day)
0
200
400
600
800
QO
QE
P
0
200
400
600
800
1000
1200
1400
Time(Days)

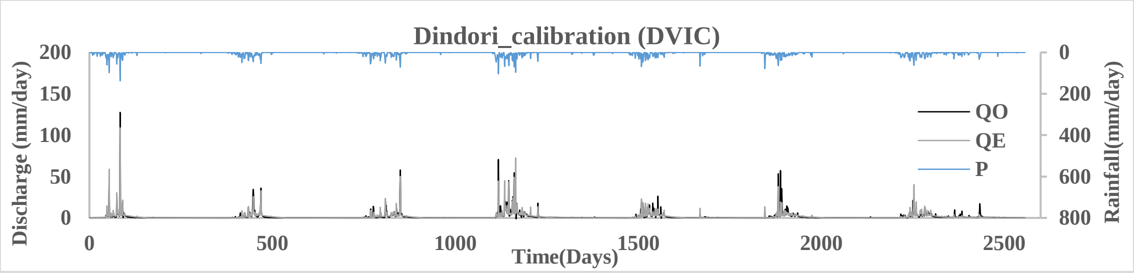

Dindori_calibration (Zhao 1992)
Discharge (mm)
200
150
100
50
0
0
300
600
900
1200
1500
1800
2100
2400
Time (Days)
QO
QE
P
0
200
400
Rainfall (mm)

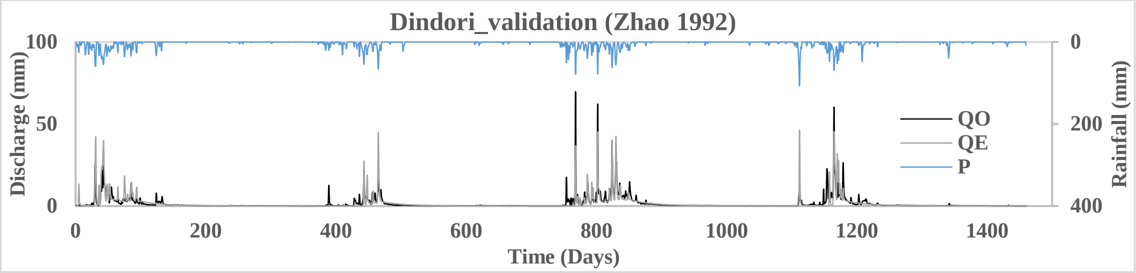

Dindori_calibration (Nirupama 1992)
Discharge (mm)
200
150
100
50
0
0
500
1000
1500
2000
2500
Time (Days)
QO
QE
P
0
200
400
Rainfall (mm)

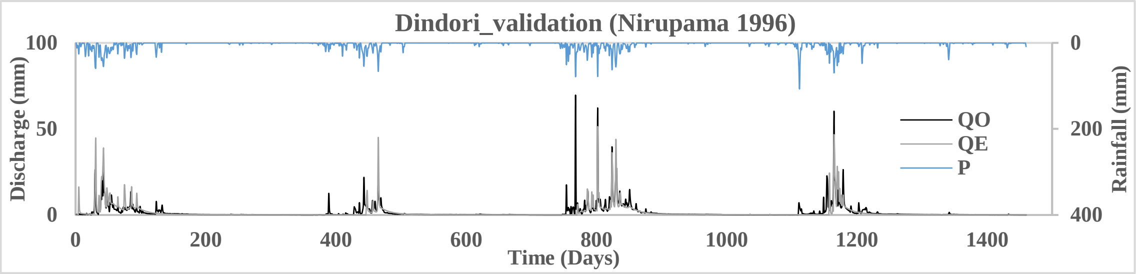

Dinori_calibration (Hu 2005)
Discharg (mm)
200
150
100
50
0
0
500
1000
1500
2000
2500
Time (Days)
QO
QE
P
0
200
400
600
800
Rainfall (mm)

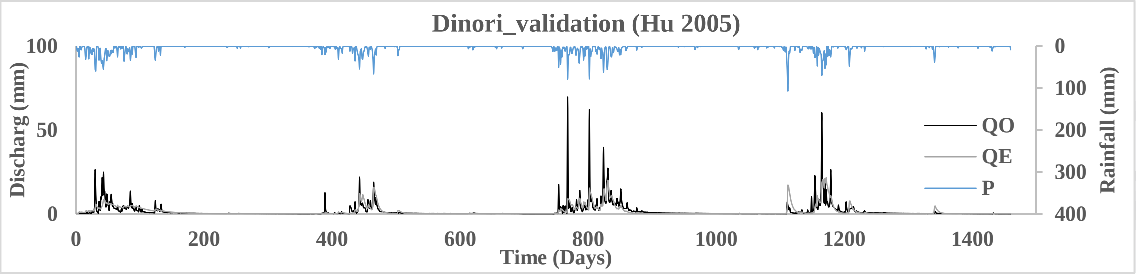

Dindori_calibration (Lin 2014)
Discharge (mm)
200
150
100
50
0
0
500
1000
1500
2000
2500
Time (Days)
QO
QE
P
0
200
400
600
800
Rainfall (mm)


Dindori_calibration (XIN-CN)
Discharge (mm)
200
150
100
50
0
0
500
1000
1500
2000
2500
Time (Days)
QO
QE
P
0
200
400
600
800
Rainfall (mm)


Dindori_calibration (DVIC)
Discharge (mm/day)
200
150
100
50
0
0
500
1000
1500
2000
2500
Time(Days)
QO
QE
P
0
200
400
600
800
Rainfall(mm/day)


Dindori_validation (Zhao 1992)
Discharge (mm)
100
50
0
Rainfall (mm)
0
200
400
QO
QE
P
0
200
400
600
800
1000
1200
1400
Time (Days)


Dindori_validation (Nirupama 1996)
Discharge (mm)
100
50
0
Rainfall (mm)
0
200
400
QO
QE
P
0
200
400
600
800
1000
1200
1400
Time (Days)


Dinori_validation (Hu 2005)
Discharg (mm)
100
50
0
Rainfall (mm)
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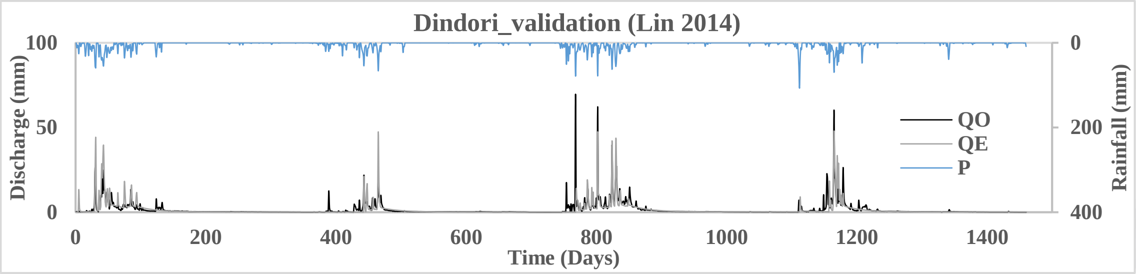
100
200
300
400
QO
QE
P
0
200
400
600
800
1000
1200
1400
Time (Days)


Dindori_validation (Lin 2014)
Discharge (mm)
100
50
0
Rainfall (mm)
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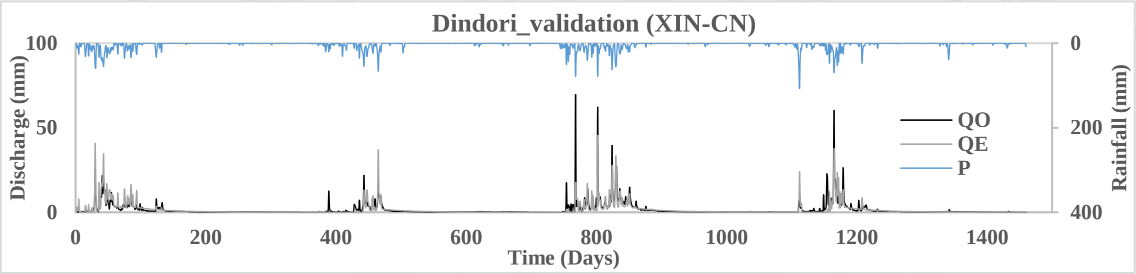
200
400
QO
QE
P
0
200
400
600
800
1000
1200
1400
Time (Days)


Dindori_validation (XIN-CN)
Discharge (mm)
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50
0
Rainfall (mm)
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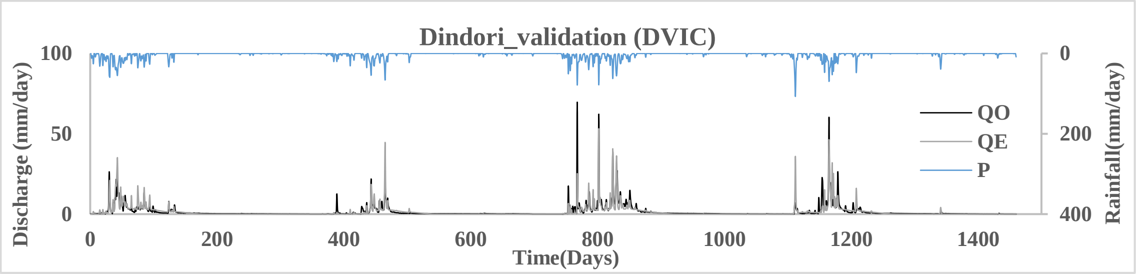
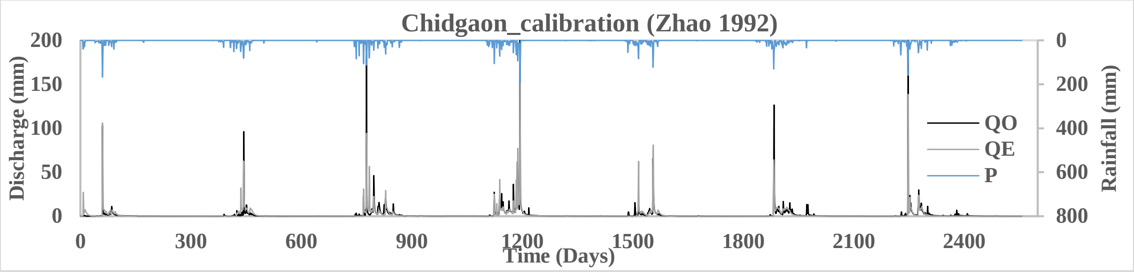
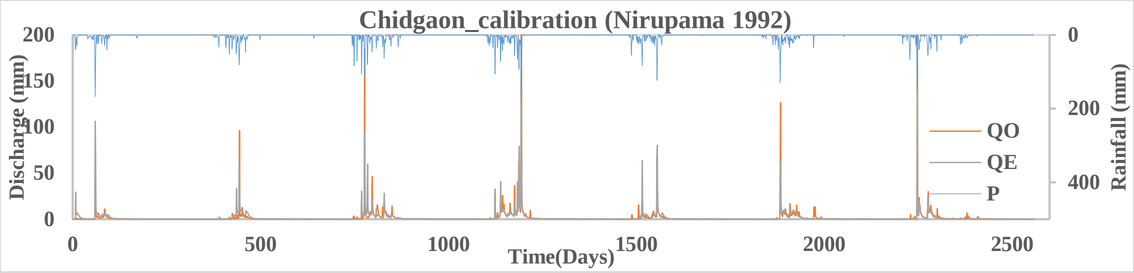
200
400
QO
QE
P
0
200
400
600
800
1000
1200
1400
Time (Days)


Dindori_validation (DVIC)
Discharge (mm/day)
100
50
0
Rainfall(mm/day)
0
200
400
QO
QE
P
0
200
400
600
800
1000
1200
1400
Time(Days)


Chidgaon_calibration (Zhao 1992)
Discharge (mm)
200
150
100
50
0
0
300
600
900
1200
1500
1800
2100
2400
Time (Days)
Rainfall (mm)
0
200
400
600
800
QO
QE
P


Chidgaon_calibration (Nirupama 1992)
Discharge (mm)
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50
0
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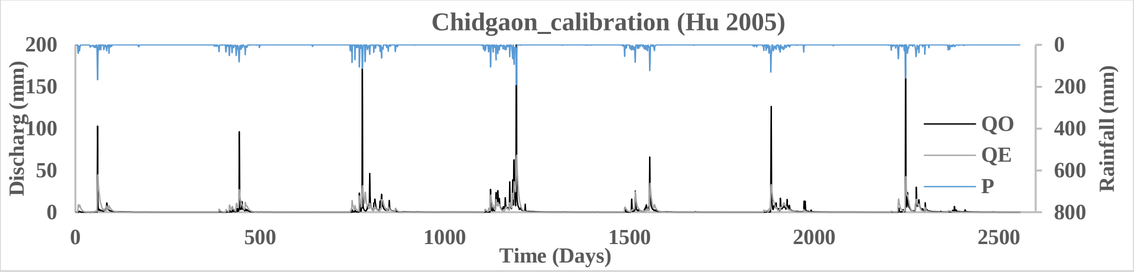
500
1000
1500
2000
2500
Time(Days)
Rainfall (mm)
0
200
400
QO
QE
P


Chidgaon_calibration (Hu 2005)
Discharg (mm)
200
150
100
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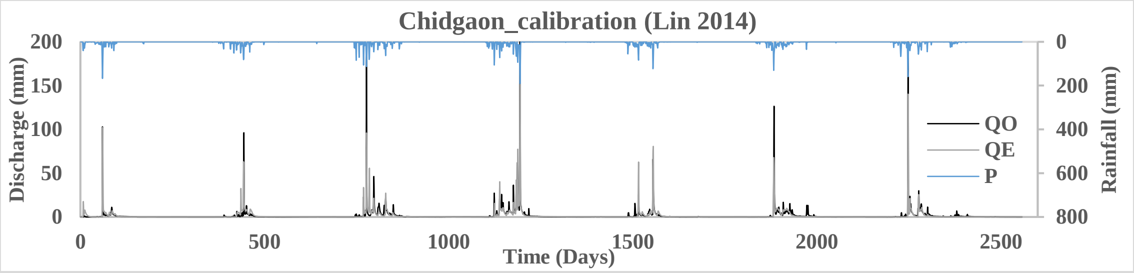
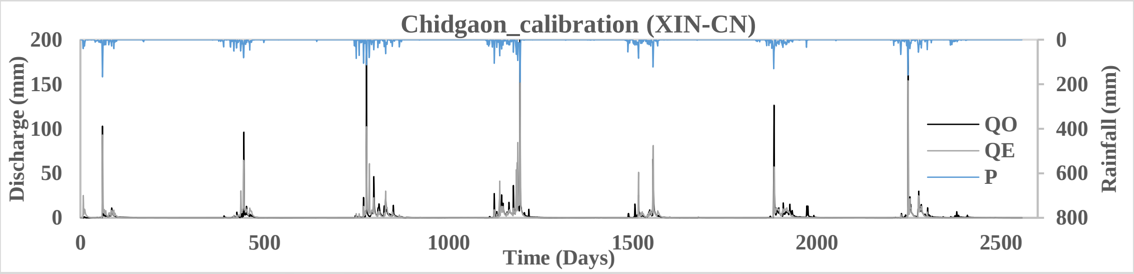
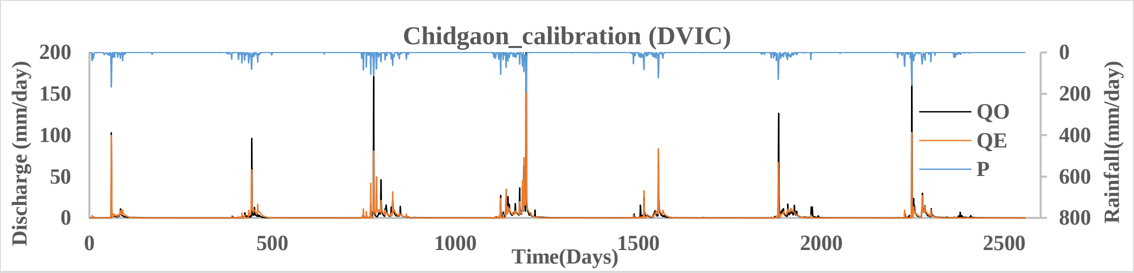
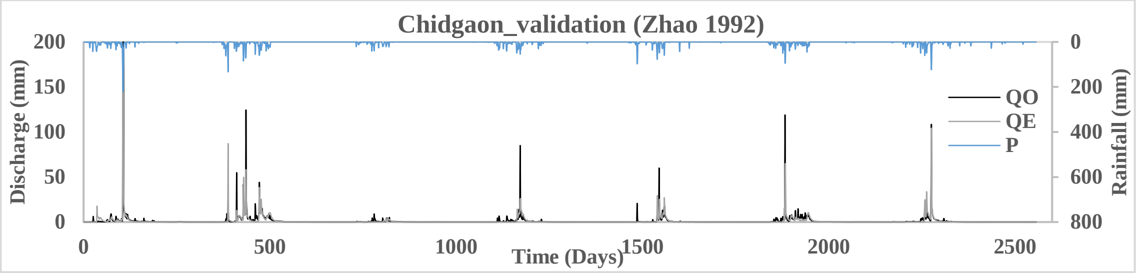
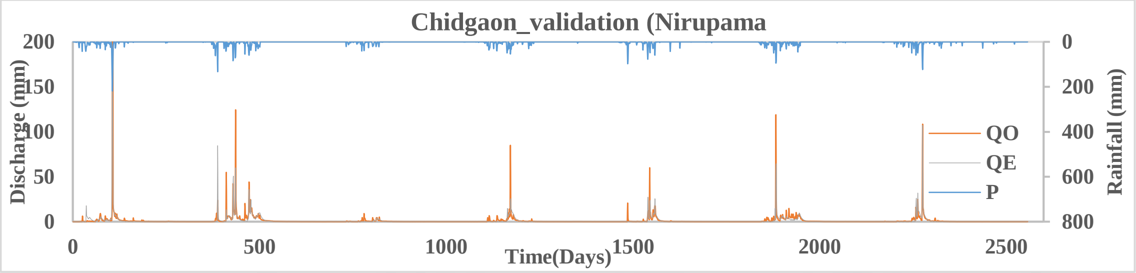
1500
2000
2500
Time (Days)
Rainfall (mm)
0
200
400
600
800
QO
QE
P

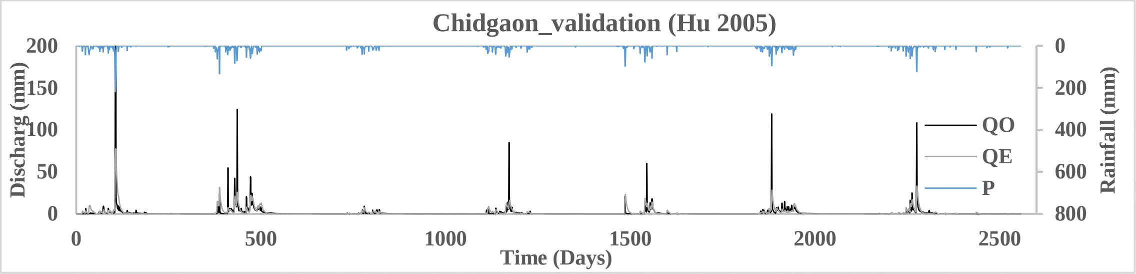

Chidgaon_calibration (Lin 2014)
Discharge (mm)
200
150
100
50
0
0
500
1000
1500
2000
2500
Time (Days)
Rainfall (mm)
0
200
400
600
800
QO
QE
P

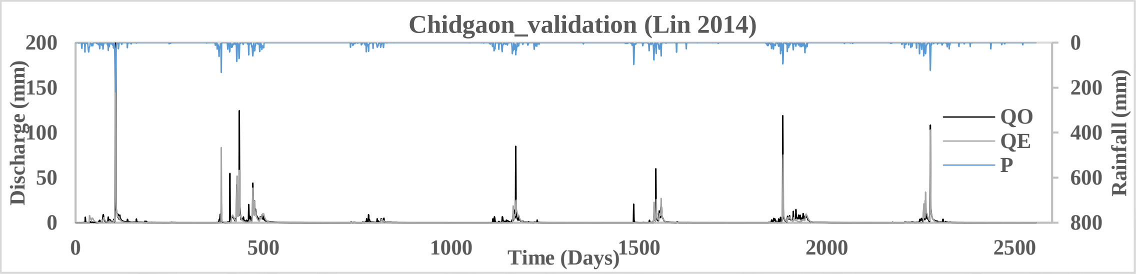

Chidgaon_calibration (XIN-CN)
Discharge (mm)
200
150
100
50
0
0
500
1000
1500
2000
2500
Time (Days)
Rainfall (mm)
0
200
400
600
800
QO
QE
P

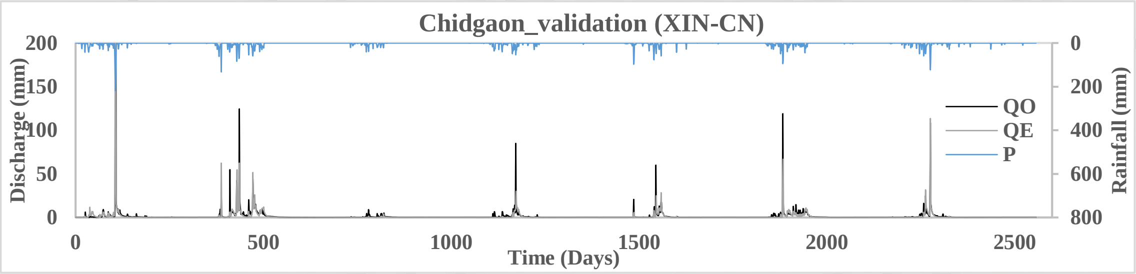

Chidgaon_calibration (DVIC)
Discharge (mm/day)
200
150
100
50
0
0
500
1000
1500
2000
2500
Time(Days)
Rainfall(mm/day)
0
200
400
600
800
QO
QE
P

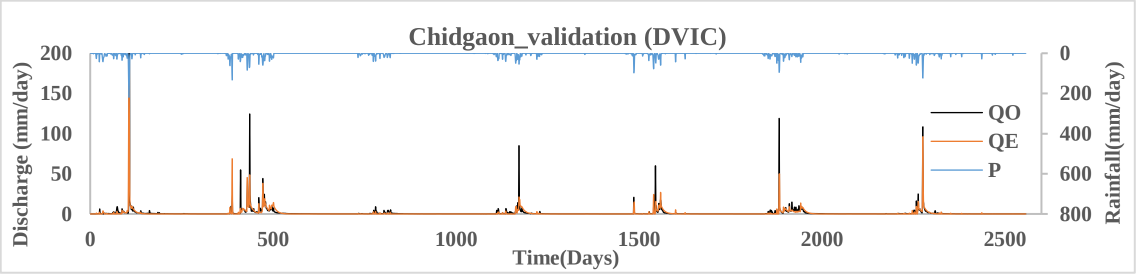

Chidgaon_validation (Zhao 1992)

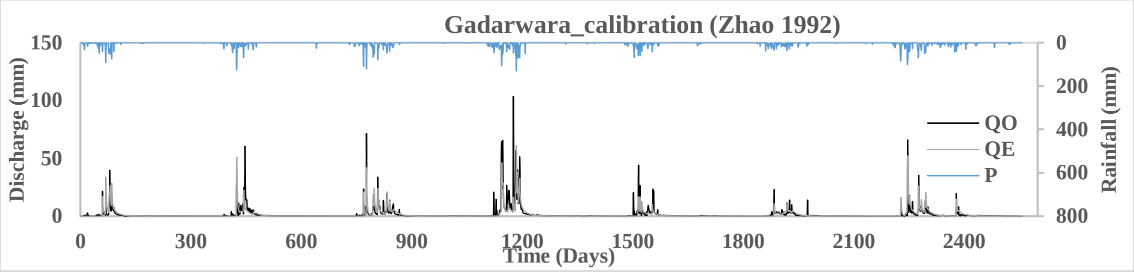

Chidgaon_validation (Nirupama

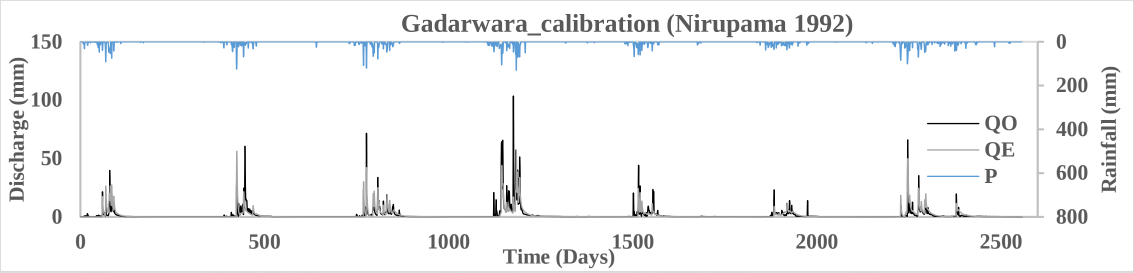

Chidgaon_validation (Hu 2005)

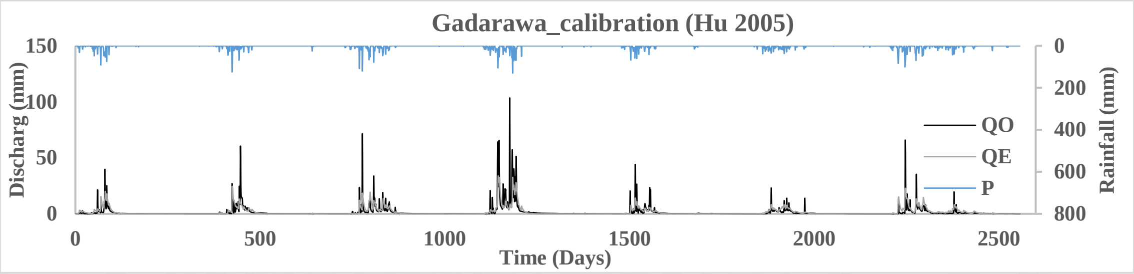

Chidgaon_validation (Lin 2014)


Chidgaon_validation (XIN-CN)


Chidgaon_validation (DVIC)


Gadarwara_calibration (Zhao 1992)
Discharge (mm)
150
100
50
0
Rainfall (mm)
0
200
400
600
800
QO
QE
P
0
300
600
900
1200
1500
1800
2100
2400
Time (Days)


Gadarwara_calibration (Nirupama 1992)
Discharge (mm)
150
100
50
0
Rainfall (mm)
0
200
400
600
800
QO
QE
P
0
500
1000
1500
2000
2500
Time (Days)


Gadarawa_calibration (Hu 2005)
Discharg (mm)
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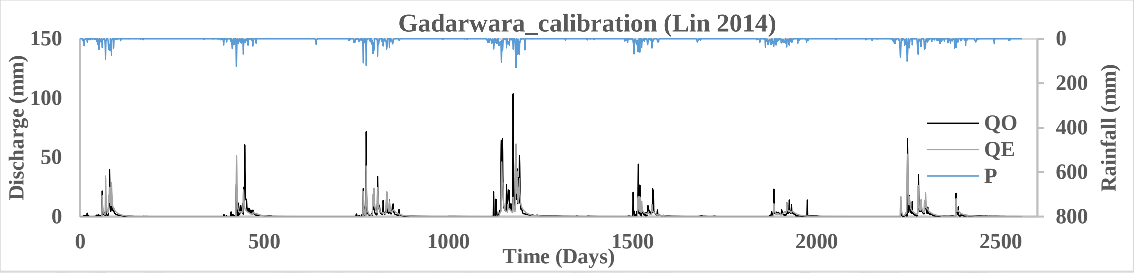
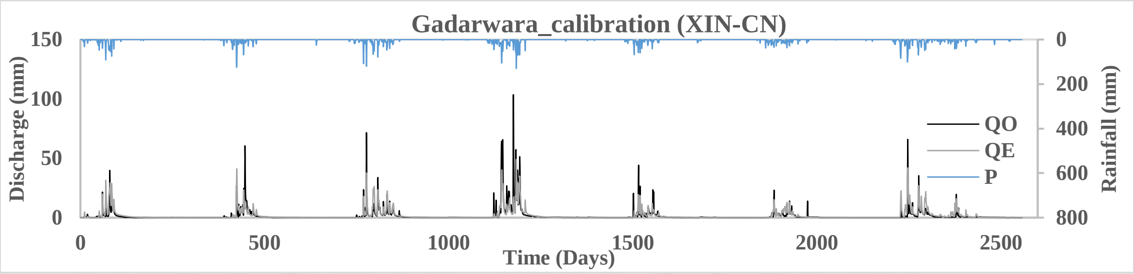
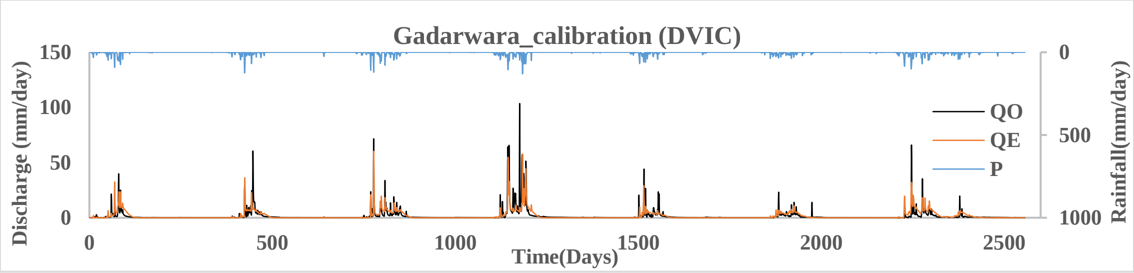
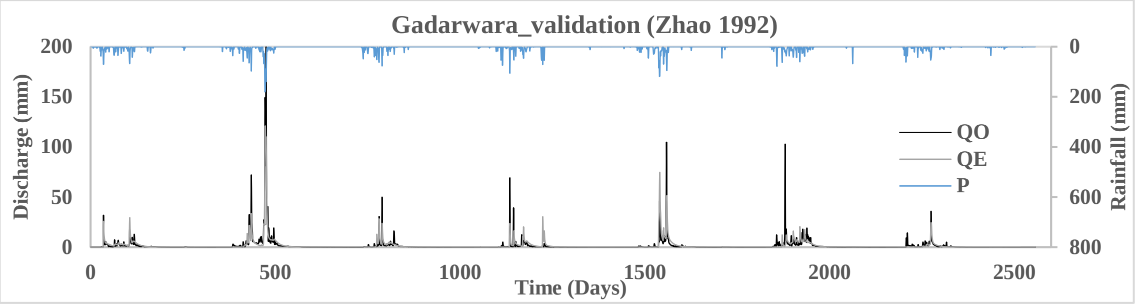
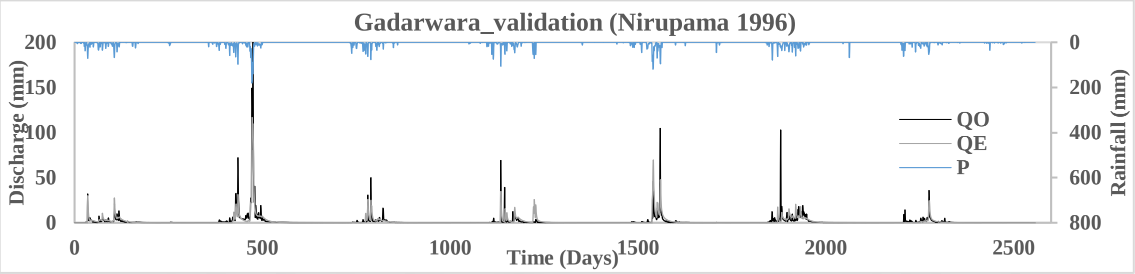
100
50
0
Rainfall (mm)
0
200
400
600
800
QO
QE
P
0
500
1000
1500
2000
2500
Time (Days)


Gadarwara_calibration (Lin 2014)
Discharge (mm)
150
100
50
0
Rainfall (mm)
0
200
400
600
800
QO
QE
P
0
500
1000
1500
2000
2500
Time (Days)


Gadarwara_calibration (XIN-CN)
Discharge (mm)
150
100
50
0
Rainfall (mm)
0
200
400
600
800
QO
QE
P
0
500
1000
1500
2000
2500
Time (Days)


Gadarwara_calibration (DVIC)
Discharge (mm/day)
150
100
50
0
Rainfall(mm/day)
0
500
1000
QO
QE
P
0
500
1000
1500
2000
2500
Time(Days)


Gadarwara_validation (Zhao 1992)
Discharge (mm)
200
150
100
50
0
Rainfall (mm)
0
200
400
600
800
QO
QE
P
0
500
1000
1500
2000
2500
Time (Days)


Gadarwara_validation (Nirupama 1996)
Discharge (mm)
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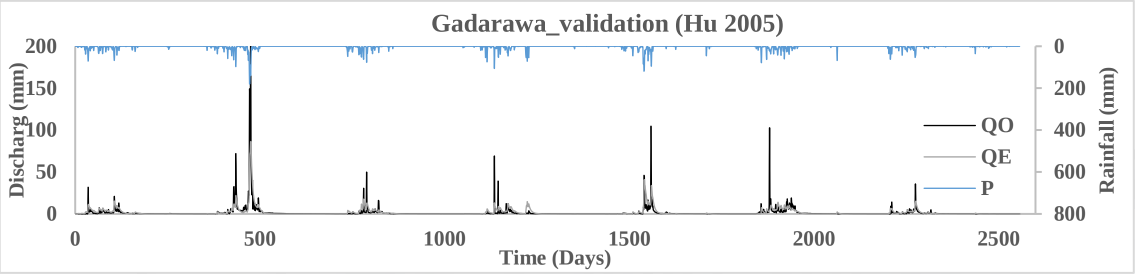
150
100
50
0
Rainfall (mm)
0
200
400
600
800
QO
QE
P
0
500
1000
1500
2000
2500
Time (Days)


Gadarawa_validation (Hu 2005)
Discharg (mm)
200
150
100
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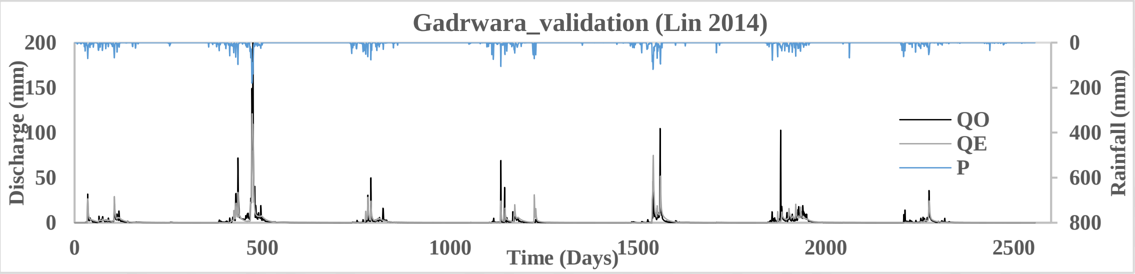
Rainfall (mm)
0
200
400
600
800
QO
QE
P
0
500
1000
1500
2000
2500
Time (Days)


Gadrwara_validation (Lin 2014)
Discharge (mm)
200
150
100
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Rainfall (mm)
0
200
400
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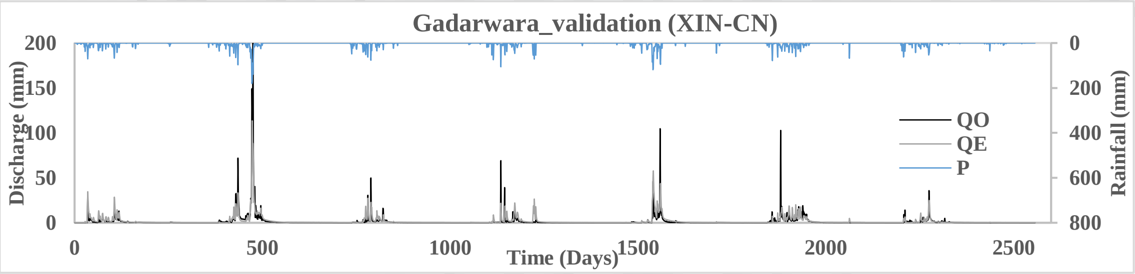
800
QO
QE
P
0
500
1000
1500
2000
2500
Time (Days)


Gadarwara_validation (XIN-CN)
Discharge (mm)
200
150
100
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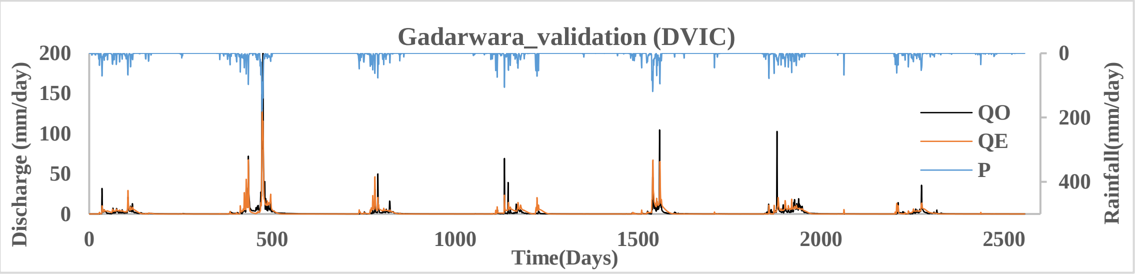
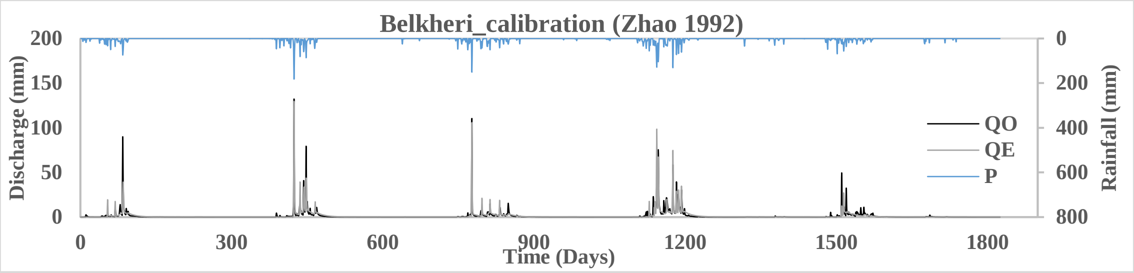
Rainfall (mm)
0
200
400
600
800
QO
QE
P
0
500
1000
1500
2000
2500
Time (Days)


Gadarwara_validation (DVIC)
Discharge (mm/day)
200
150
100
50
0
Rainfall(mm/day)
0
200
400
QO
QE
P
0
500
1000
1500
2000
2500
Time(Days)


Belkheri_calibration (Zhao 1992)
Discharge (mm)
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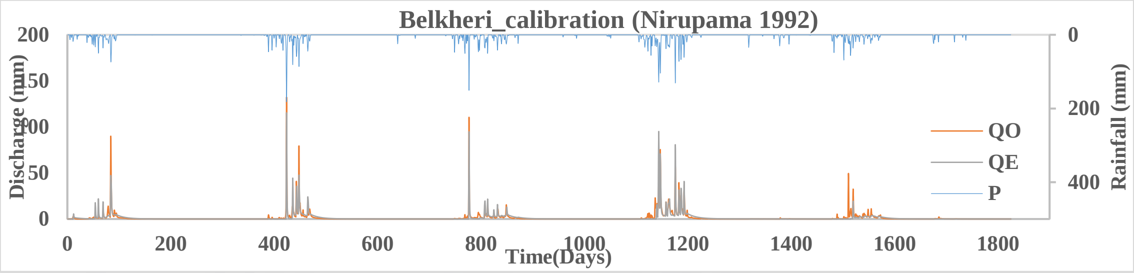
150
100
50
0
0
300
600
900
1200
1500
1800
Time (Days)
Rainfall (mm)
0
200
400
600
800
QO
QE
P


Belkheri_calibration (Nirupama 1992)
Discharge (mm)
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100
50
0
0
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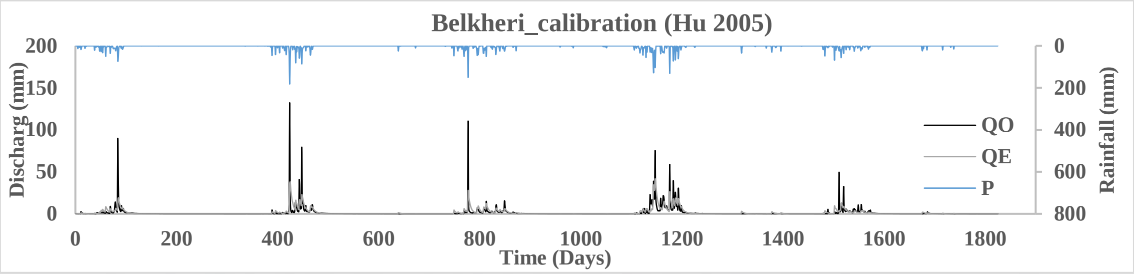
400
600
800
1000
1200
1400
1600
1800
Time(Days)
Rainfall (mm)
0
200
400
QO
QE
P


Belkheri_calibration (Hu 2005)
Discharg (mm)
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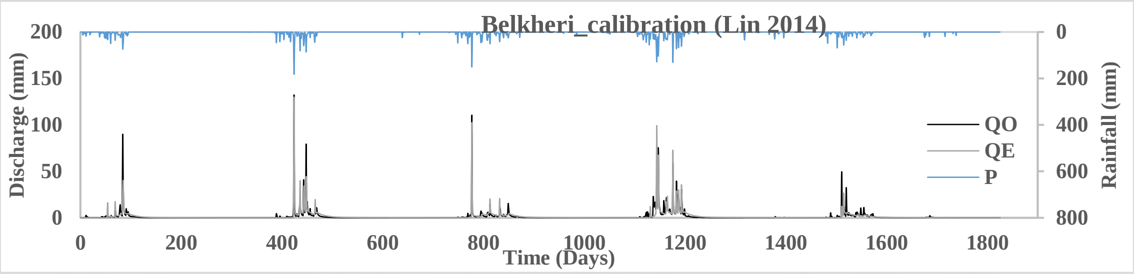
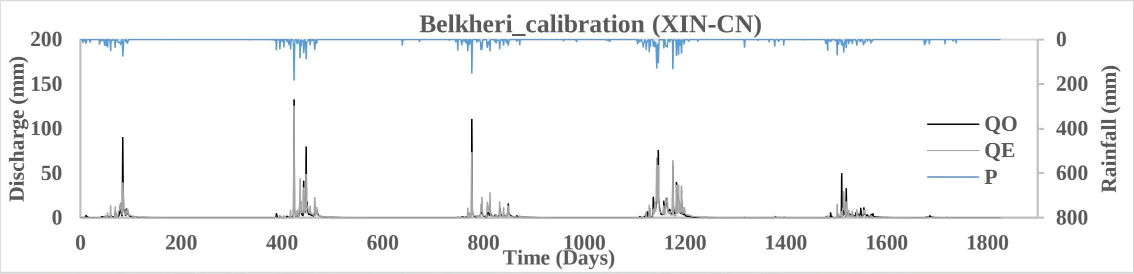
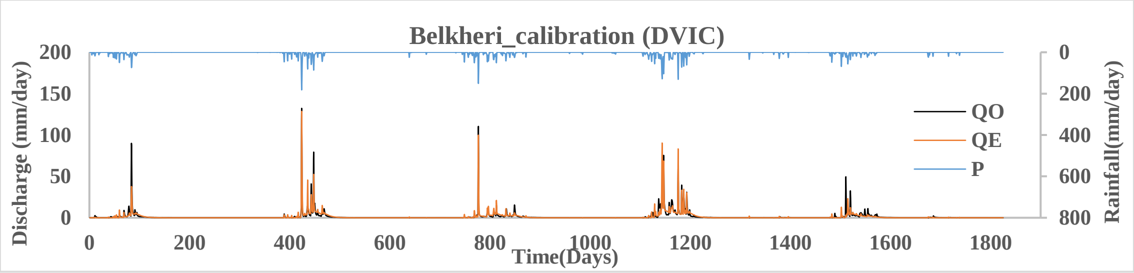
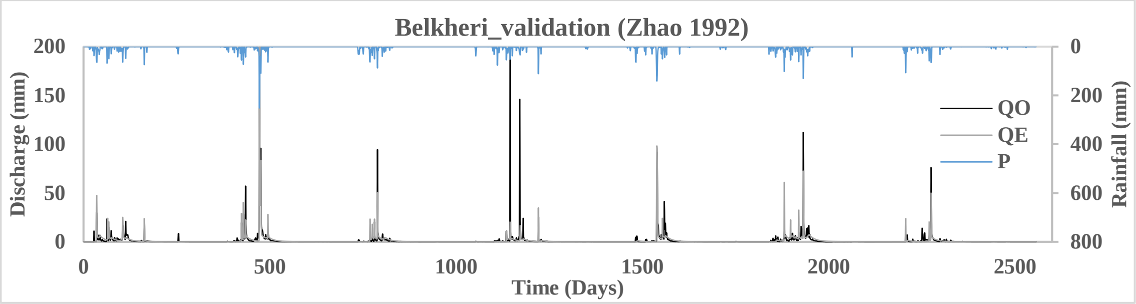
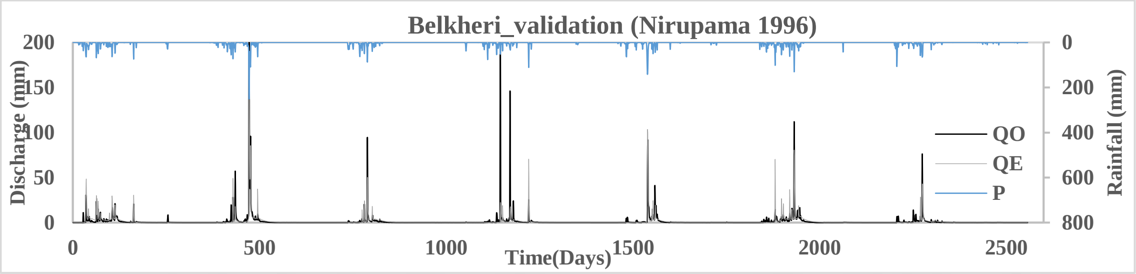
150
100
50
0
0
200
400
600
800
1000
1200
1400
1600
1800
Time (Days)
Rainfall (mm)
0
200
400
600
800
QO
QE
P


Belkheri_calibration (Lin 2014)
Discharge (mm)
200
150
100
50
0
0
200
400
600
800
1000
1200
1400
1600
1800
Time (Days)
Rainfall (mm)
0
200
400
600
800
QO
QE
P


Belkheri_calibration (XIN-CN)
Discharge (mm)
200
150
100
50
0
0
200
400
600
800
1000
1200
1400
1600
1800
Time (Days)
Rainfall (mm)
0
200
400
600
800
QO
QE
P


Belkheri_calibration (DVIC)
Discharge (mm/day)
200
150
100
50
0
0
200
400
600
800
1000
1200
1400
1600
1800
Time(Days)
Rainfall(mm/day)
0
200
400
600
800
QO
QE
P


Belkheri_validation (Zhao 1992)
Discharge (mm)
Rainfall (mm)
Time (Days)
0
50
100
150
200
0
200
400
600
800
0
500
1000
1500
2000
2500
QO
QE
P


Belkheri_validation (Nirupama 1996)
Discharge (mm)
Rainfall (mm)
Time(Days)
0
50
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0
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400
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800
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1000
1500
2000
2500
QO
QE
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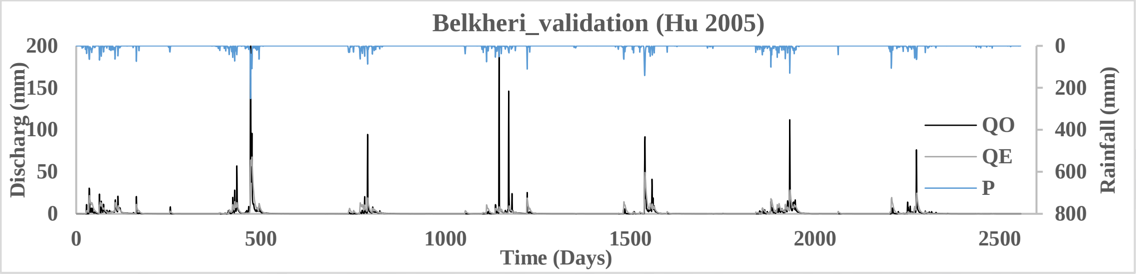
Belkheri_validation (Hu 2005)
Discharg (mm)
Rainfall (mm)
Time (Days)
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1000
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QE
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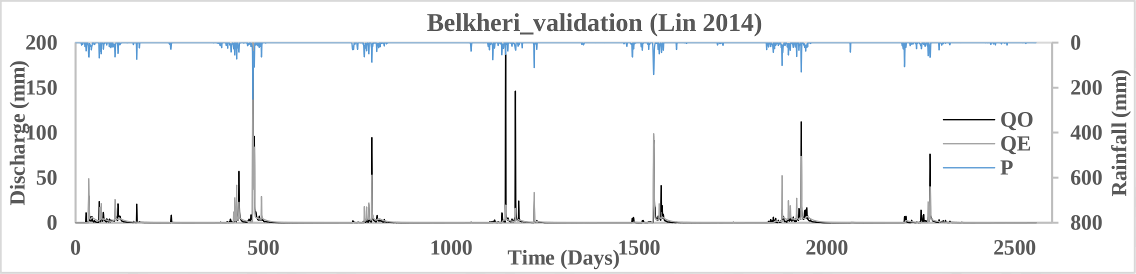
Belkheri_validation (Lin 2014)
Discharge (mm)
Rainfall (mm)
Time (Days)
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1000
1500
2000
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QO
QE
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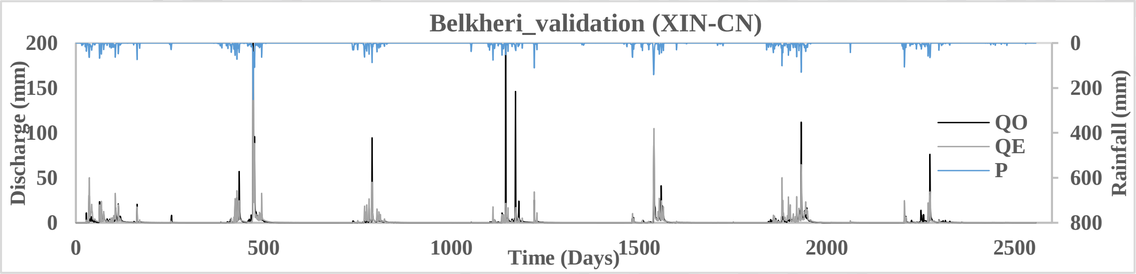
Belkheri_validation (XIN-CN)
Discharge (mm)
Rainfall (mm)
Time (Days)
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50
100
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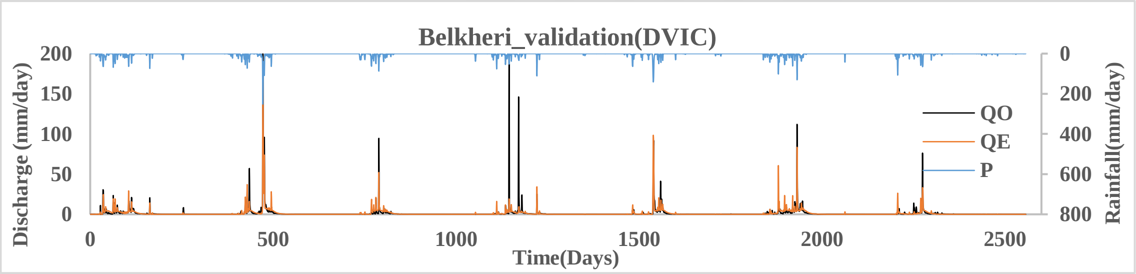
1000
1500
2000
2500
QO
QE
P

80


Belkheri_validation(DVIC)
Discharge (mm/day)
Rainfall(mm/day)
Time(Days)
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50
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800
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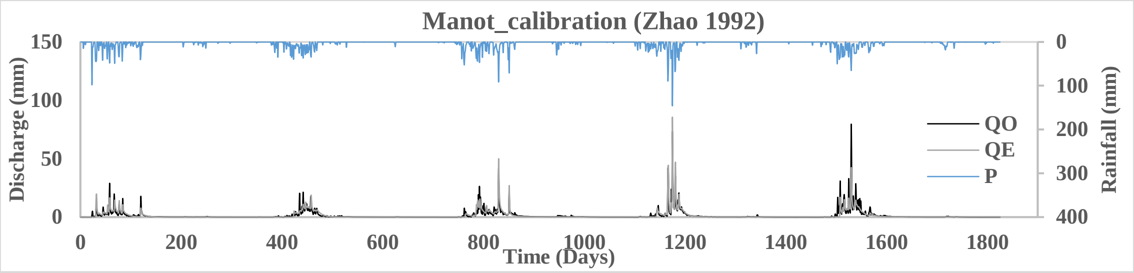
1000
1500
2000
2500
QO
QE
P


Manot_calibration (Zhao 1992)
Discharge (mm)
150
100
50
0
0
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400
600
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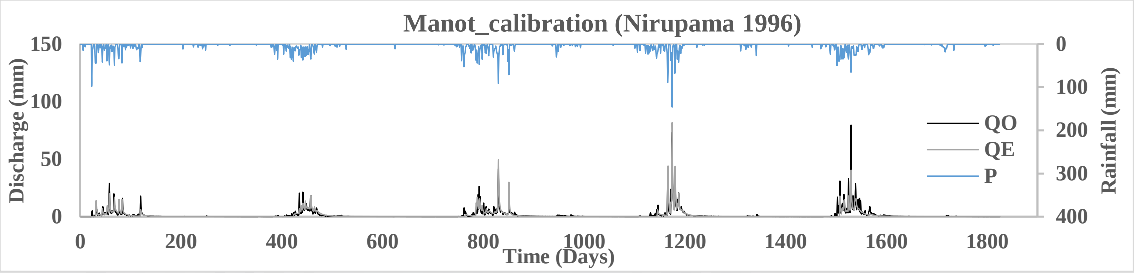
1600
1800
Time (Days)
QO
QE
P
0
100
200
300
400
Rainfall (mm)


Manot_calibration (Nirupama 1996)
Discharge (mm)
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1600
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Time (Days)
QO
QE
P
0
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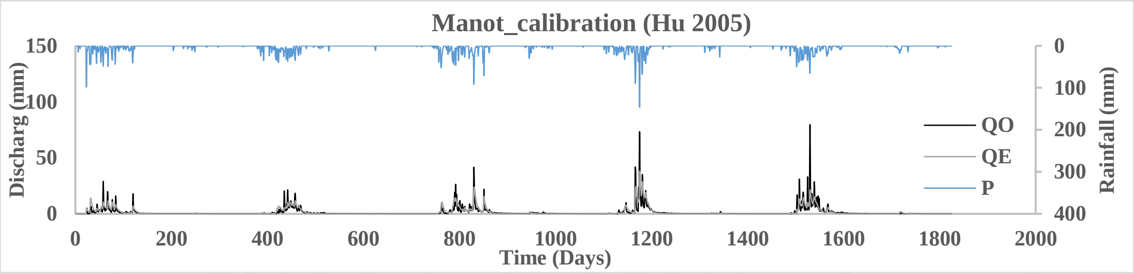
200
300
400
Rainfall (mm)


Manot_calibration (Hu 2005)
Discharg (mm)
150
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Time (Days)
QO
QE
P
0
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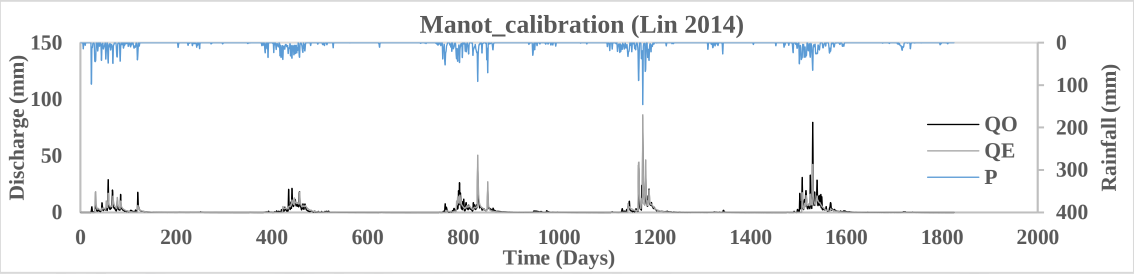
Rainfall (mm)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Discharge (mm)
150
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Time (Days)
QO
QE
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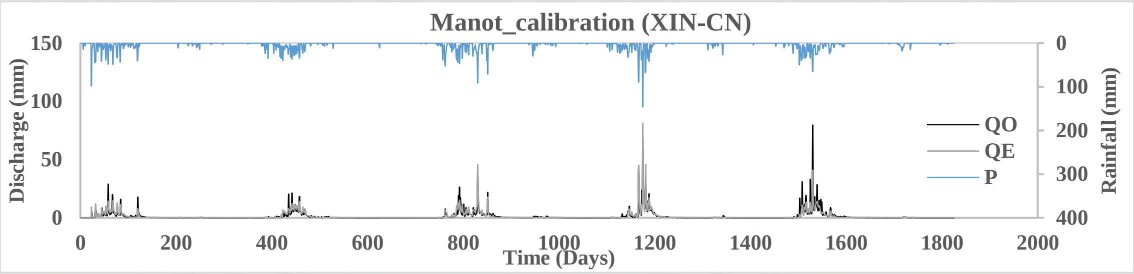
Rainfall (mm)


Manot_calibration (XIN-CN)
Discharge (mm)
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Time (Days)
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QE
P
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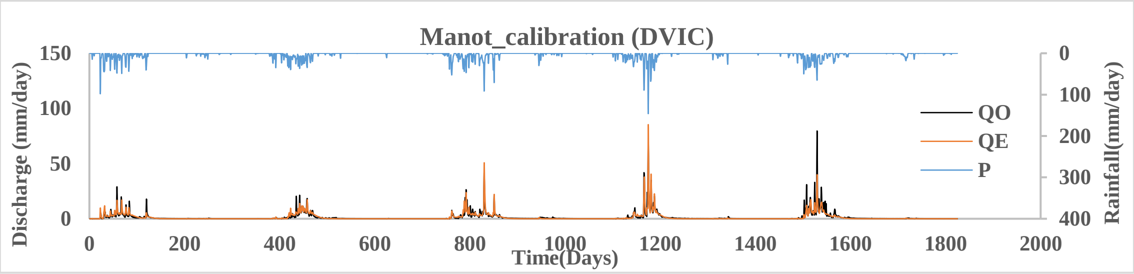
Rainfall (mm)


Manot_calibration (DVIC)
Discharge (mm/day)
150
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Time(Days)
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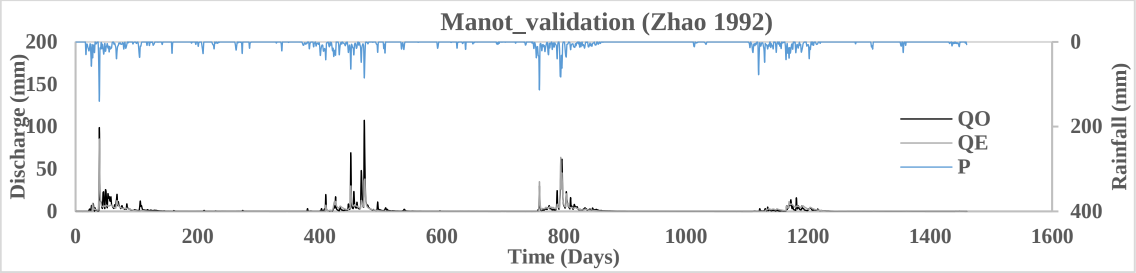
300
400
Rainfall(mm/day)


Manot_validation (Zhao 1992)
Discharge (mm)
Rainfall (mm)
Time (Days)
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QE
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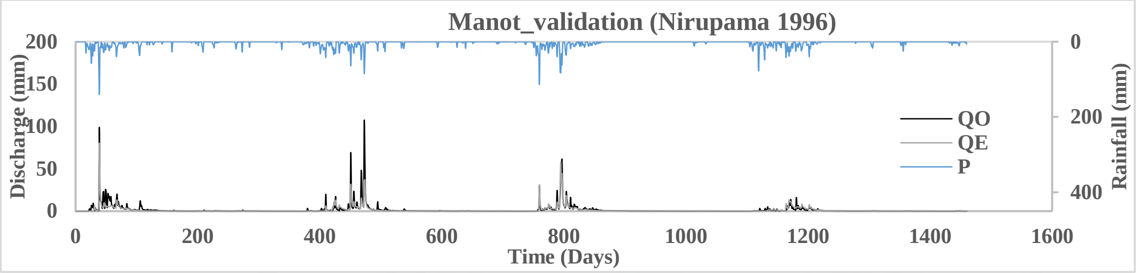
Manot_validation (Nirupama 1996)
Discharge (mm)
Rainfall (mm)
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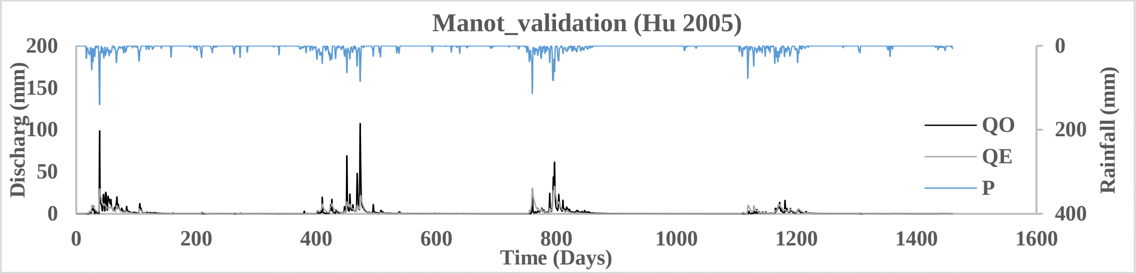
Manot_validation (Hu 2005)
Discharg (mm)
Rainfall (mm)
Time (Days)
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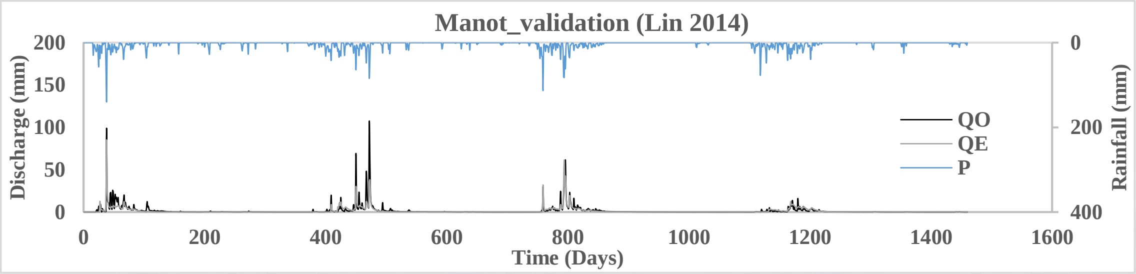
Manot_validation (Lin 2014)
Discharge (mm)
Rainfall (mm)
Time (Days)
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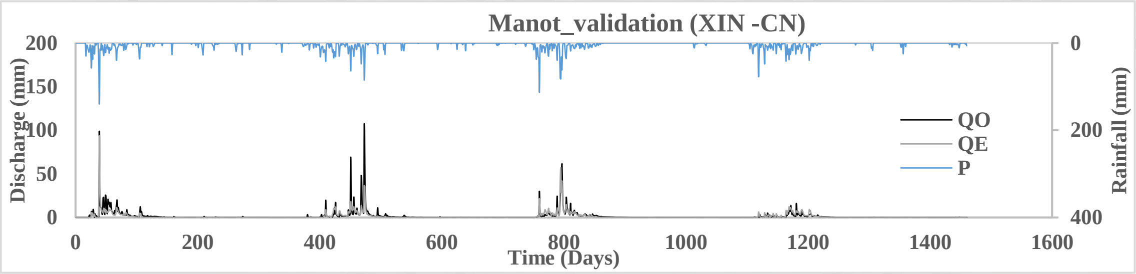
Manot_validation (XIN -CN)
Discharge (mm)
Rainfall (mm)
Time (Days)
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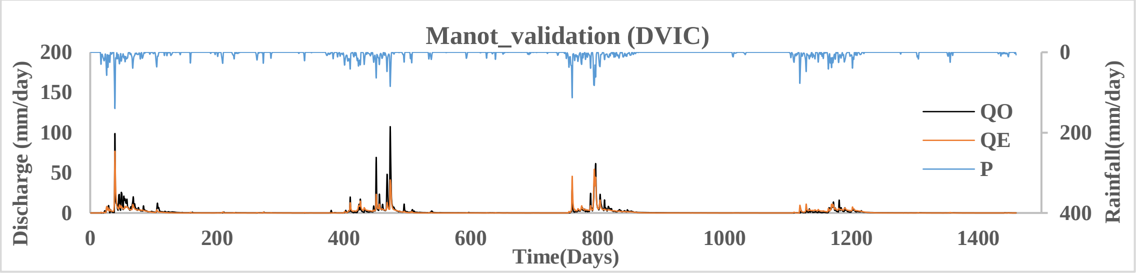
Manot_validation (DVIC)
Discharge (mm/day)
Rainfall(mm/day)
Time(Days)
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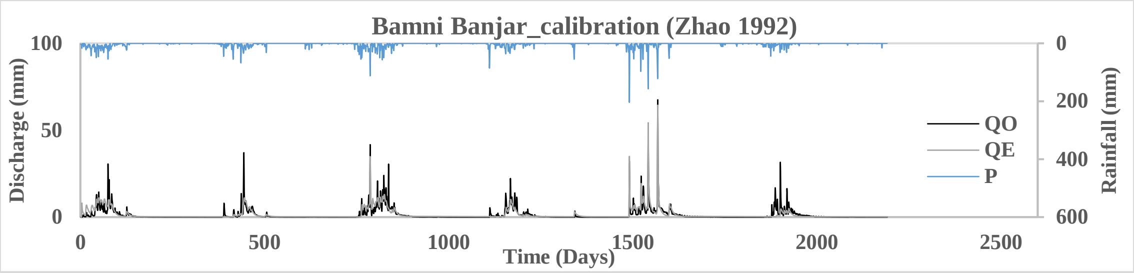
Bamni Banjar_calibration (Zhao 1992)
Discharge (mm)
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Time (Days)
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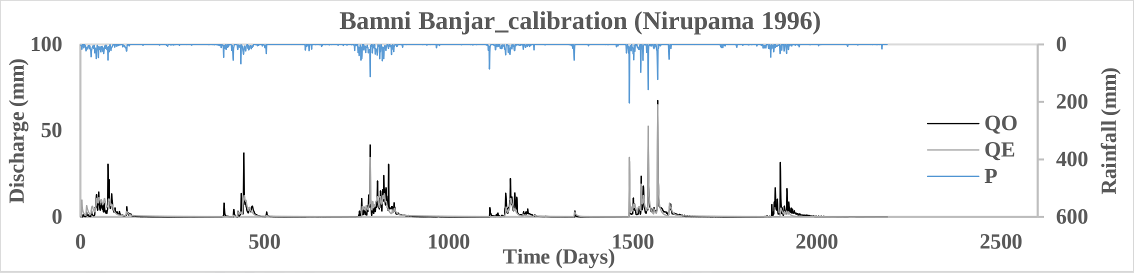
Rainfall (mm)
QO
QE
P


Bamni Banjar_calibration (Nirupama 1996)
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Time (Days)
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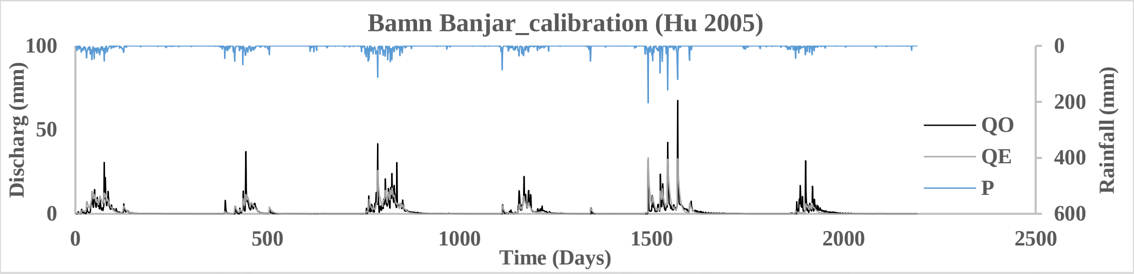
Rainfall (mm)
QO
QE
P


Bamn Banjar_calibration (Hu 2005)
Discharg (mm)
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Time (Days)
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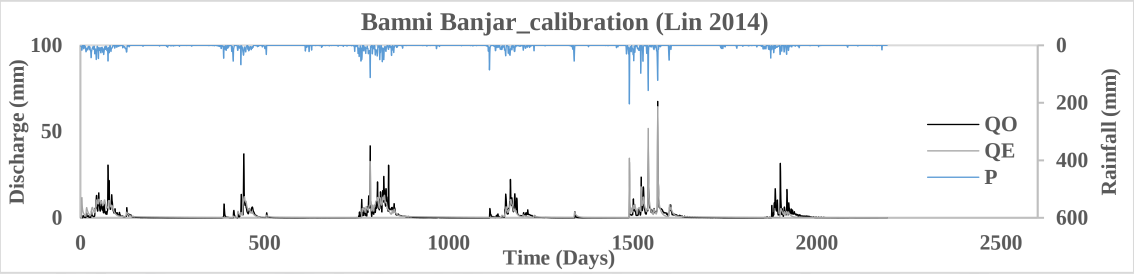
Rainfall (mm)
QO
QE
P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Time (Days)
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Rainfall (mm)
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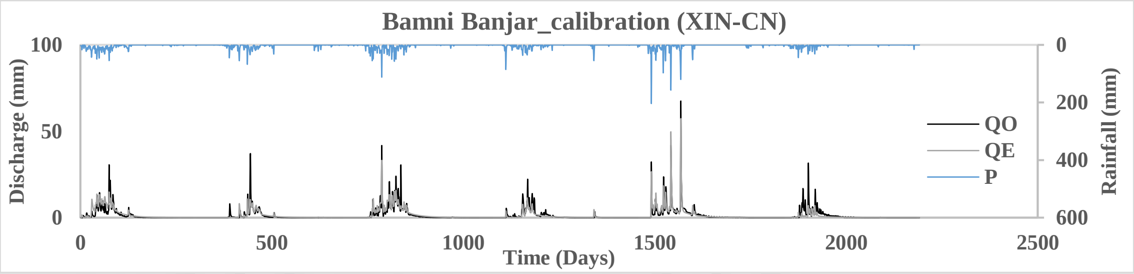
QE
P


Bamni Banjar_calibration (XIN-CN)
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Time (Days)
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Rainfall (mm)
QO
QE
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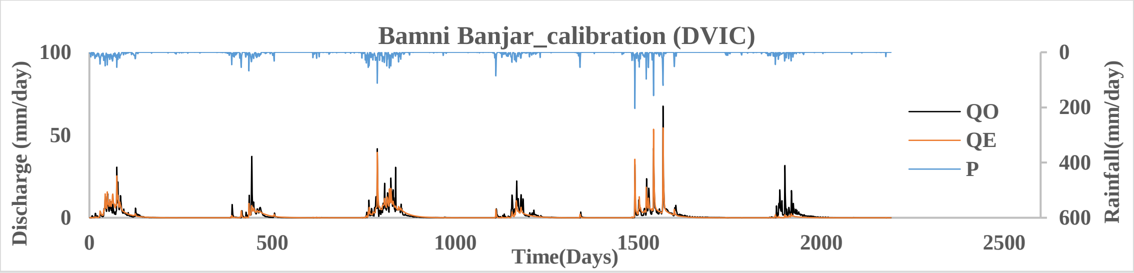
Bamni Banjar_calibration (DVIC)
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Time(Days)
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Rainfall(mm/day)
QO
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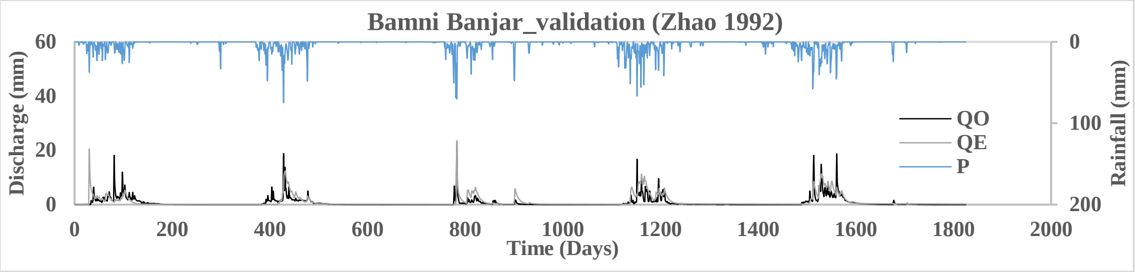
Bamni Banjar_validation (Zhao 1992)
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Rainfall (mm)
Time (Days)
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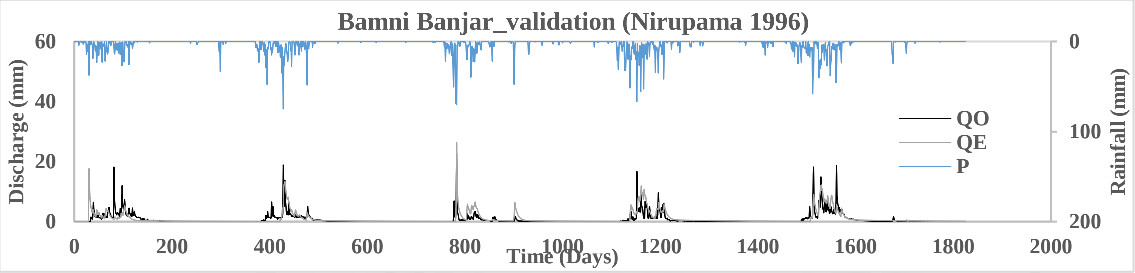
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Rainfall (mm)
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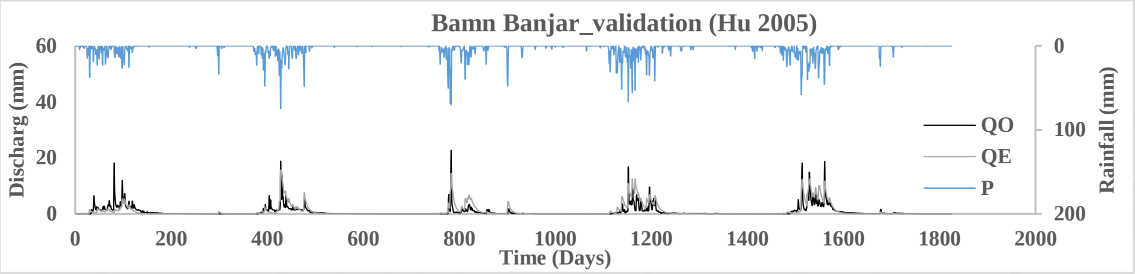
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Discharg (mm)
Rainfall (mm)
Time (Days)
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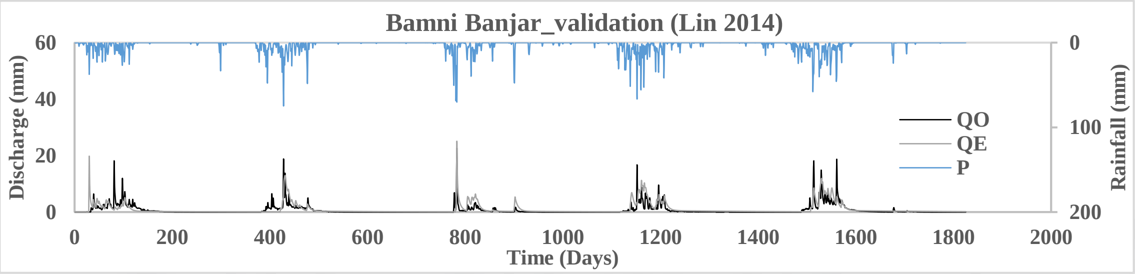
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Discharge (mm)
Rainfall (mm)
Time (Days)
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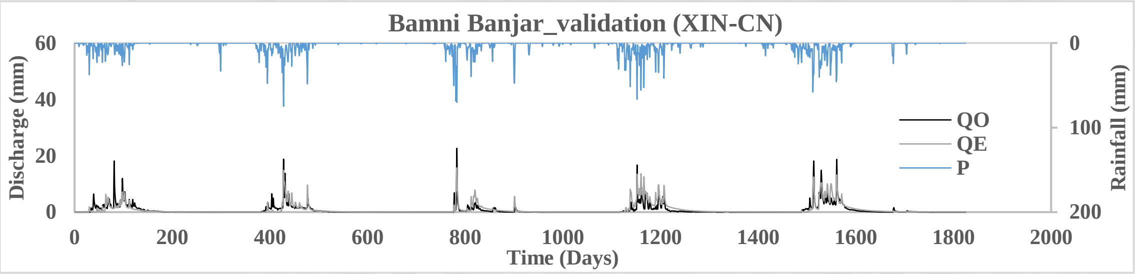
Bamni Banjar_validation (XIN-CN)
Discharge (mm)
Rainfall (mm)
Time (Days)
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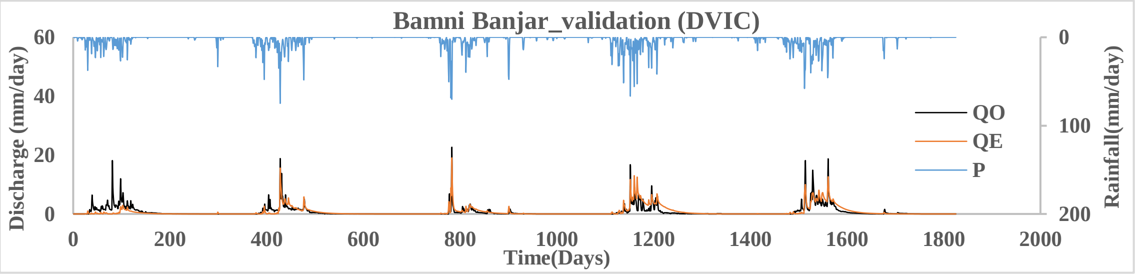
Bamni Banjar_validation (DVIC)
Discharge (mm/day)
Rainfall(mm/day)
Time(Days)
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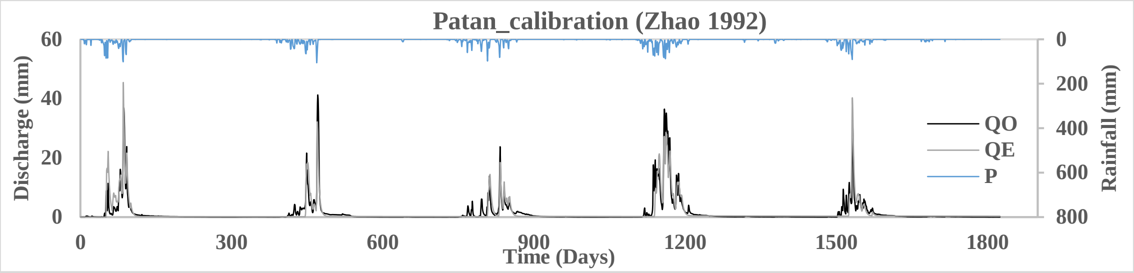
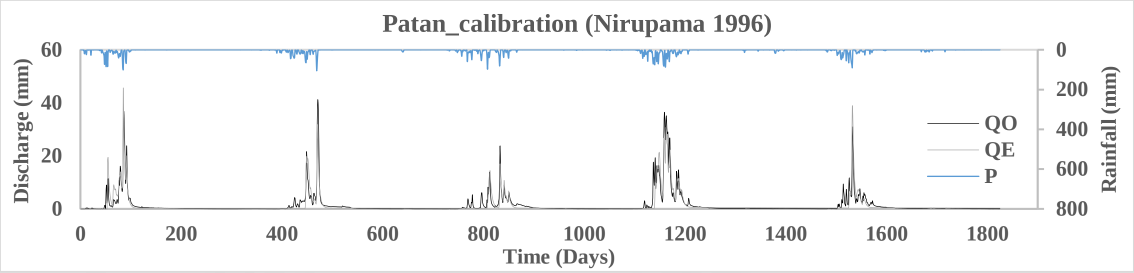

Patan_calibration (Zhao 1992)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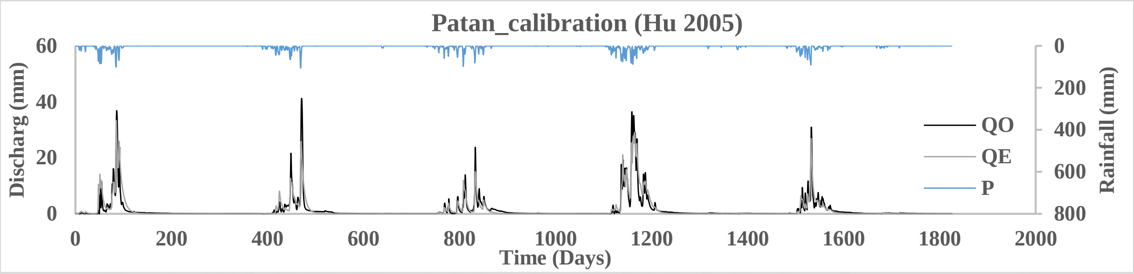
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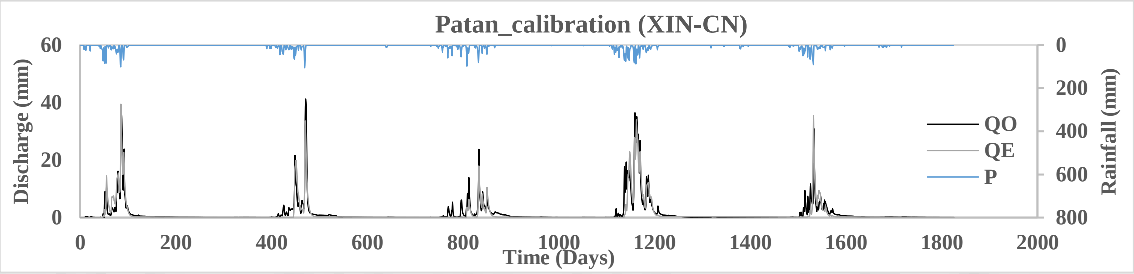
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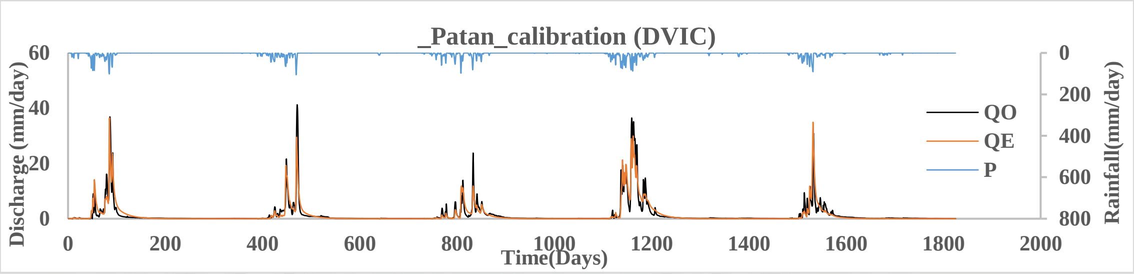
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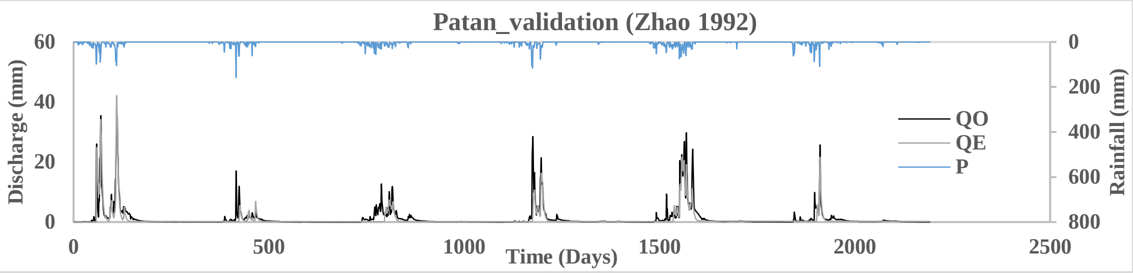
Patan_validation (Zhao 1992)
Discharge (mm)
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Time (Days)
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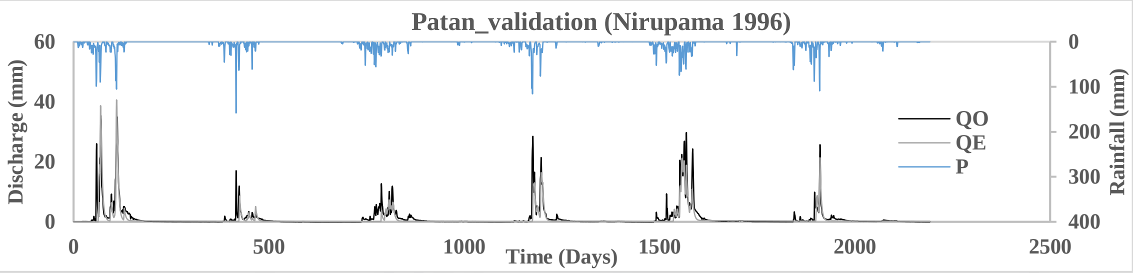
Rainfall (mm)
QO
QE
P


Patan_validation (Nirupama 1996)
Discharge (mm)
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Rainfall (mm)
QO
QE
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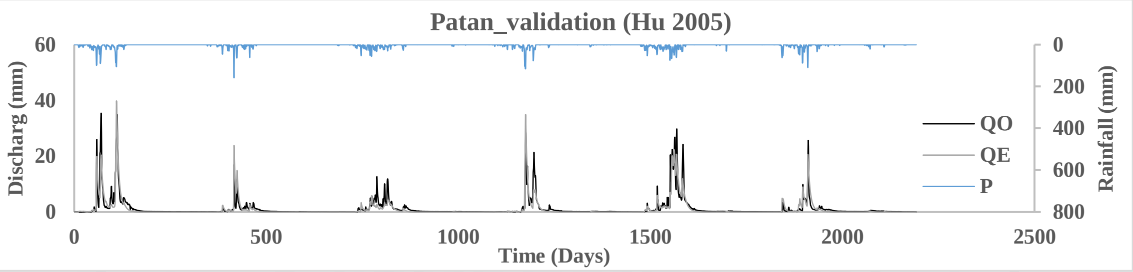
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Rainfall (mm)
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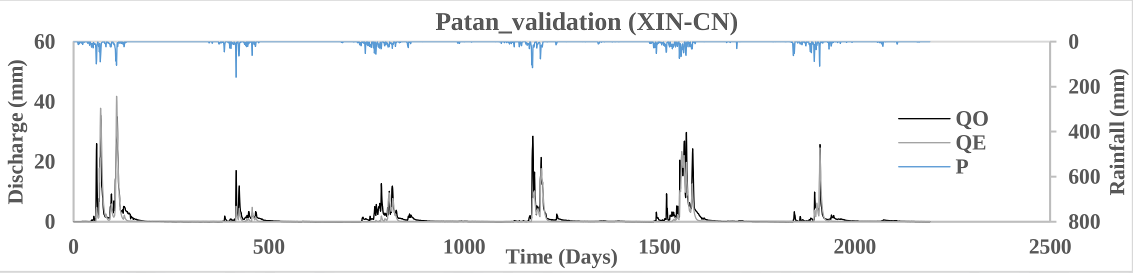
Patan_validation (XIN-CN)
Discharge (mm)
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Rainfall (mm)
QO
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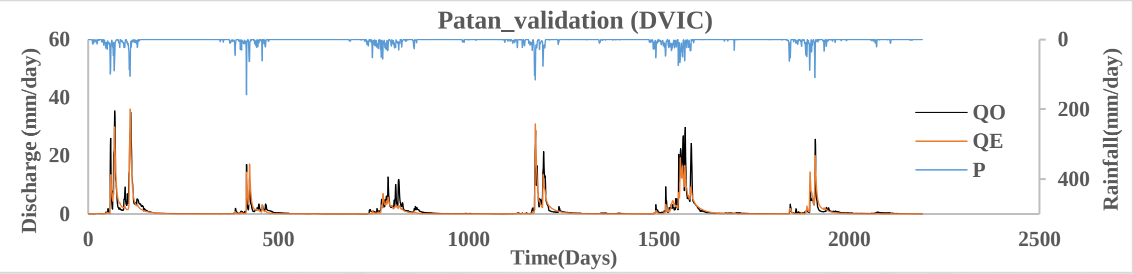
Patan_validation (DVIC)
Discharge (mm/day)
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Time(Days)
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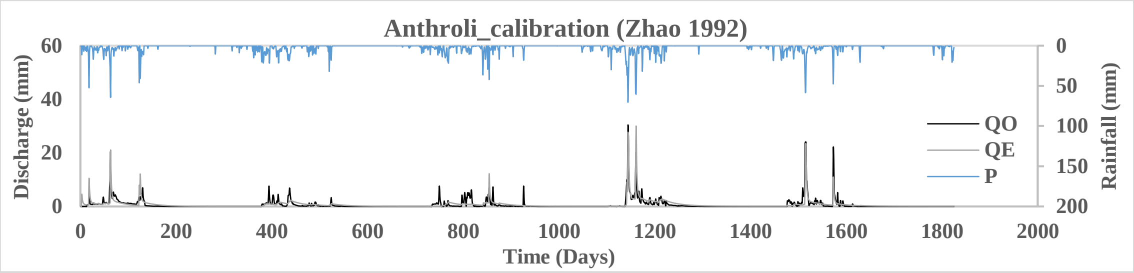
400
Rainfall(mm/day)
QO
QE
P


Anthroli_calibration (Zhao 1992)
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Time (Days)
Rainfall (mm)
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QO
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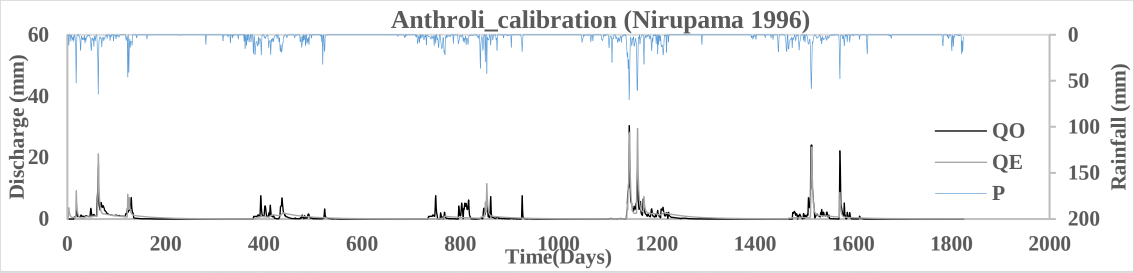
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Time(Days)
Rainfall (mm)
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QO
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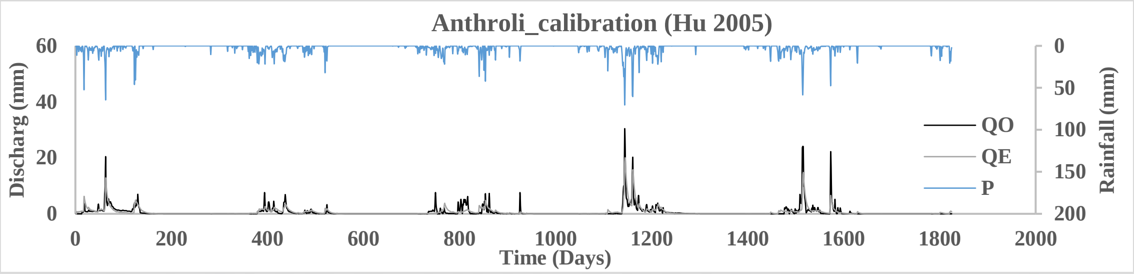
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Discharg (mm)
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Time (Days)
Rainfall (mm)
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QE
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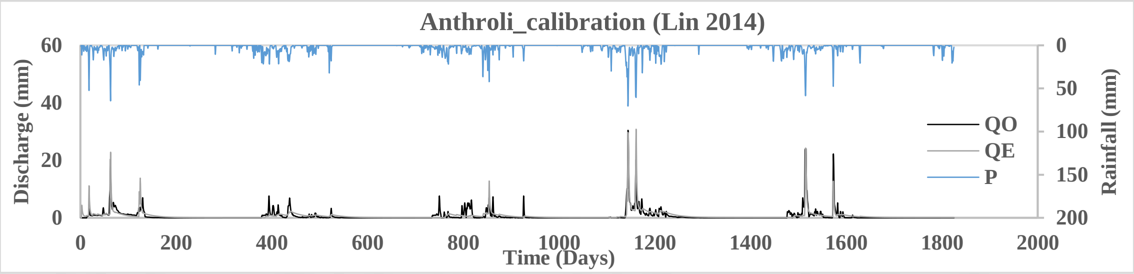
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Time (Days)
Rainfall (mm)
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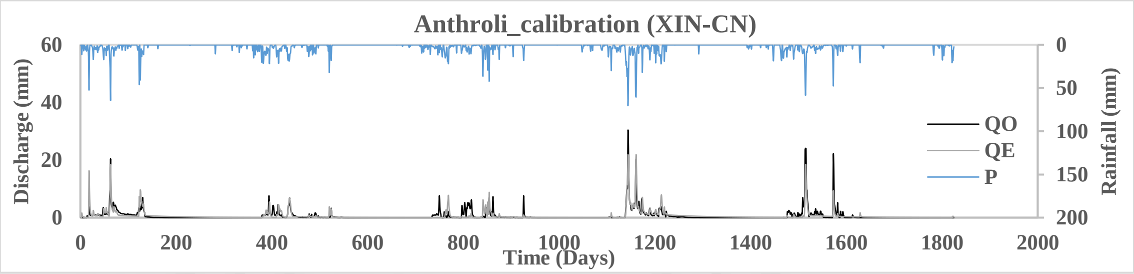
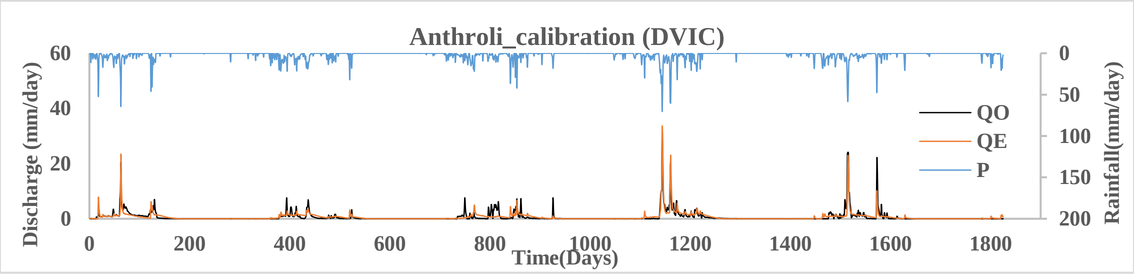
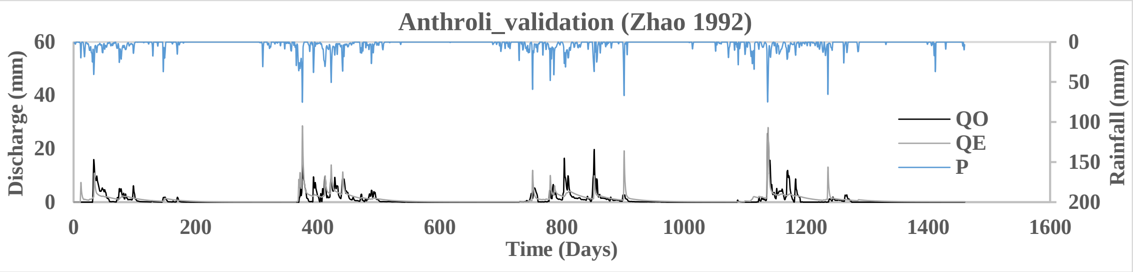
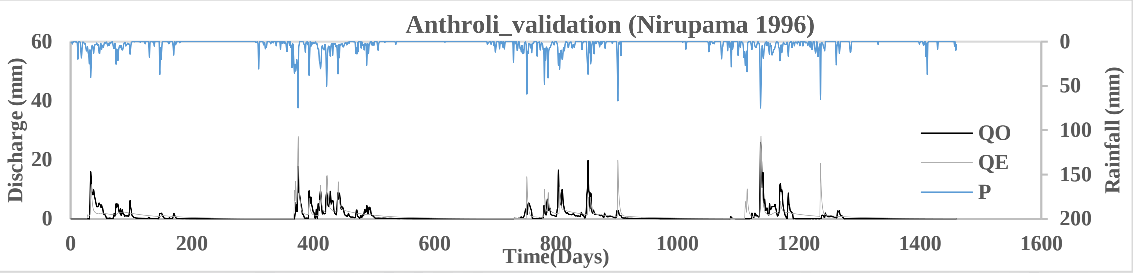
QO
QE
P


Anthroli_calibration (XIN-CN)
Discharge (mm)
60
40
20
0
0
200
400
600
800
1000
1200
1400
1600
1800
2000
Time (Days)
Rainfall (mm)
0
50
100
150
200
QO
QE
P


Anthroli_calibration (DVIC)
Discharge (mm/day)
60
40
20
0
0
200
400
600
800
1000
1200
1400
1600
1800
Time(Days)
Rainfall(mm/day)
0
50
100
150
200
QO
QE
P


Anthroli_validation (Zhao 1992)
Discharge (mm)
Rainfall (mm)
60
40
20
0
0
50
100
150
200
0
200
400
600
800
1000
1200
1400
1600
Time (Days)
QO
QE
P


Anthroli_validation (Nirupama 1996)
Discharge (mm)
Rainfall (mm)
60
40
20
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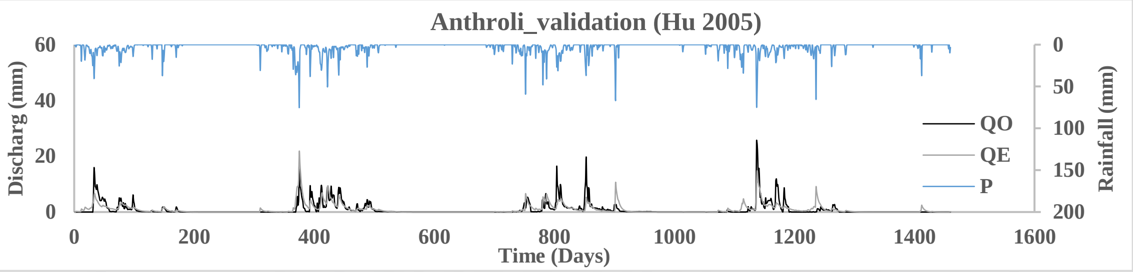
200
0
200
400
600
800
1000
1200
1400
1600
Time(Days)
QO
QE
P


Anthroli_validation (Hu 2005)
Discharg (mm)
Rainfall (mm)
60
40
20
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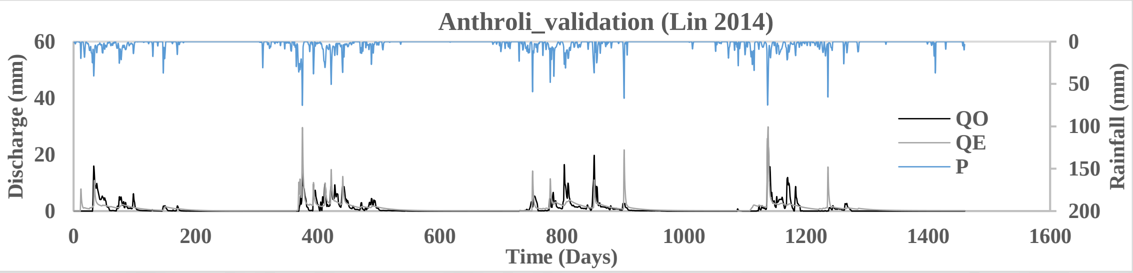
0
50
100
150
200
0
200
400
600
800
1000
1200
1400
1600
Time (Days)
QO
QE
P


Anthroli_validation (Lin 2014)
Discharge (mm)
Rainfall (mm)
60
40
20
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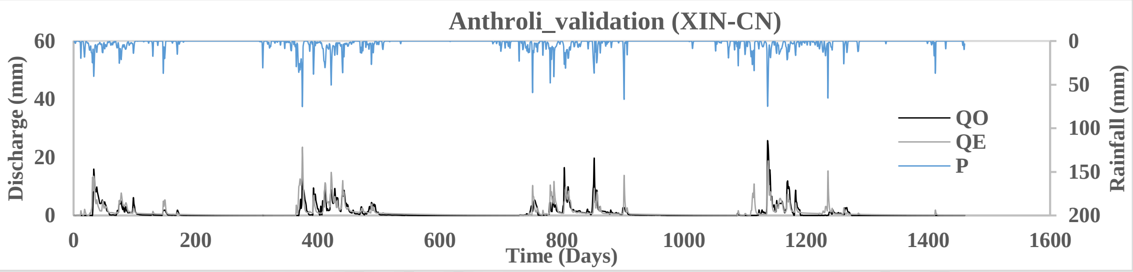
200
0
200
400
600
800
1000
1200
1400
1600
Time (Days)
QO
QE
P


Anthroli_validation (XIN-CN)
Discharge (mm)
Rainfall (mm)
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40
20
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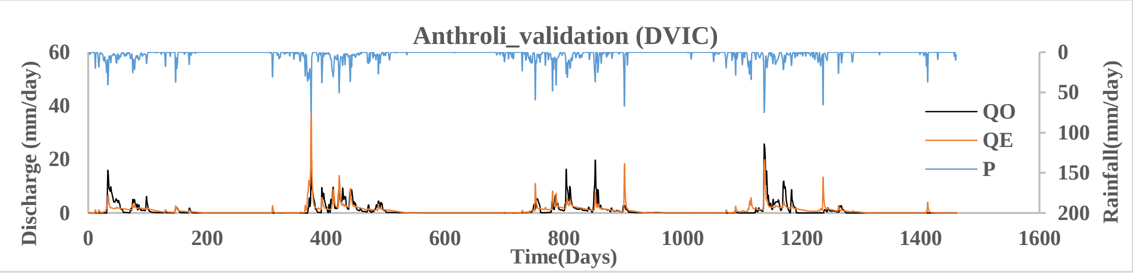
600
800
1000
1200
1400
1600
Time (Days)
QO
QE
P


Anthroli_validation (DVIC)
Discharge (mm/day)
Rainfall(mm/day)
60
40
20
0
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0
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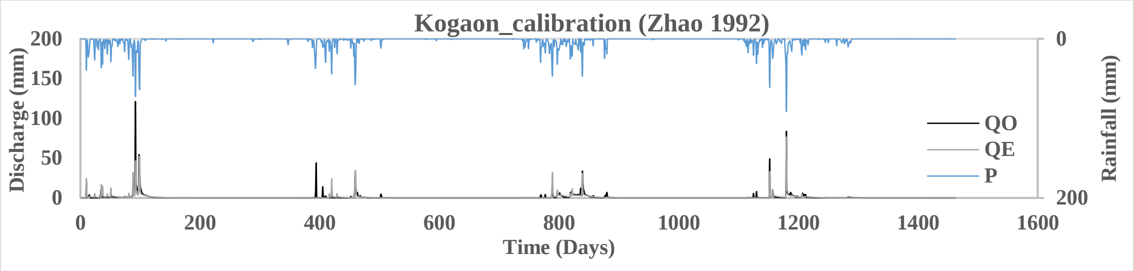
400
600
800
1000
1200
1400
1600
Time(Days)
QO
QE
P


Kogaon_calibration (Zhao 1992)
Discharge (mm)
200
150
100
50
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600
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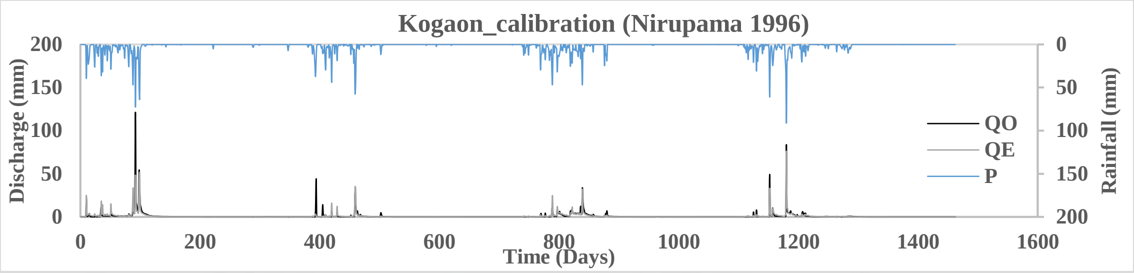
1200
1400
1600
Time (Days)
0
200
Rainfall (mm)
QO
QE
P


Kogaon_calibration (Nirupama 1996)
Discharge (mm)
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0
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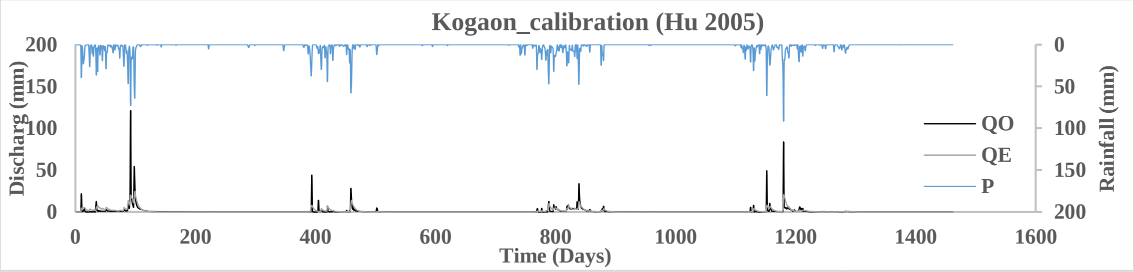
1400
1600
Time (Days)
0
50
100
150
200
Rainfall (mm)
QO
QE
P


Kogaon_calibration (Hu 2005)
Discharg (mm)
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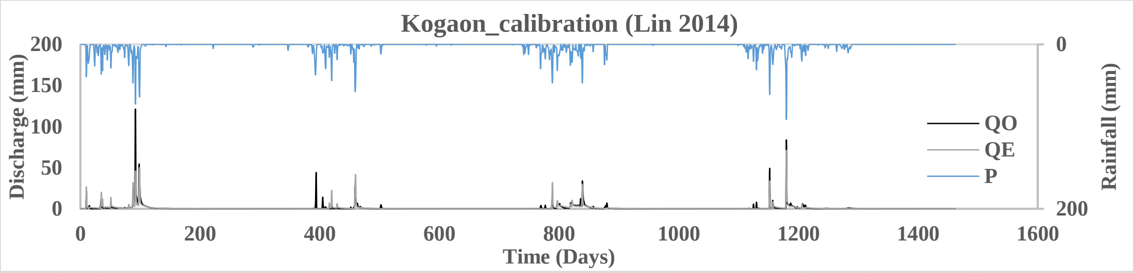
1600
Time (Days)
0
50
100
150
200
Rainfall (mm)
QO
QE
P


Kogaon_calibration (Lin 2014)
Discharge (mm)
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50
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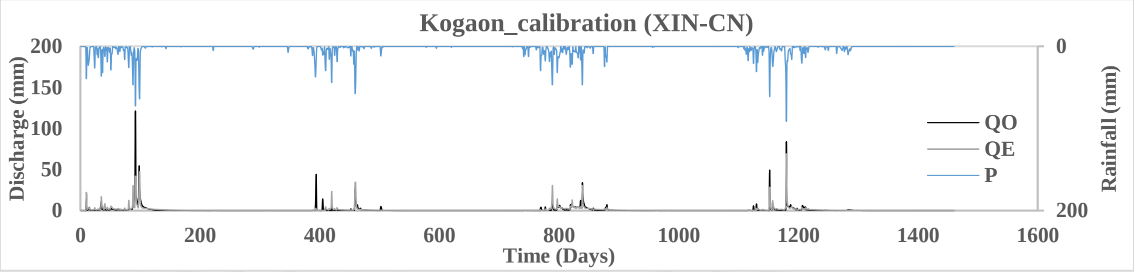
1200
1400
1600
Time (Days)
0
200
Rainfall (mm)
QO
QE
P


Kogaon_calibration (XIN-CN)
Discharge (mm)
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150
100
50
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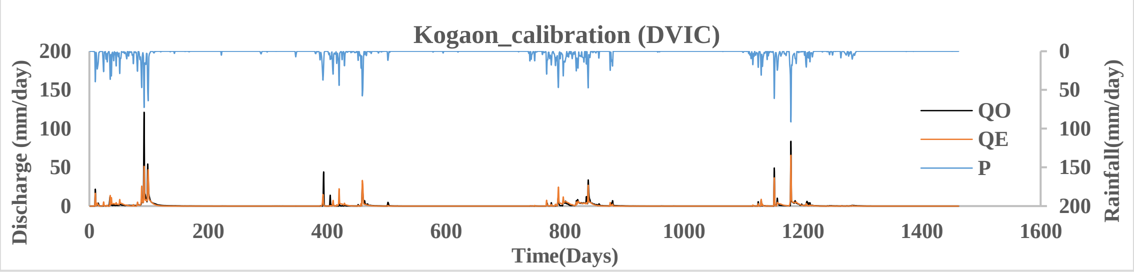
600
800
1000
1200
1400
1600
Time (Days)
0
200
Rainfall (mm)
QO
QE
P


Kogaon_calibration (DVIC)
Discharge (mm/day)
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50
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0
200
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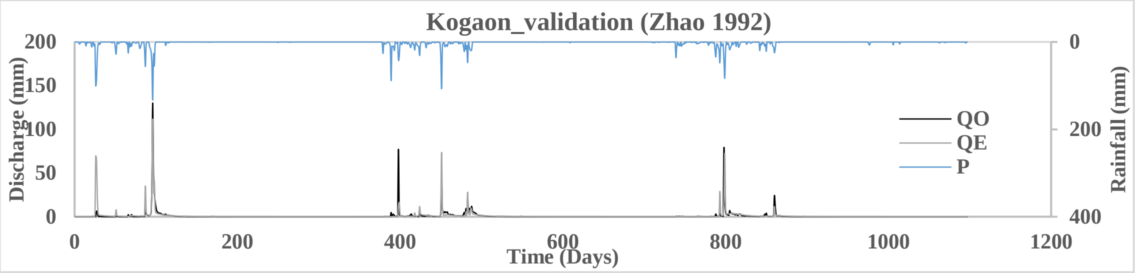
1400
1600
Time(Days)
0
50
100
150
200
Rainfall(mm/day)
QO
QE
P


Kogaon_validation (Zhao 1992)
Discharge (mm)
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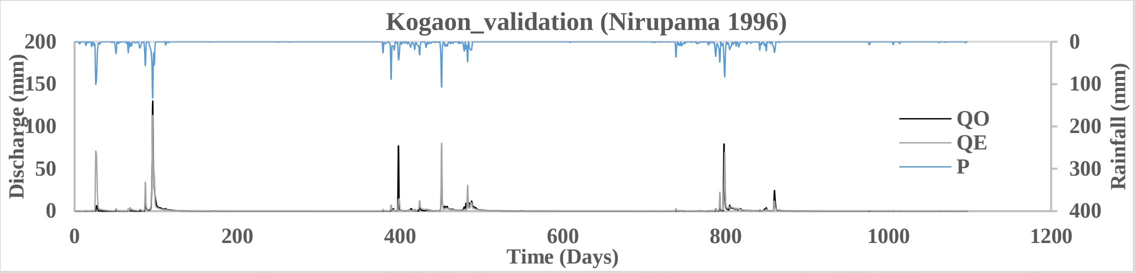
400
600
800
1000
1200
Time (Days)
Rainfall (mm)
0
200
400
QO
QE
P


Kogaon_validation (Nirupama 1996)
Discharge (mm)
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150
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50
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800
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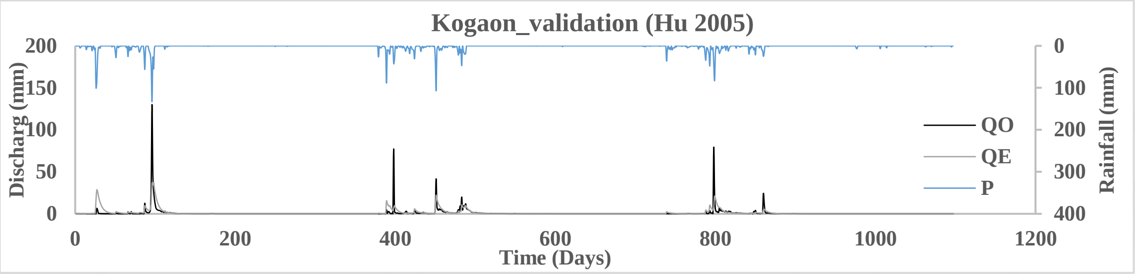
1200
Time (Days)
Rainfall (mm)
0
100
200
300
400
QO
QE
P


Kogaon_validation (Hu 2005)
Discharg (mm)
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800
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Time (Days)
Rainfall (mm)
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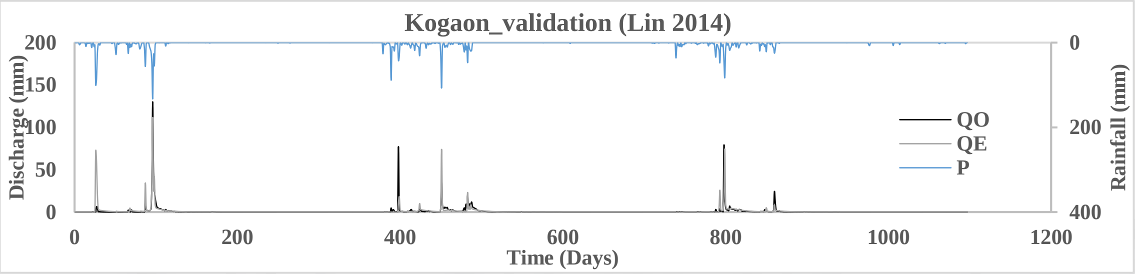
QO
QE
P


Kogaon_validation (Lin 2014)
Discharge (mm)
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1200
Time (Days)
Rainfall (mm)
0
200
400
QO
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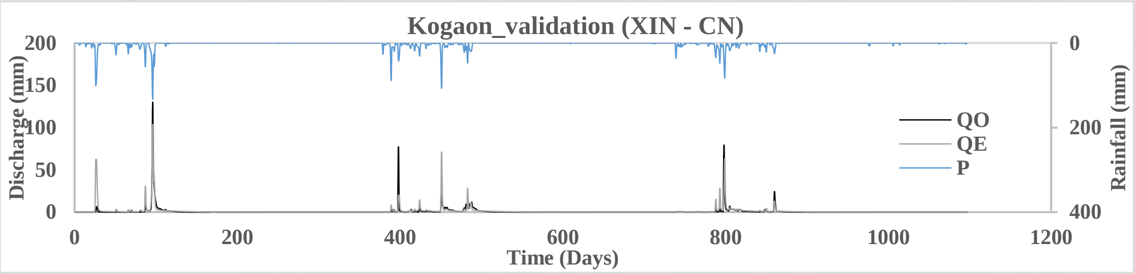
Kogaon_validation (XIN - CN)
Discharge (mm)
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600
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1200
Time (Days)
Rainfall (mm)
0
200
400
QO
QE
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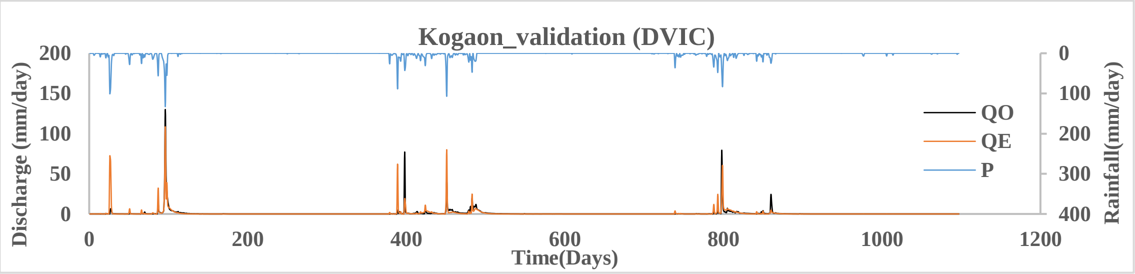
Kogaon_validation (DVIC)
Discharge (mm/day)
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100
50
0
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1200
Time(Days)
Rainfall(mm/day)
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100
200
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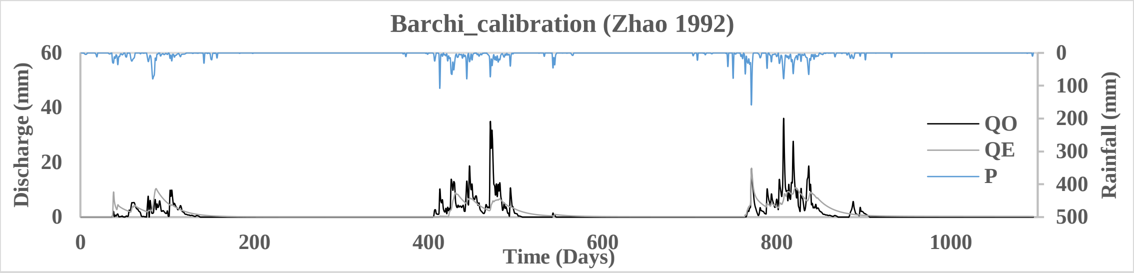
QO
QE
P


Barchi_calibration (Zhao 1992)
Discharge (mm)
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40
20
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800
1000
Time (Days)
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200
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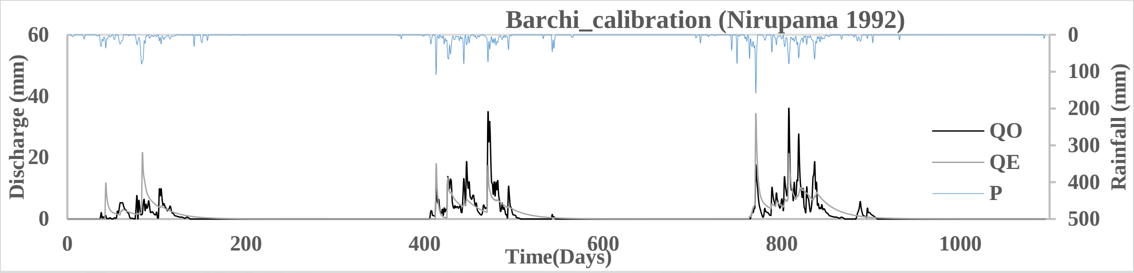
400
500
Rainfall (mm)
QO
QE
P


Barchi_calibration (Nirupama 1992)
Discharge (mm)
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Time(Days)
0
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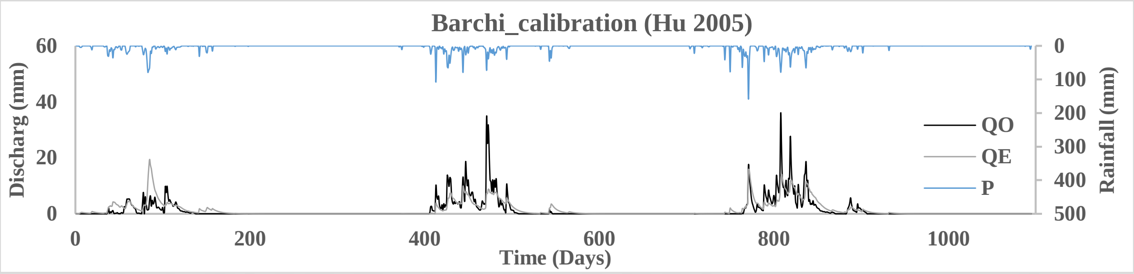
400
500
Rainfall (mm)
QO
QE
P


Barchi_calibration (Hu 2005)
Discharg (mm)
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Time (Days)
0
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200
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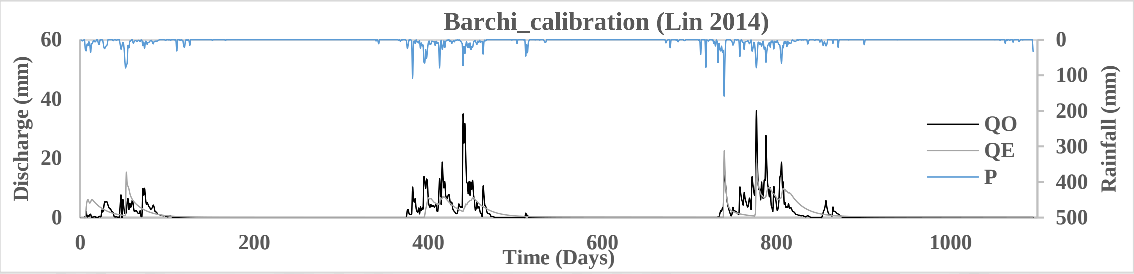
400
500
Rainfall (mm)
QO
QE
P


Barchi_calibration (Lin 2014)
Discharge (mm)
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Time (Days)
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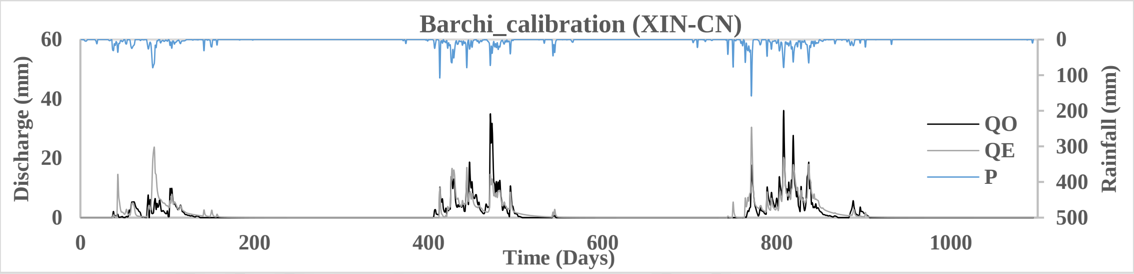
400
500
Rainfall (mm)
QO
QE
P


Barchi_calibration (XIN-CN)
Discharge (mm)
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Time (Days)
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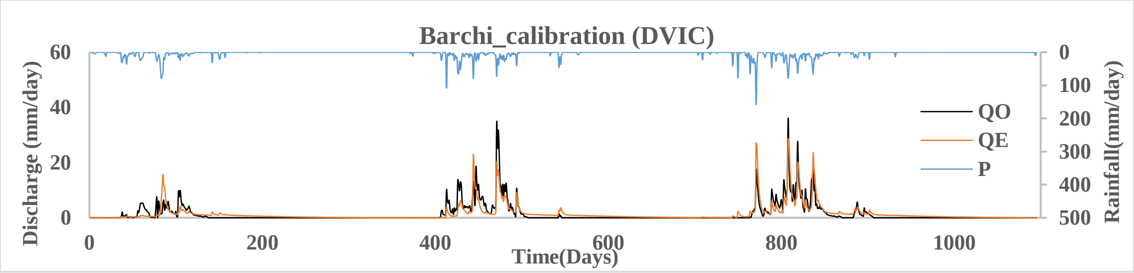
400
500
Rainfall (mm)
QO
QE
P


Barchi_calibration (DVIC)
Discharge (mm/day)
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Time(Days)
0
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200
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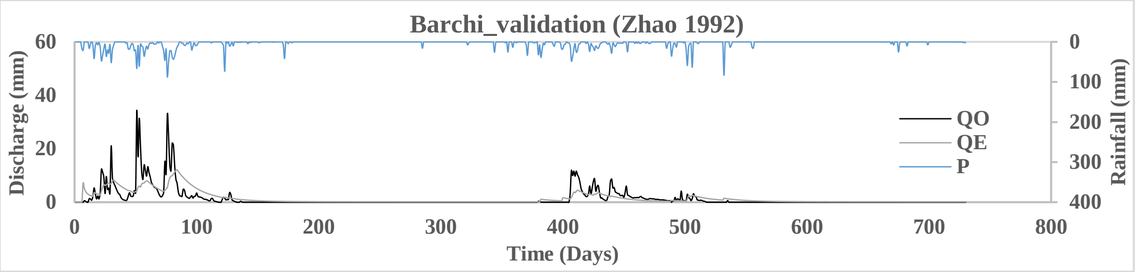
400
500
Rainfall(mm/day)
QO
QE
P


Barchi_validation (Zhao 1992)
Discharge (mm)
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Rainfall (mm)
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QO
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P
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700
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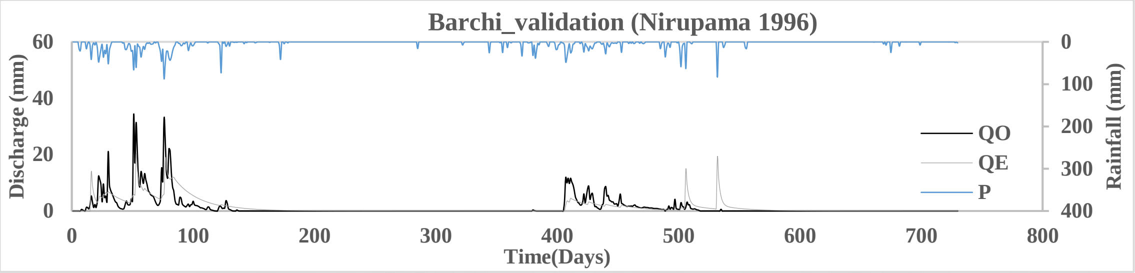
Time (Days)


Barchi_validation (Nirupama 1996)
Discharge (mm)
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Rainfall (mm)
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QO
QE
P
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300
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700
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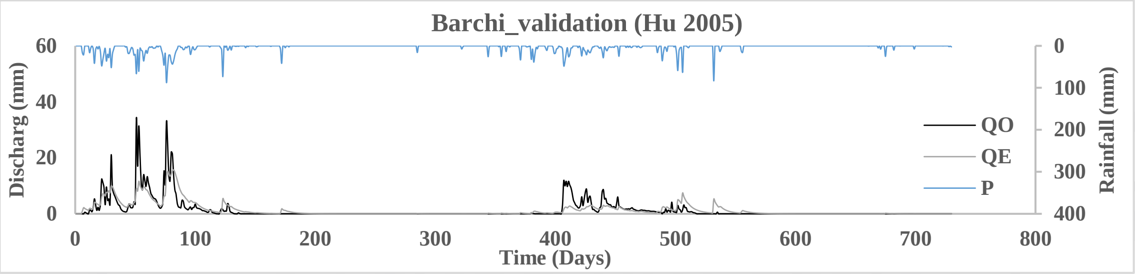
Time(Days)


Barchi_validation (Hu 2005)
Discharg (mm)
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0
Rainfall (mm)
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QO
QE
P
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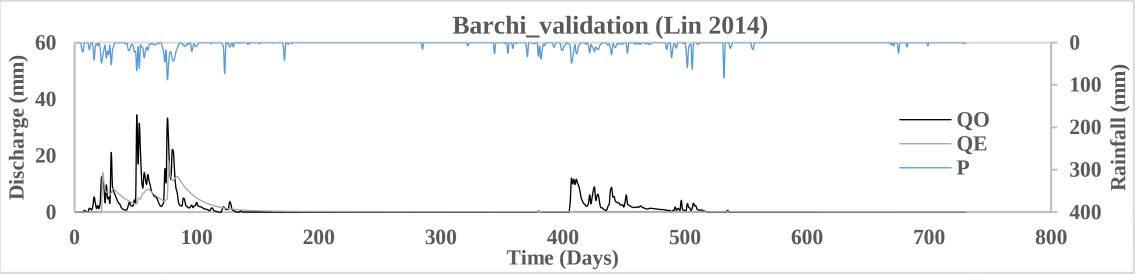
300
400
500
600
700
800
Time (Days)


Barchi_validation (Lin 2014)
Discharge (mm)
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0
Rainfall (mm)
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QO
QE
P
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300
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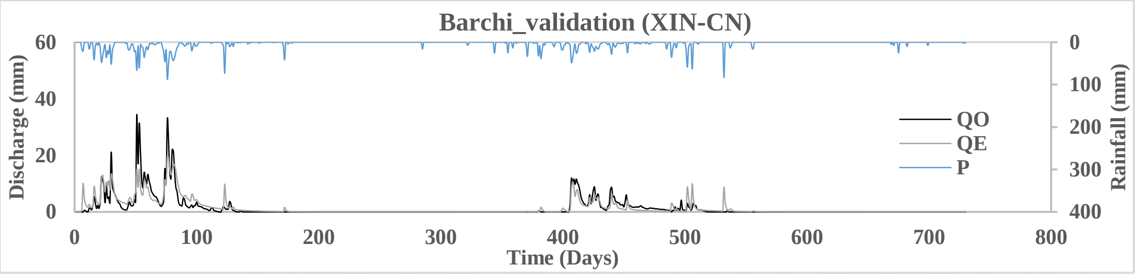
500
600
700
800
Time (Days)


Barchi_validation (XIN-CN)
Discharge (mm)
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Rainfall (mm)
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QO
QE
P
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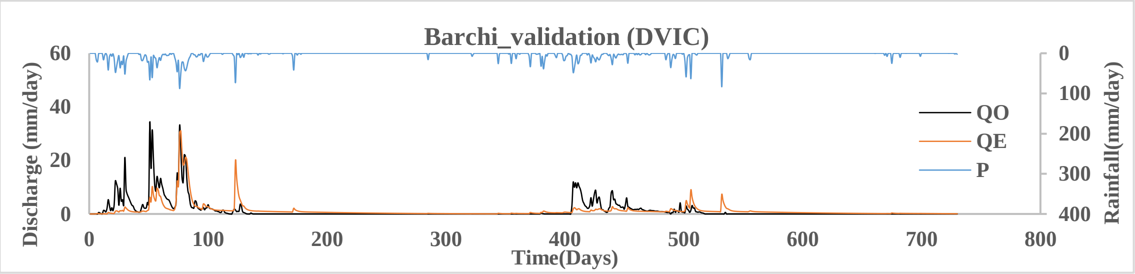
700
800
Time (Days)


Barchi_validation (DVIC)
Discharge (mm/day)
60
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20
0
Rainfall(mm/day)
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QO
QE
P
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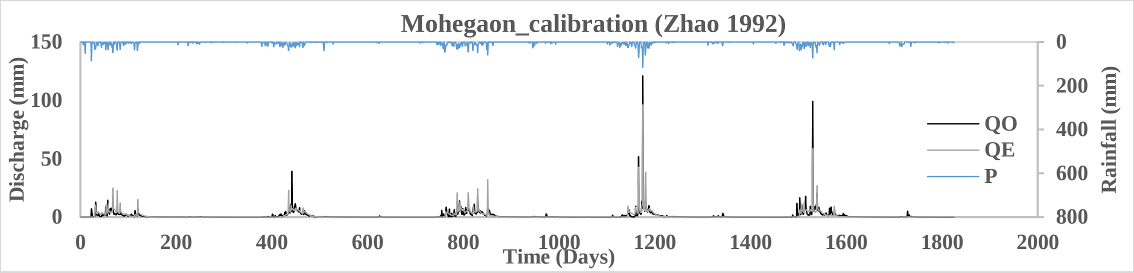
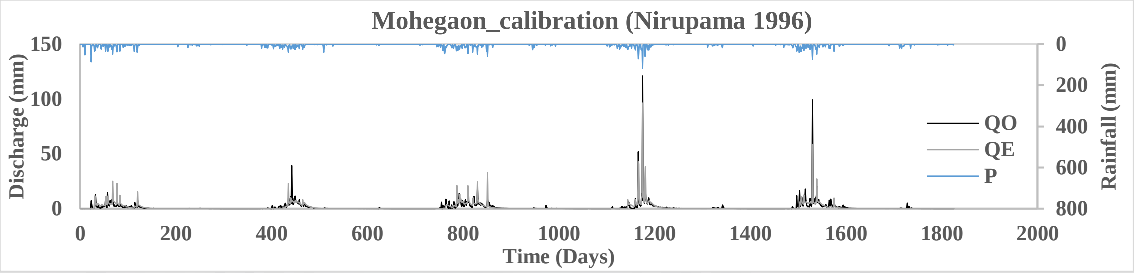
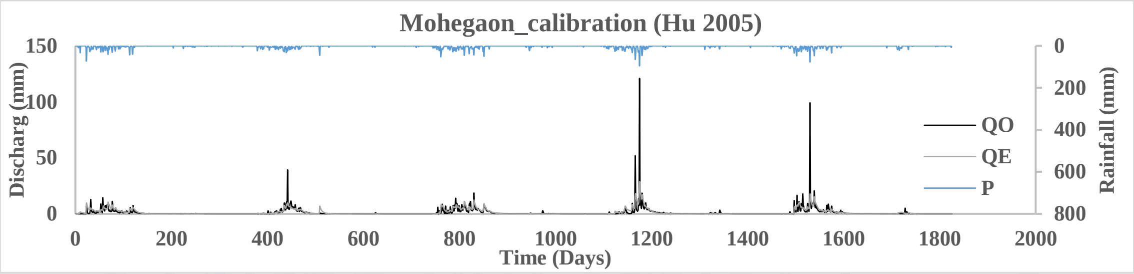
700
800
Time(Days)



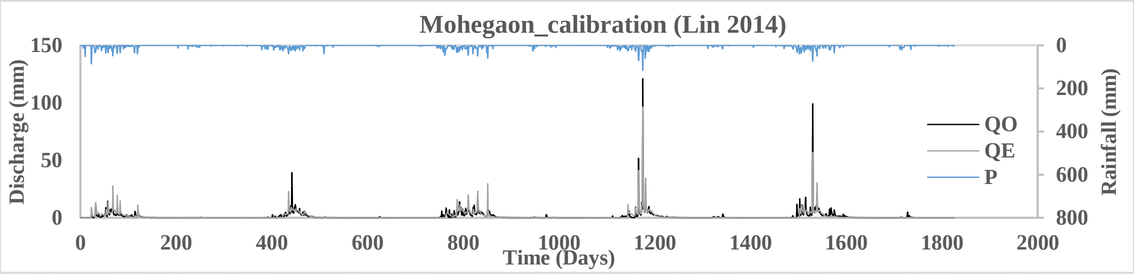
Mohegaon_calibration (Zhao 1992)



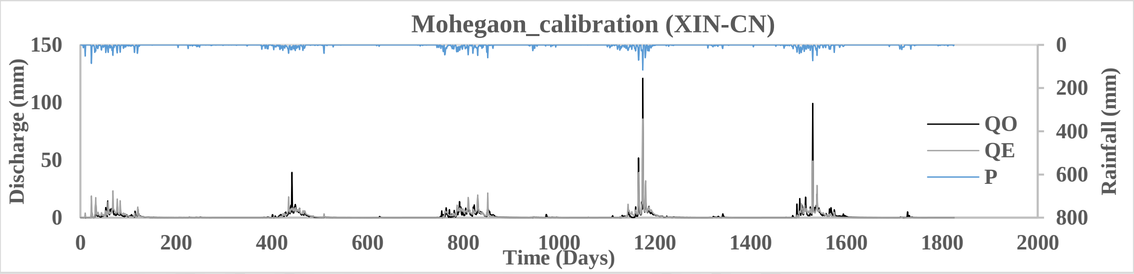
Mohegaon_calibration (Nirupama 1996)



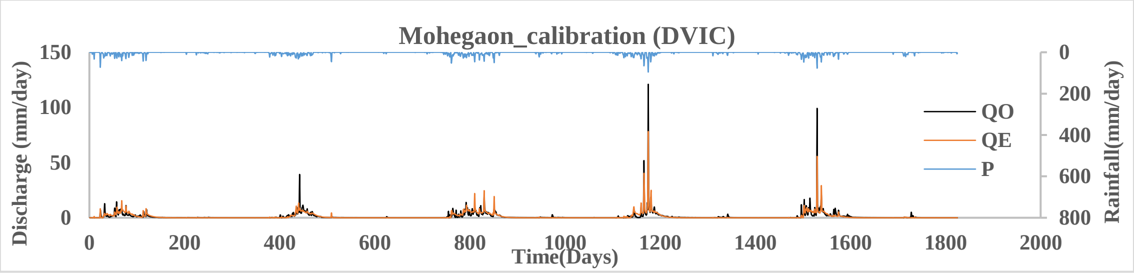
Mohegaon_calibration (Hu 2005)



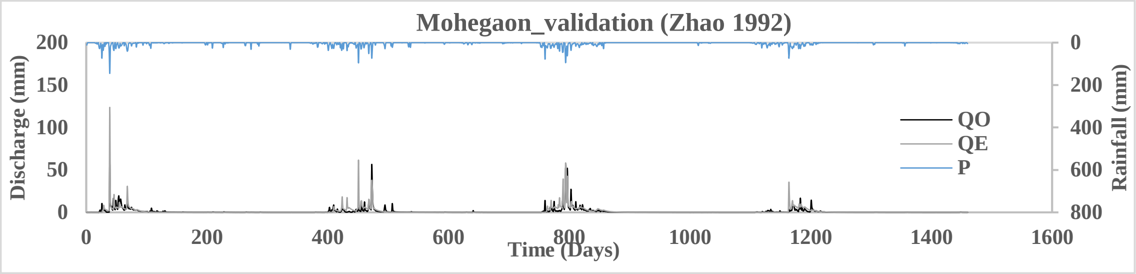
Mohegaon_calibration (Lin 2014)



Mohegaon_calibration (XIN-CN)



Mohegaon_calibration (DVIC)


Mohegaon_validation (Zhao 1992)
Discharge (mm)
200
150
100
50
0
0
200
400
600
800
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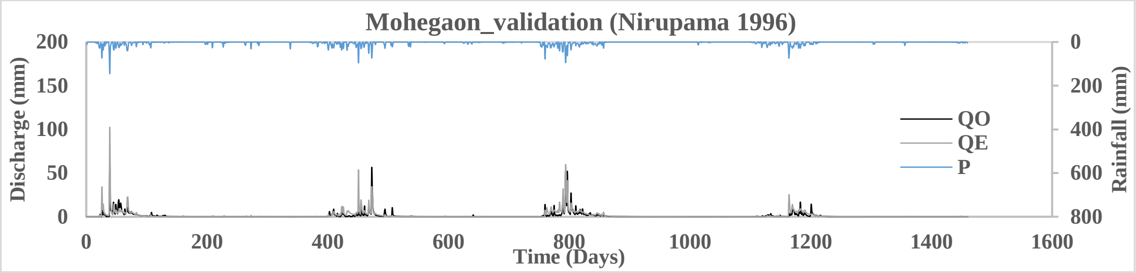
1200
1400
1600
Time (Days)
Rainfall (mm)
0
200
400
600
800
QO
QE
P


Mohegaon_validation (Nirupama 1996)
Discharge (mm)
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1600
Time (Days)
Rainfall (mm)
0
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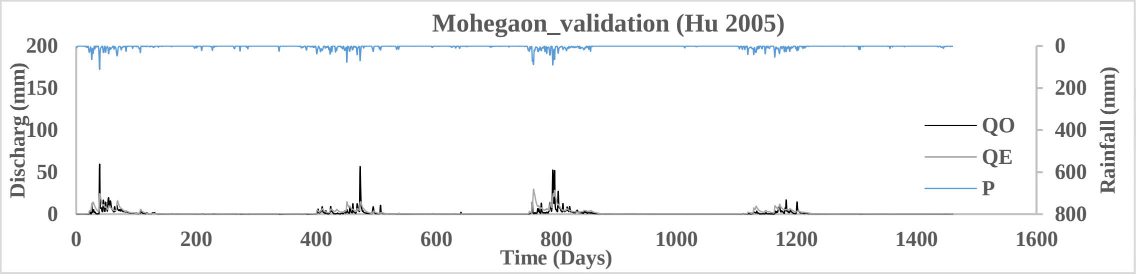
400
600
800
QO
QE
P


Mohegaon_validation (Hu 2005)
Discharg (mm)
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Time (Days)
Rainfall (mm)
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QO
QE
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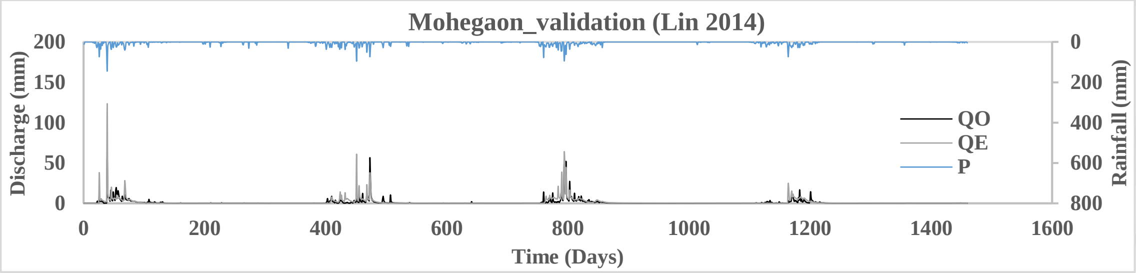
Mohegaon_validation (Lin 2014)
Discharge (mm)
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1600
Time (Days)
Rainfall (mm)
0
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400
600
800
QO
QE
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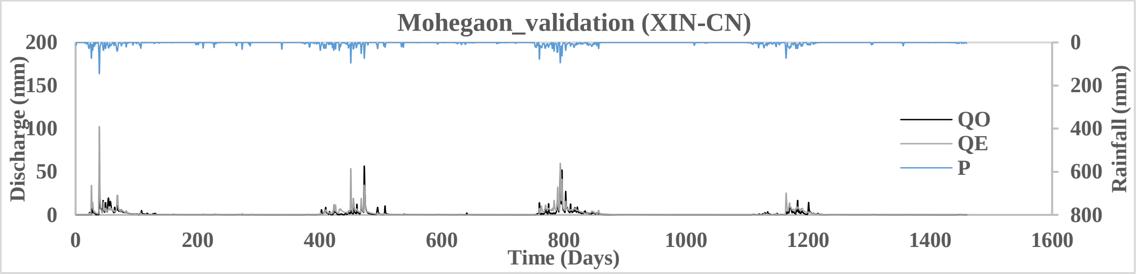
Mohegaon_validation (XIN-CN)
Discharge (mm)
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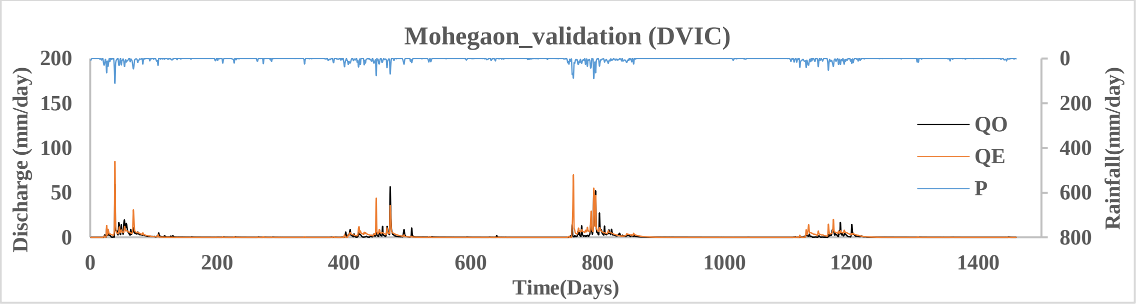
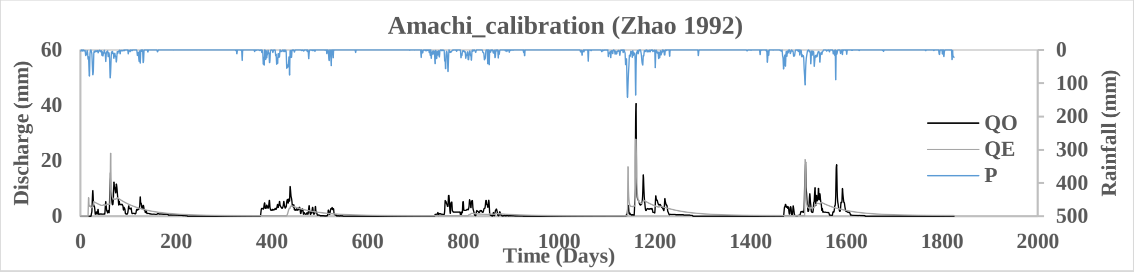
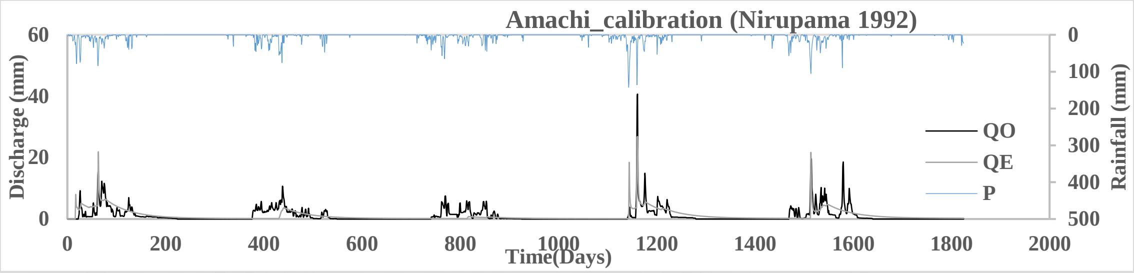
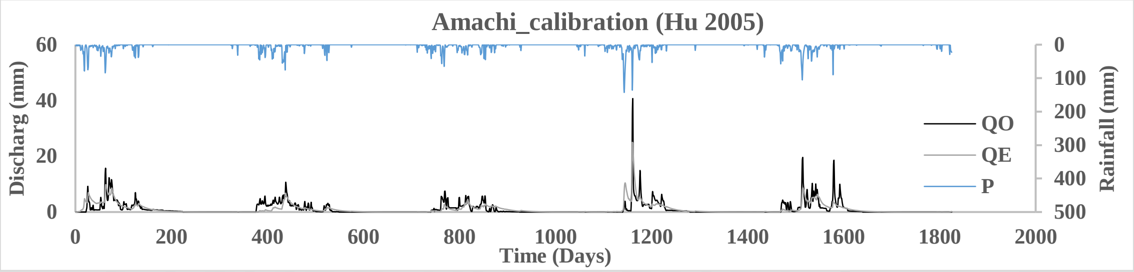
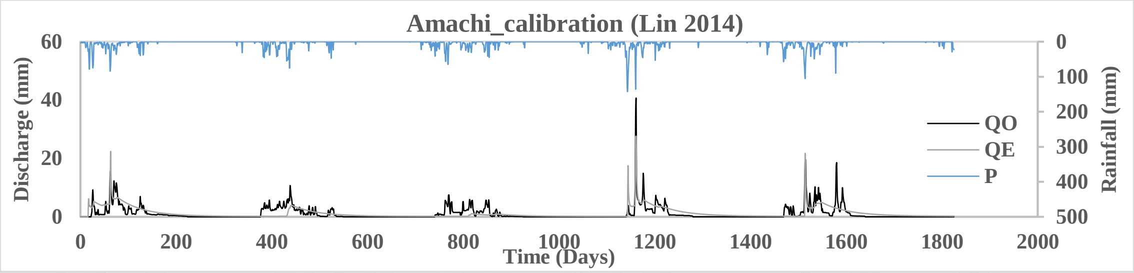
600
800
1000
1200
1400
1600
Time (Days)
Rainfall (mm)
0
200
400
600
800
QO
QE
P

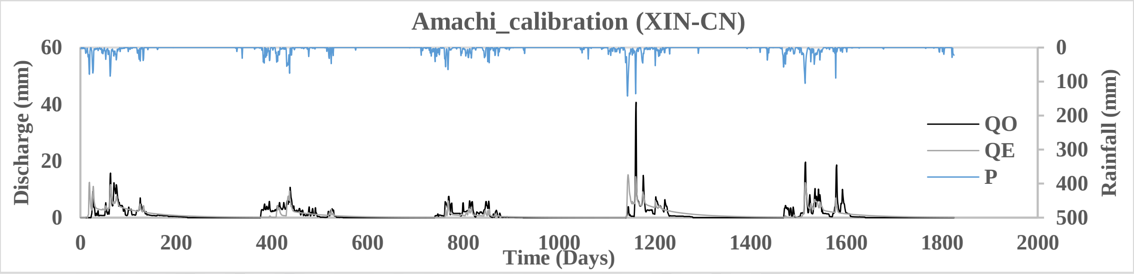

Mohegaon_validation (DVIC)
Discharge (mm/day)
200
150
100
50
0
0
200
400
600
800
1000
1200
1400
Time(Days)
Rainfall(mm/day)
0
200
400
600
800
QO
QE
P

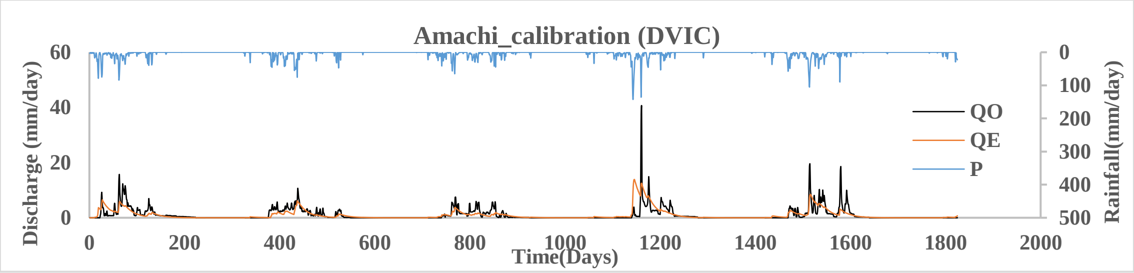

Amachi_calibration (Zhao 1992)
Discharge (mm)
60
40
20
0
Rainfall (mm)
0
100
200
300
400
500
QO
QE
P
0
200
400
600
800
1000
1200
1400
1600
1800
2000
Time (Days)

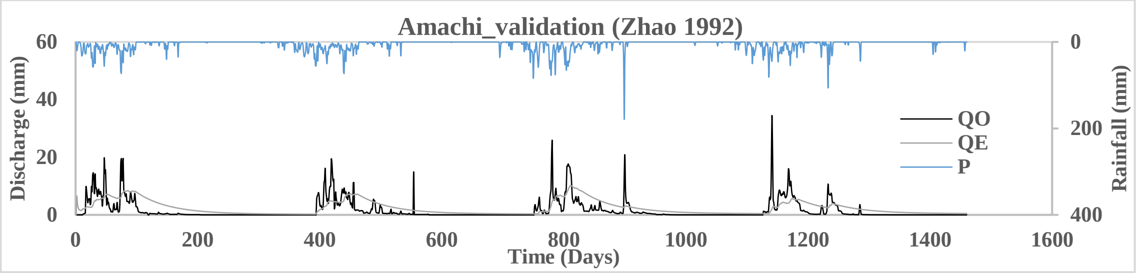

Amachi_calibration (Nirupama 1992)
Discharge (mm)
60
40
20
0
Rainfall (mm)
0
100
200
300
400
500
QO
QE
P
0
200
400
600
800
1000
1200
1400
1600
1800
2000
Time(Days)

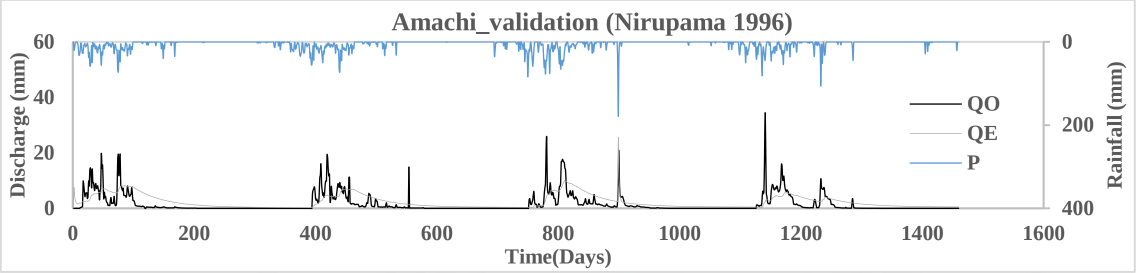

Amachi_calibration (Hu 2005)
Discharg (mm)
60
40
20
0
Rainfall (mm)
0
100
200
300
400
500
QO
QE
P
0
200
400
600
800
1000
1200
1400
1600
1800
2000
Time (Days)

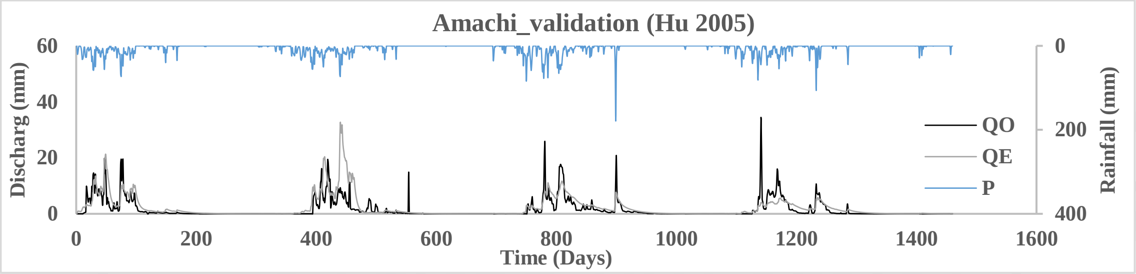

Amachi_calibration (Lin 2014)
Discharge (mm)
60
40
20
0
Rainfall (mm)
0
100
200
300
400
500
QO
QE
P
0
200
400
600
800
1000
1200
1400
1600
1800
2000
Time (Days)

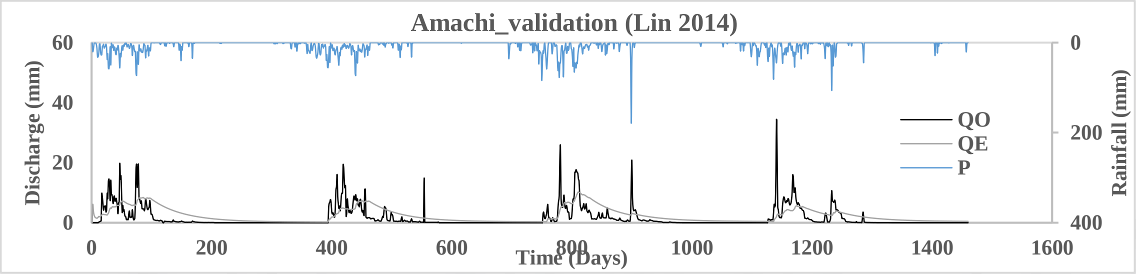

Amachi_calibration (XIN-CN)
Discharge (mm)
60
40
20
0
Rainfall (mm)
0
100
200
300
400
500
QO
QE
P
0
200
400
600
800
1000
1200
1400
1600
1800
2000
Time (Days)

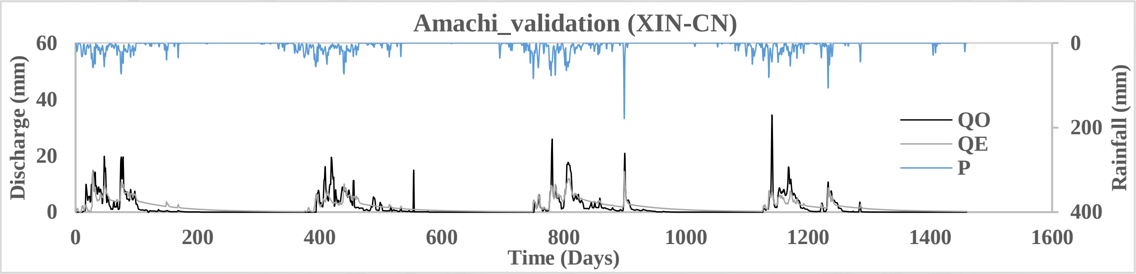

Amachi_calibration (DVIC)
Discharge (mm/day)
60
40
20
0
Rainfall(mm/day)
0
100
200
300
400
500
QO
QE
P
0
200
400
600
800
1000
1200
1400
1600
1800
2000
Time(Days)

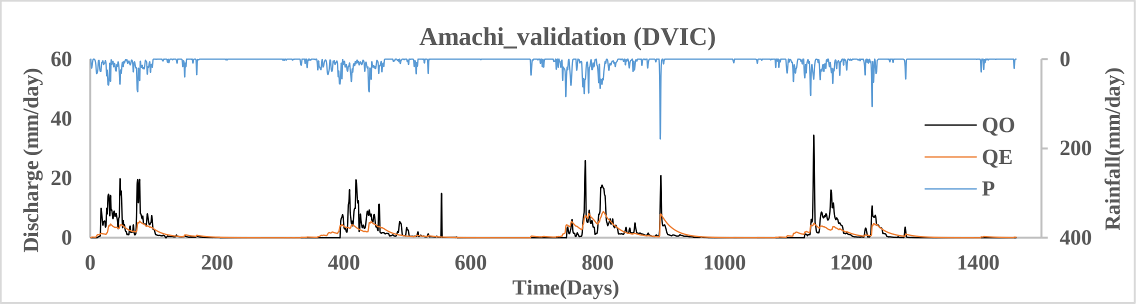

Amachi_validation (Zhao 1992)
Discharge (mm)
60
40
20
0
0
200
400
600
800
1000
1200
1400
1600
Time (Days)
Rainfall (mm)
0
200
400
QO
QE
P

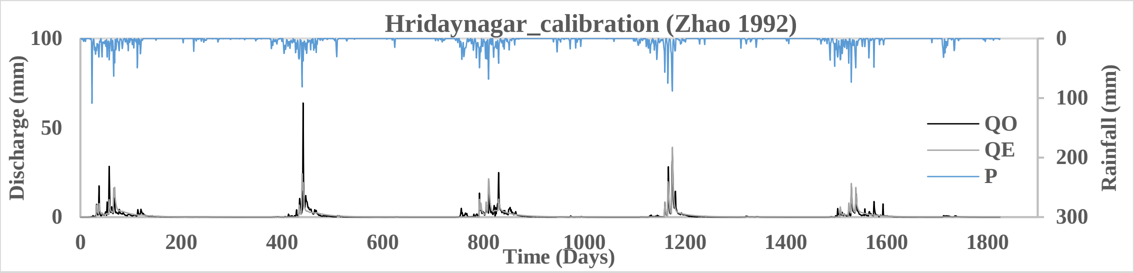

Amachi_validation (Nirupama 1996)
Discharge (mm)
60
40
20
0
0
200
400
600
800
1000
1200
1400
1600
Time(Days)
Rainfall (mm)
0
200
400
QO
QE
P

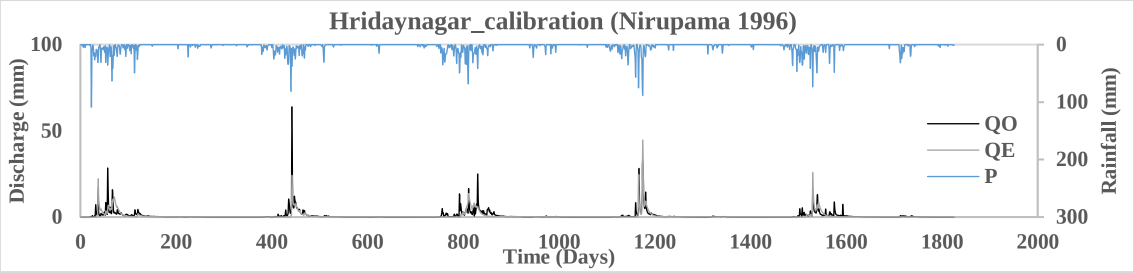

Amachi_validation (Hu 2005)
Discharg (mm)
60
40
20
0
0
200
400
600
800
1000
1200
1400
1600
Time (Days)
Rainfall (mm)
0
200
400
QO
QE
P

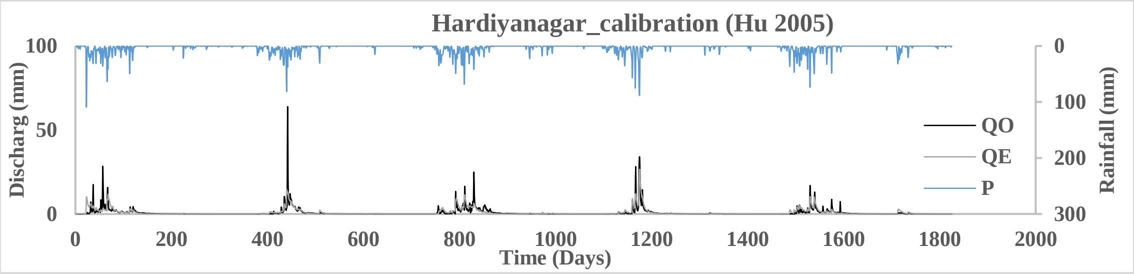

Amachi_validation (Lin 2014)
Discharge (mm)
60
40
20
0
0
200
400
600
800
1000
1200
1400
1600
Time (Days)
Rainfall (mm)
0
200
400
QO
QE
P

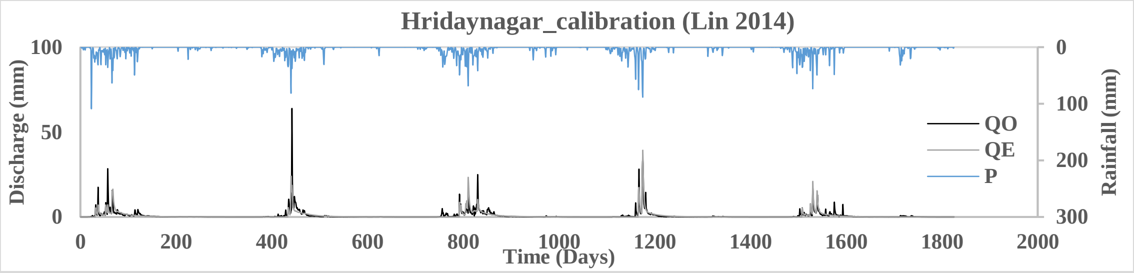

Amachi_validation (XIN-CN)
Discharge (mm)
60
40
20
0
0
200
400
600
800
1000
1200
1400
1600
Time (Days)
Rainfall (mm)
0
200
400
QO
QE
P

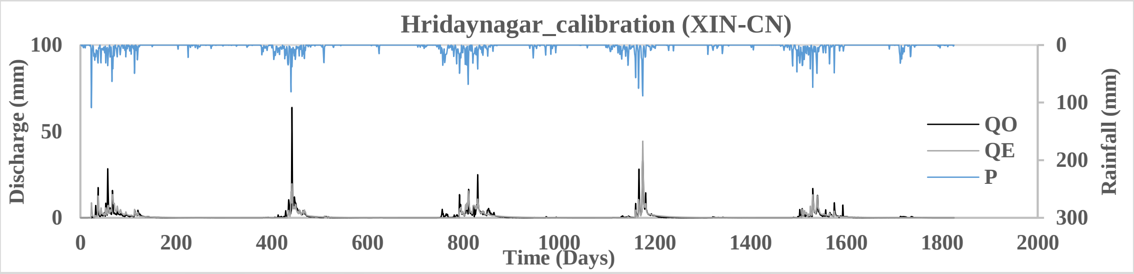

Amachi_validation (DVIC)
Discharge (mm/day)
60
40
20
0
0
200
400
600
800
1000
1200
1400
Time(Days)
Rainfall(mm/day)
0
200
400
QO
QE
P

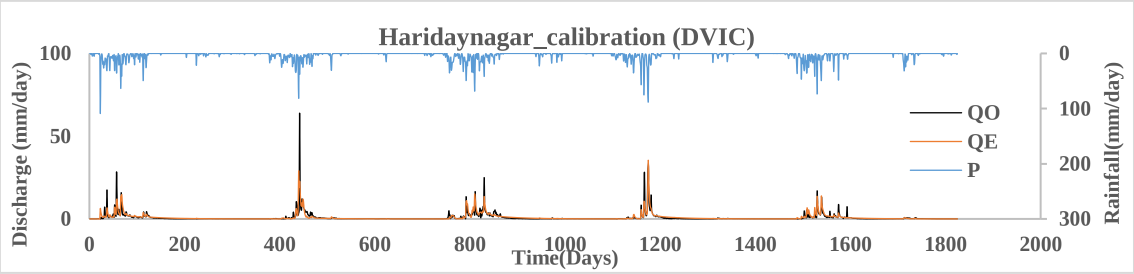

Hridaynagar_calibration (Zhao 1992)
Discharge (mm)
100
50
0
0
200
400
600
800
1000
1200
1400
1600
1800
Time (Days)
Rainfall (mm)
0
100
200
300
QO
QE
P

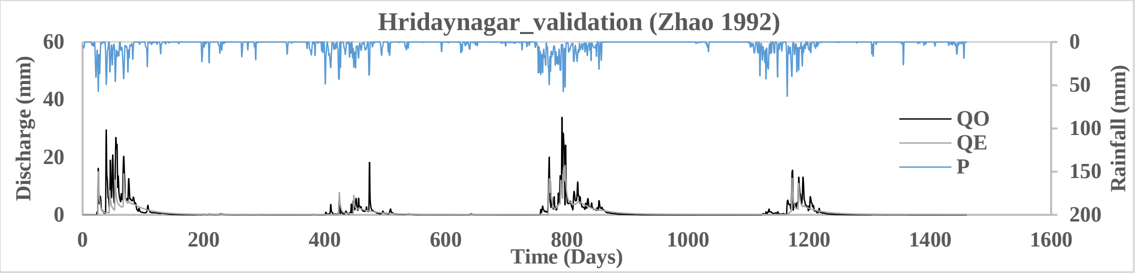

Hridaynagar_calibration (Nirupama 1996)
Discharge (mm)
100
50
0
0
200
400
600
800
1000
1200
1400
1600
1800
2000
Time (Days)
Rainfall (mm)
0
100
200
300
QO
QE
P

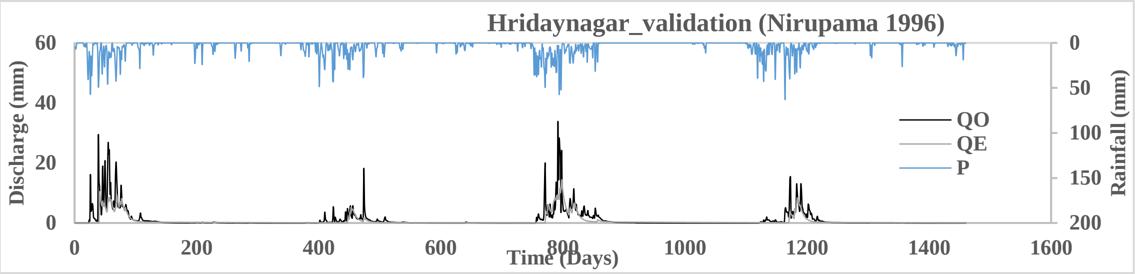

Hardiyanagar_calibration (Hu 2005)
Discharg (mm)
100
50
0
0
200
400
600
800
1000
1200
1400
1600
1800
2000
Time (Days)
Rainfall (mm)
0
100
200
300
QO
QE
P

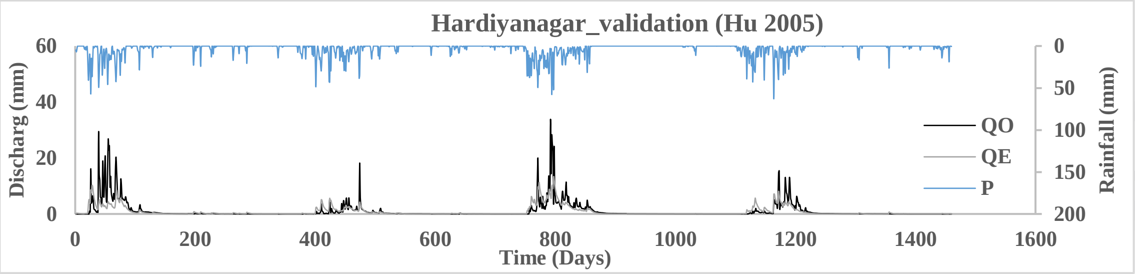

Hridaynagar_calibration (Lin 2014)
Discharge (mm)
100
50
0
0
200
400
600
800
1000
1200
1400
1600
1800
2000
Time (Days)
Rainfall (mm)
0
100
200
300
QO
QE
P

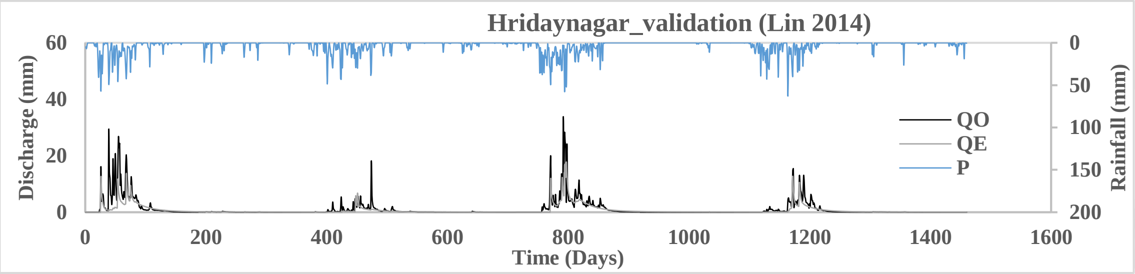

Hridaynagar_calibration (XIN-CN)
Discharge (mm)
100
50
0
0
200
400
600
800
1000
1200
1400
1600
1800
2000
Time (Days)
Rainfall (mm)
0
100
200
300
QO
QE
P

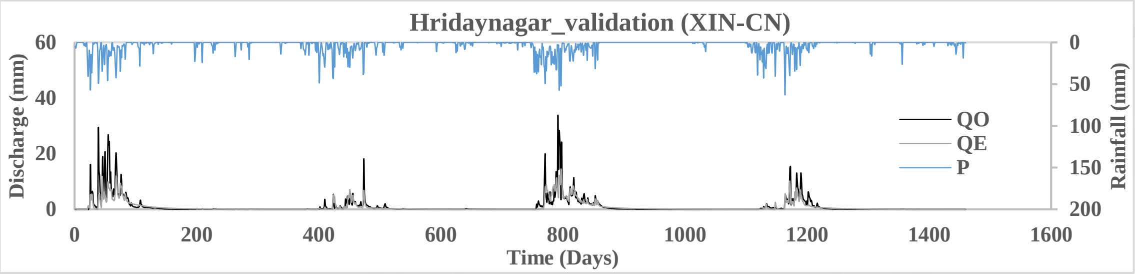

Haridaynagar_calibration (DVIC)
Discharge (mm/day)
100
50
0
0
200
400
600
800
1000
1200
1400
1600
1800
2000
Time(Days)
Rainfall(mm/day)
0
100
200
300
QO
QE
P

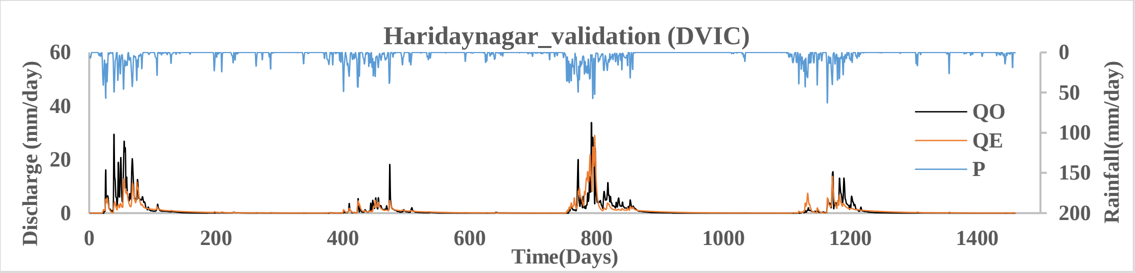

Hridaynagar_validation (Zhao 1992)
Discharge (mm)
60
40
20
0
0
200
400
600
800
1000
1200
1400
1600
Time (Days)
0
50
100
150
200
Rainfall (mm)
QO
QE
P


Hridaynagar_validation (Nirupama 1996)
Discharge (mm)
60
40
20
0
0
200
400
600
800
1000
1200
1400
1600
Time (Days)
0
50
100
150
200
Rainfall (mm)
QO
QE
P


Hardiyanagar_validation (Hu 2005)
Discharg (mm)
60
40
20
0
0
200
400
600
800
1000
1200
1400
1600
Time (Days)
0
50
100
150
200
Rainfall (mm)
QO
QE
P

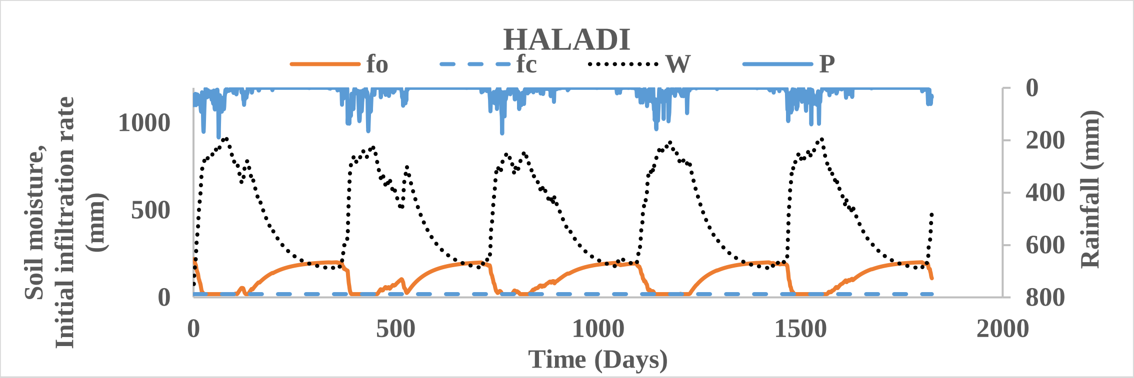

Hridaynagar_validation (Lin 2014)
Discharge (mm)
60
40
20
0
0
200
400
600
800
1000
1200
1400
1600
Time (Days)
0
50
100
150
200
Rainfall (mm)
QO
QE
P

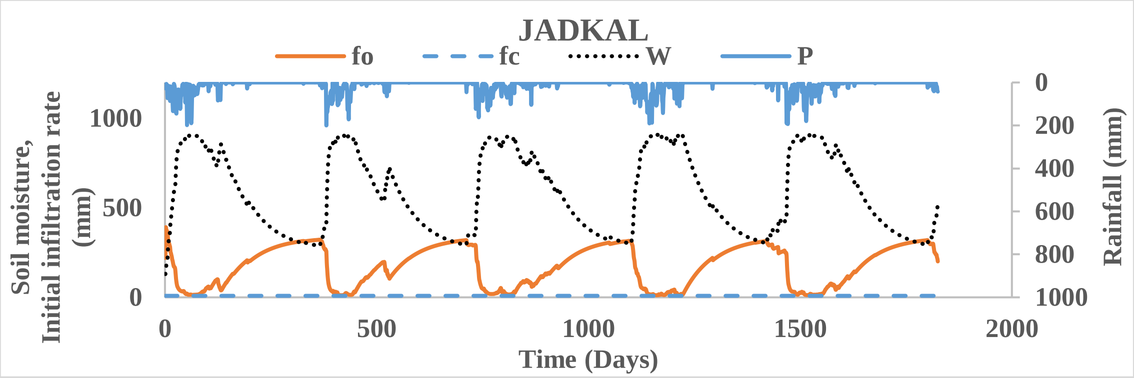

Hridaynagar_validation (XIN-CN)
Discharge (mm)
60
40
20
0
0
200
400
600
800
1000
1200
1400
1600
Time (Days)
0
50
100
150
200
Rainfall (mm)
QO
QE
P

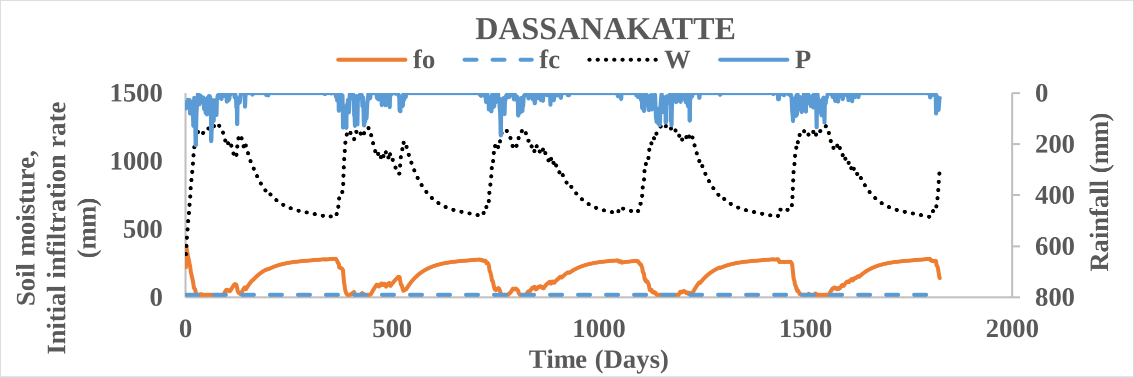

Haridaynagar_validation (DVIC)
Discharge (mm/day)
60
40
20
0
0
200
400
600
800
1000
1200
1400
Time(Days)
0
50
100
150
200
Rainfall(mm/day)
QO
QE
P

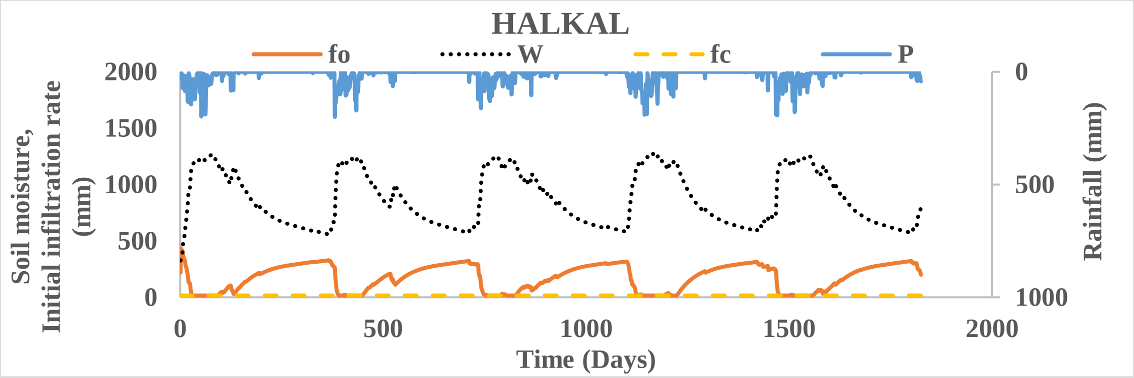
APPENDIX-III

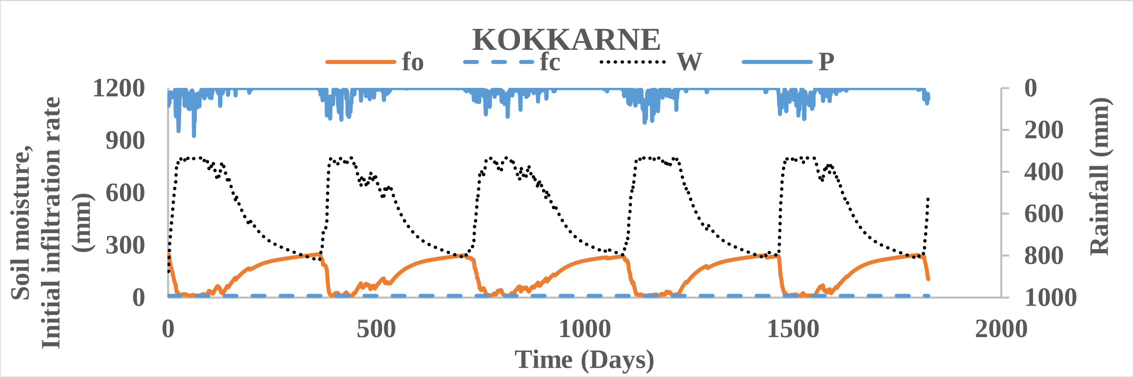
SOIL MOISTURE VS INITIAL INFILTRATION RATE (Fo) AND FINAL CONSTANT INFILTRATION RATE (Fc) IN DVIC MODEL

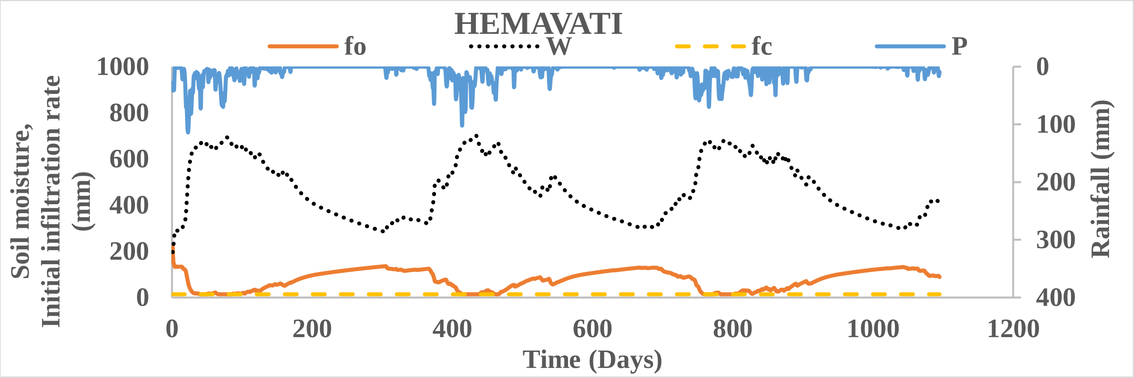


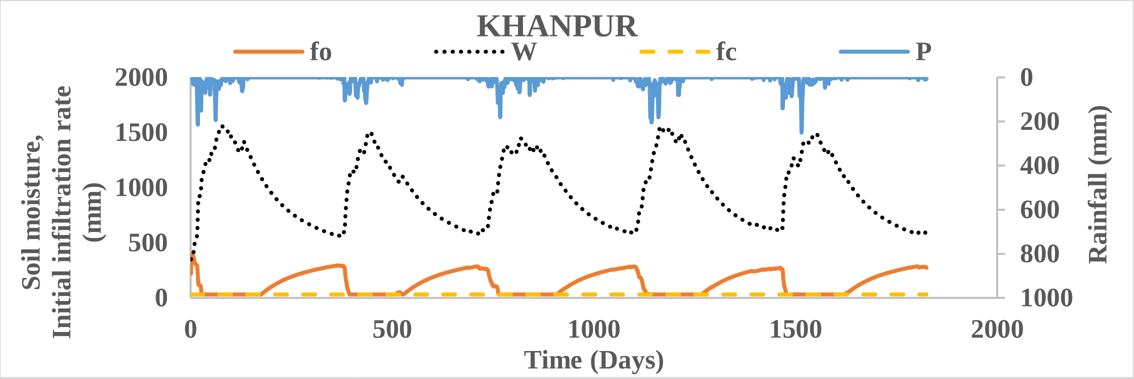


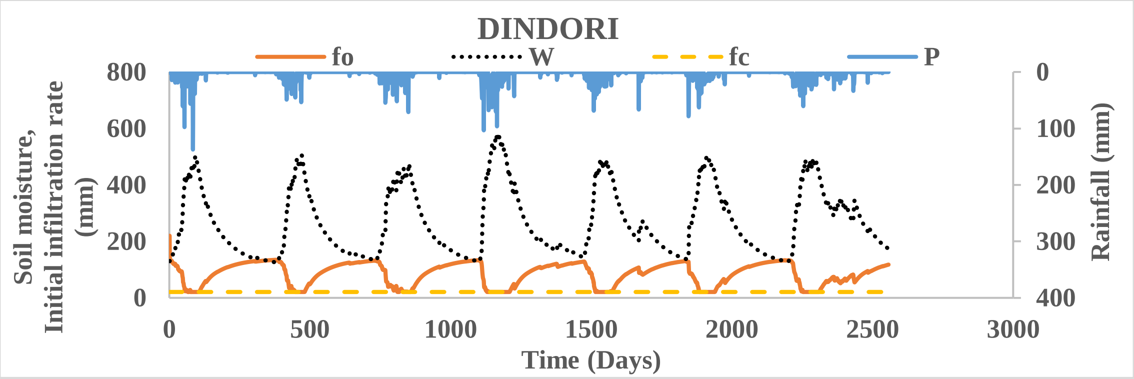


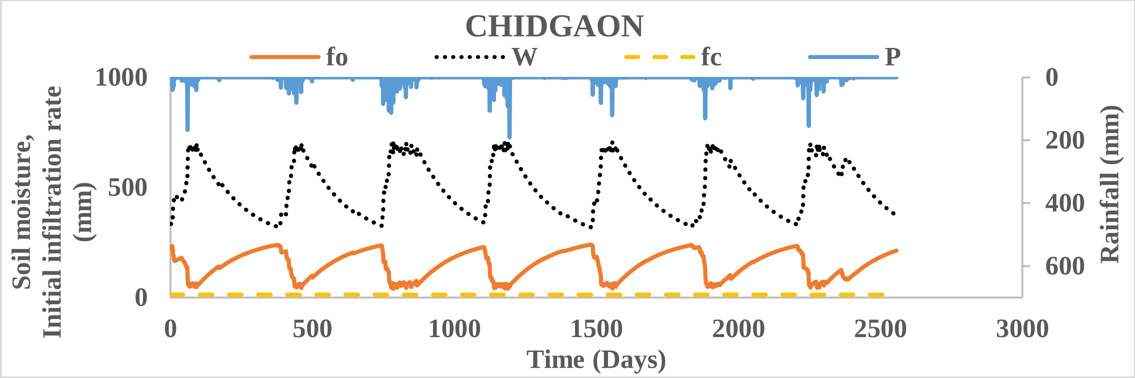


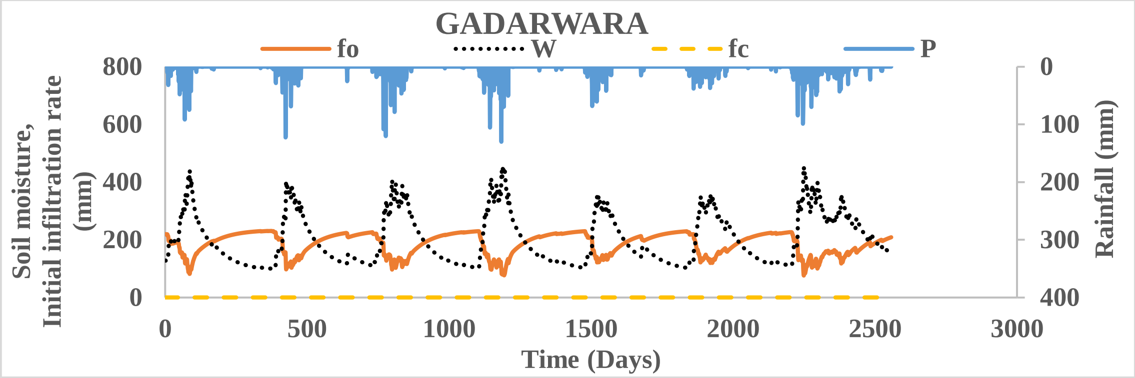

KOKKARNE
fo
fc
W
P
Soil moisture, Initial infiltration rate (mm)
1200
900
600
300
0
0
500
1000
1500
2000
Time (Days)
Rainfall (mm)
0
200
400
600
800
1000

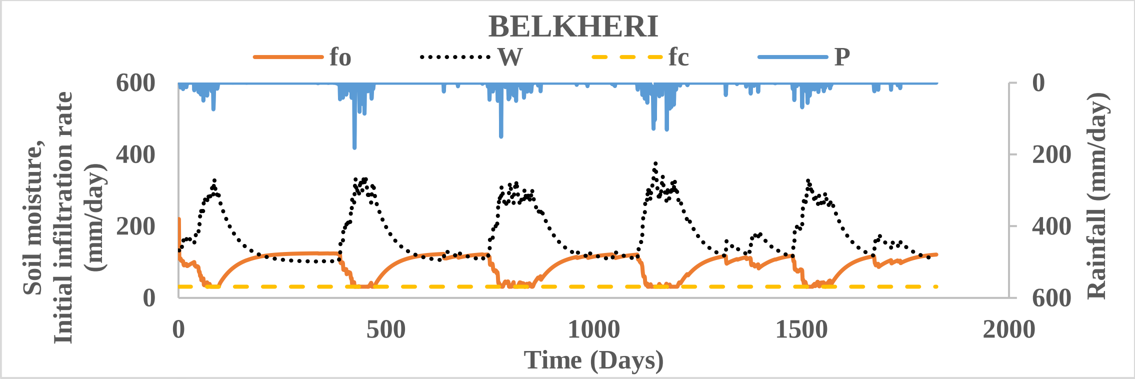

HEMAVATI
fo
W
fc
P
Soil moisture, Initial infiltration rate (mm)
1000
800
600
400
200
0
0
200
400
600
800
1000
1200
Time (Days)
Rainfall (mm)
0
100
200
300
400

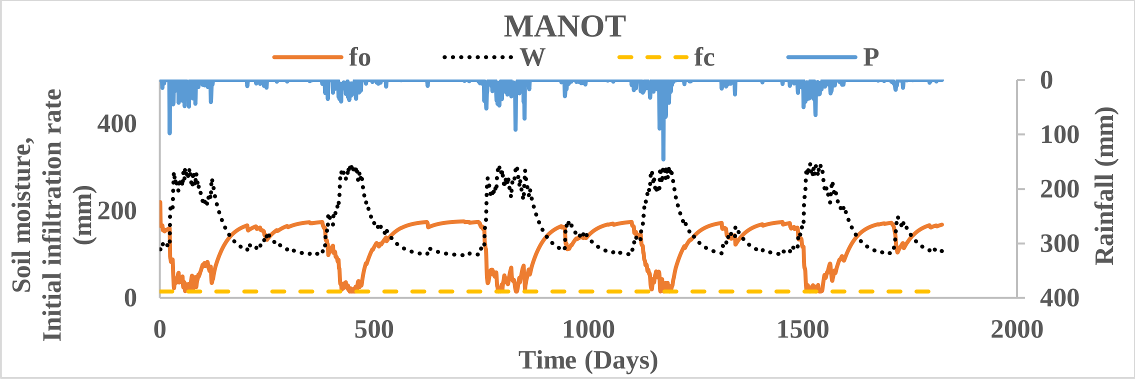

KHANPUR
fo
W
fc
P
Soil moisture, Initial infiltration rate (mm)
2000
1500
1000
500
0
0
500
1000
1500
2000
Time (Days)
Rainfall (mm)
0
200
400
600
800
1000

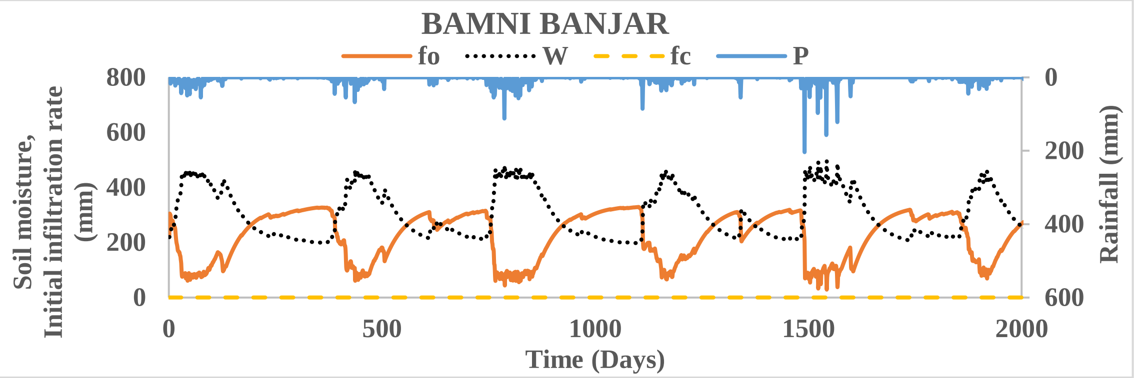

DINDORI
fo
W
fc
P
Soil moisture, Initial infiltration rate (mm)
800
600
400
200
0
0
500
1000
1500
2000
2500
3000
Time (Days)
Rainfall (mm)
0
100
200
300
400

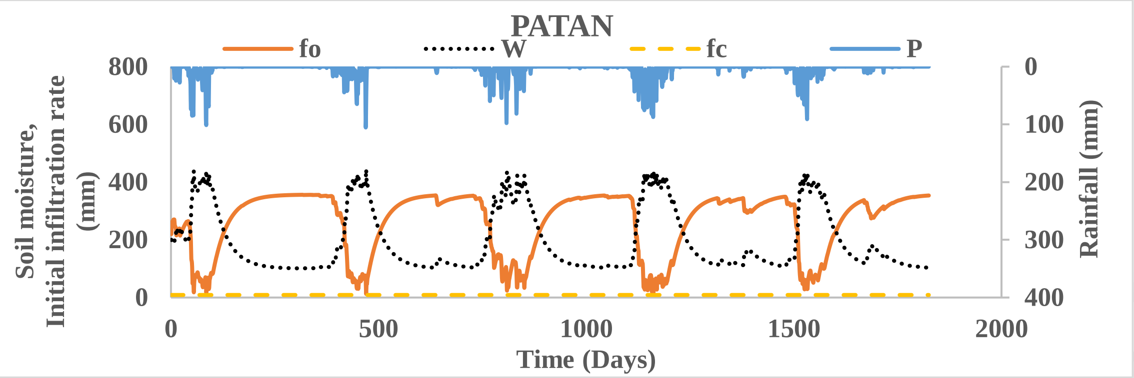

CHIDGAON
fo
W
fc
P
Soil moisture, Initial infiltration rate (mm)
1000
500
0
0
500
1000
1500
2000
2500
3000
Time (Days)
0
200
400
600
Rainfall (mm)

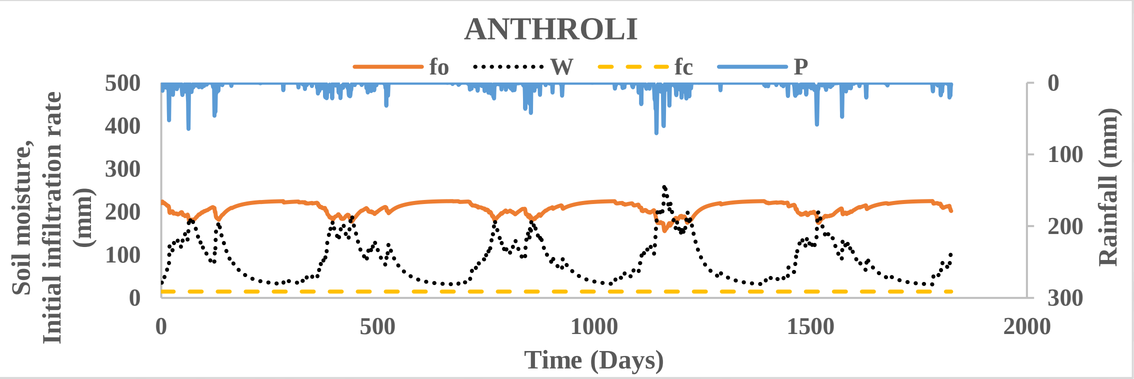

GADARWARA
fo
W
fc
P
Soil moisture, Initial infiltration rate (mm)
800
600
400
200
0
0
500
1000
1500
2000
2500
3000
Time (Days)
0
100
200
300
400
Rainfall (mm)

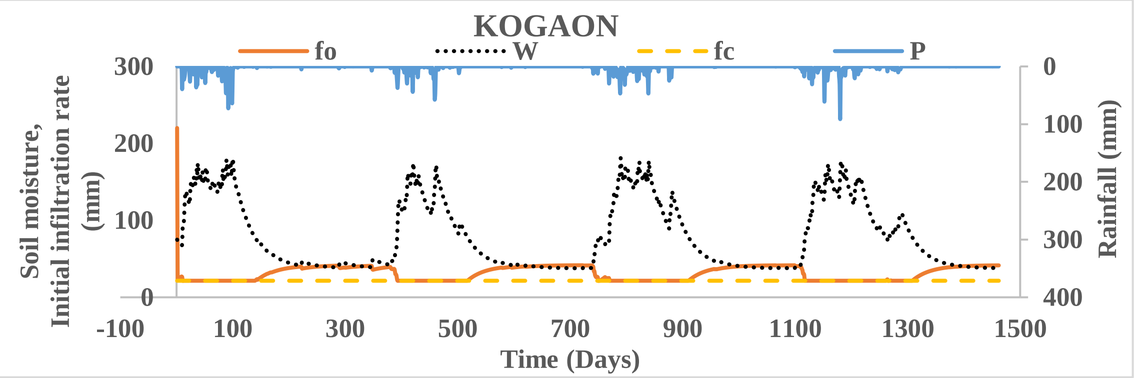

BELKHERI
fo
W
fc
P
Soil moisture, Initial infiltration rate (mm/day)
600
400
200
0
0
500
1000
1500
2000
Time (Days)
0
200
400
600
Rainfall (mm/day)

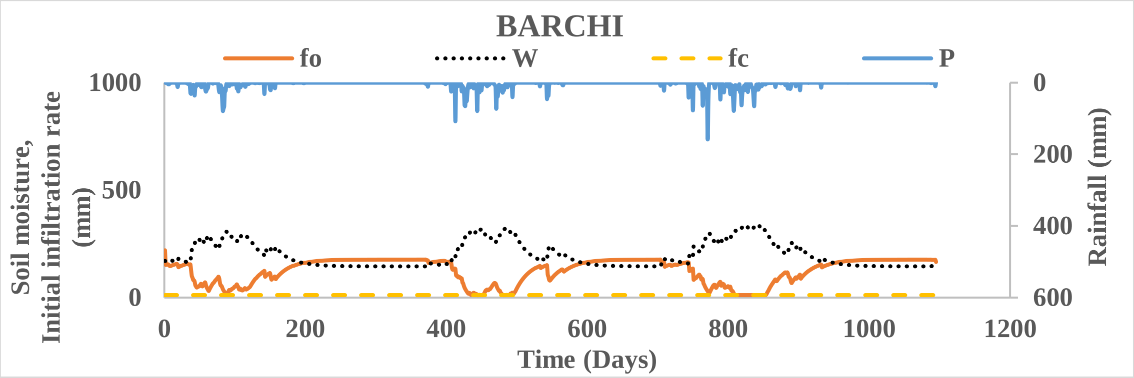

MANOT
fo
W
fc
P
Soil moisture, Initial infiltration rate (mm)
400
200
0
0
500
1000
1500
2000
Time (Days)
0
100
200
300
400
Rainfall (mm)

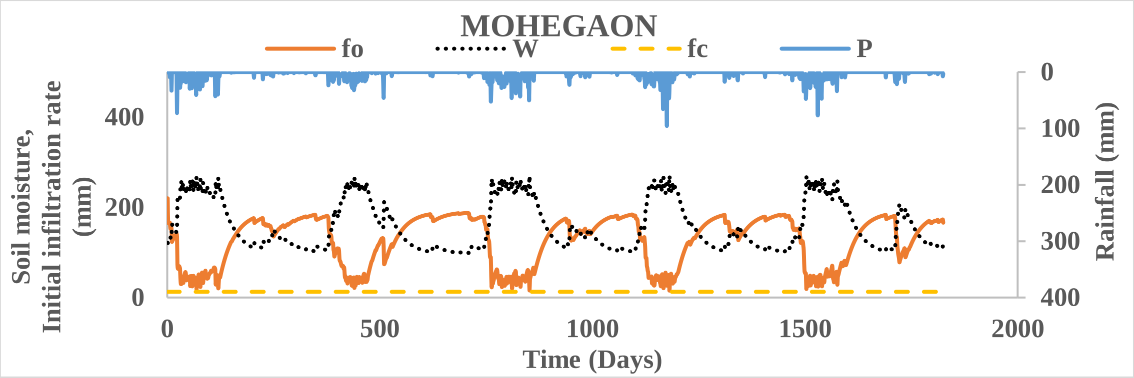

BAMNI BANJAR
fo
W
fc
P
Soil moisture, Initial infiltration rate (mm)
800
600
400
200
0
0
500
1000
1500
2000
Time (Days)
Rainfall (mm)
0
200
400
600

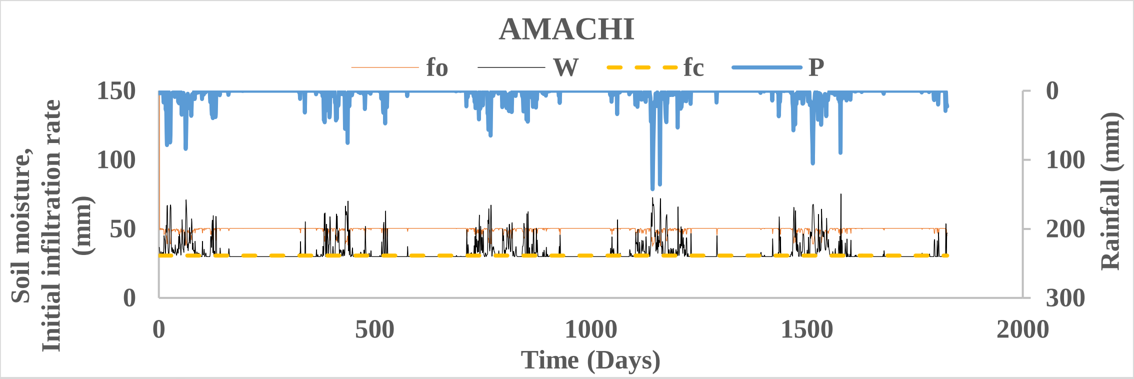

PATAN
fo
W
fc
P
Soil moisture, Initial infiltration rate (mm)
800
600
400
200
0
0
500
1000
1500
2000
Time (Days)
Rainfall (mm)
0
100
200
300
400

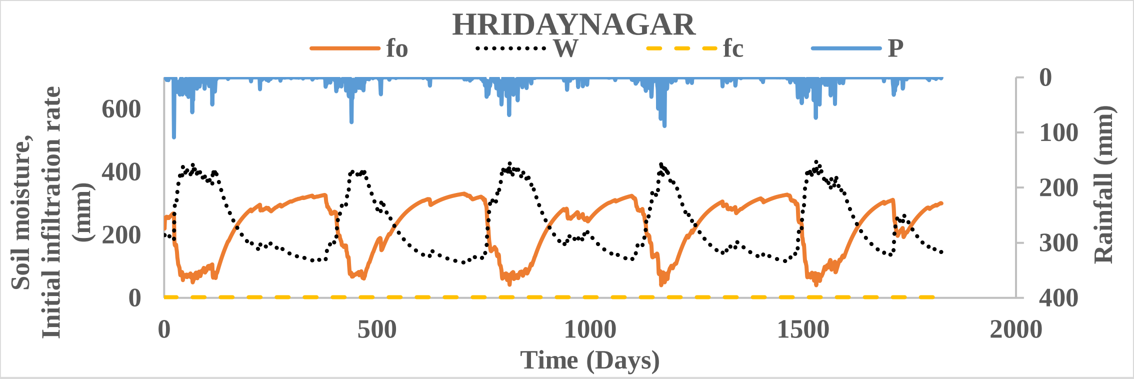

ANTHROLI
fo
W
fc
P
Soil moisture, Initial infiltration rate (mm)
500
400
300
200
100
0
0
500
1000
1500
2000
Time (Days)
Rainfall (mm)
0
100
200
300


KOGAON
fo
W
fc
P
Soil moisture, Initial infiltration rate (mm)
300
200
100
0
-100
100
300
500
700
900
1100
1300
1500
Time (Days)
Rainfall (mm)
0
100
200
300
400

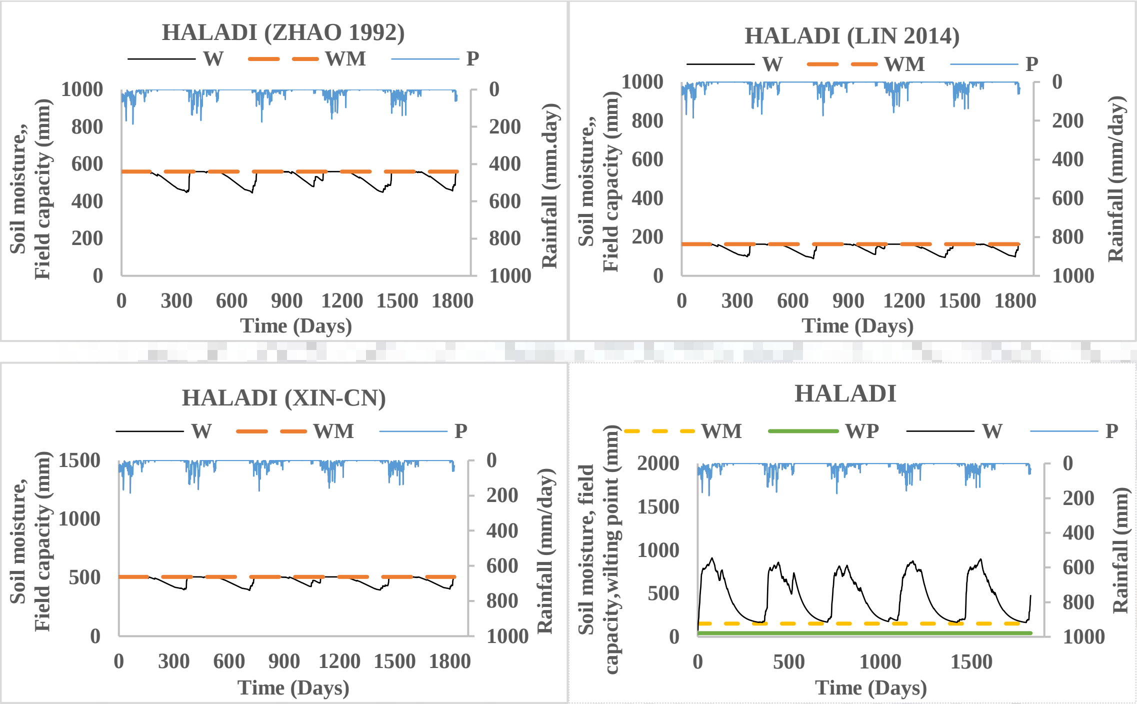

BARCHI
fo
W
fc
P
Soil moisture, Initial infiltration rate (mm)
1000
500
0
0
200
400
600
800
1000
1200
Time (Days)
0
200
400
600
Rainfall (mm)


MOHEGAON
fo
W
fc
P
Soil moisture, Initial infiltration rate (mm)
400
200
0
0
500
1000
1500
2000
Time (Days)
0
100
200
300
400
Rainfall (mm)

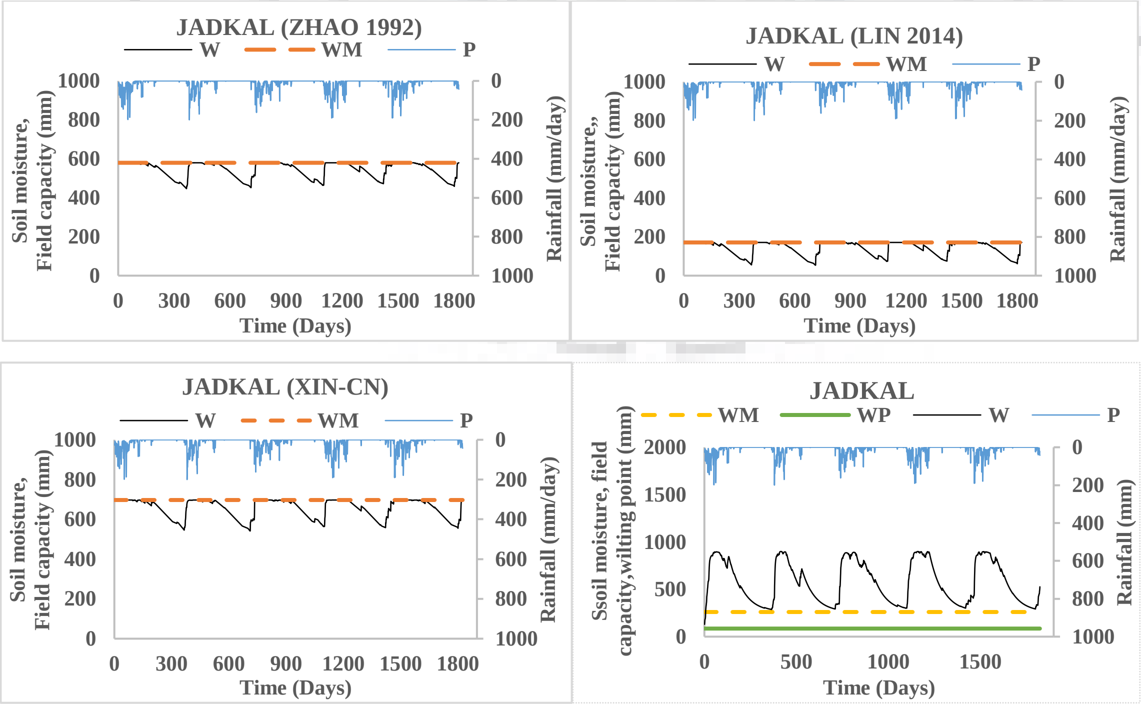

AMACHI
fo
W
fc
P
Soil moisture, Initial infiltration rate (mm)
150
100
50
0
0
500
1000
1500
2000
Time (Days)
0
100
200
300
Rainfall (mm)


HRIDAYNAGAR
fo
W
fc
P
Soil moisture, Initial infiltration rate (mm)
600
400
200
0
0
500
1000
1500
2000
Time (Days)
0
100
200
300
400
Rainfall (mm)

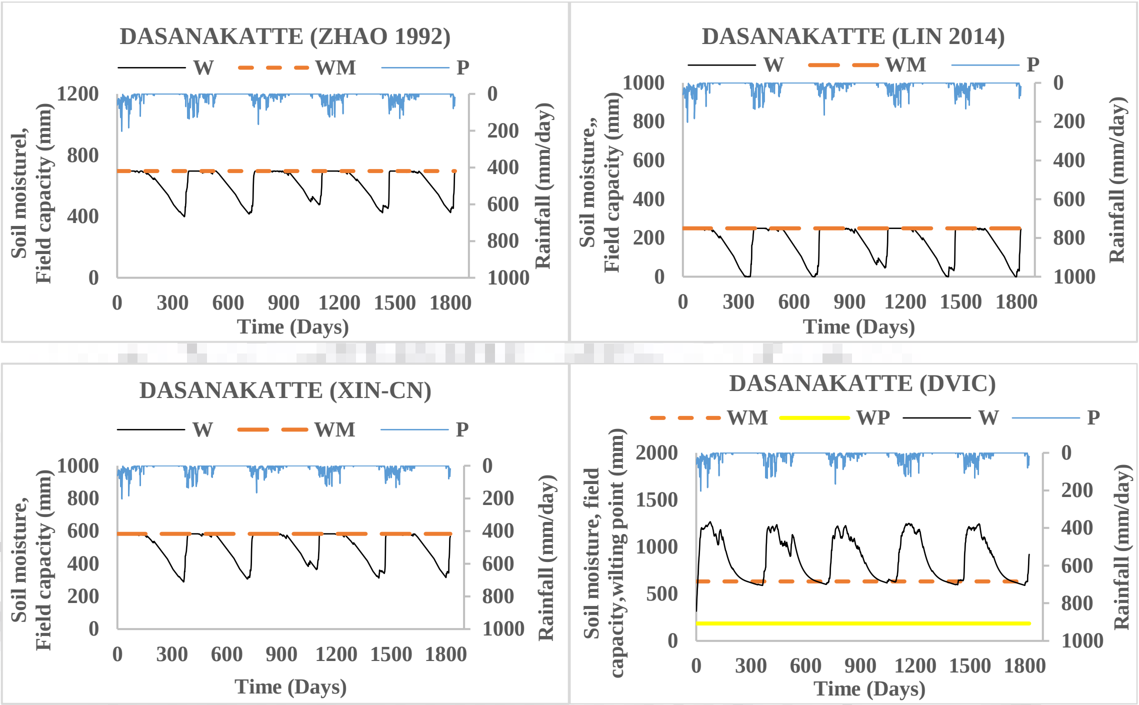
APPENDIX-IV COMPARISON OF SOIL MOISTURE PROFILE OF STUDIED CATCHMENTS OBTAINED FROM ORIGINAL XINANJIANG MODEL *ZHAO (1992), LIN ET AL. (2014)* AND PROPOSED VERSIONS OF XINANJIANG MODEL *XIN-CN* AND *DVIC* MODEL



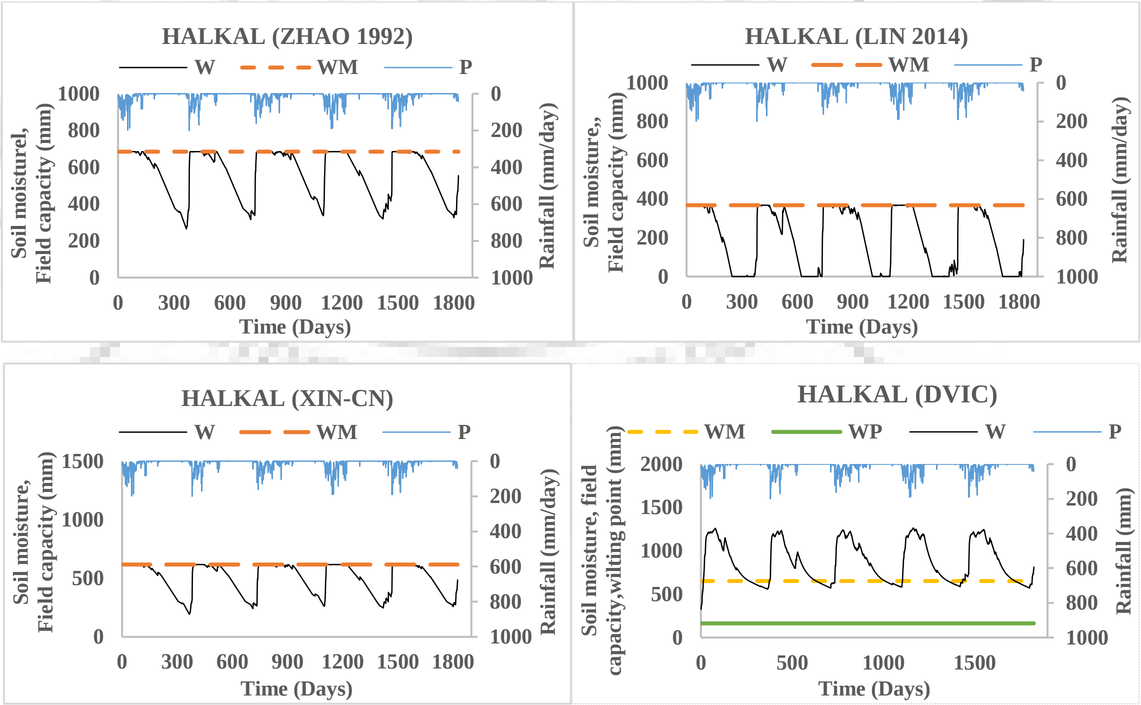
(1)



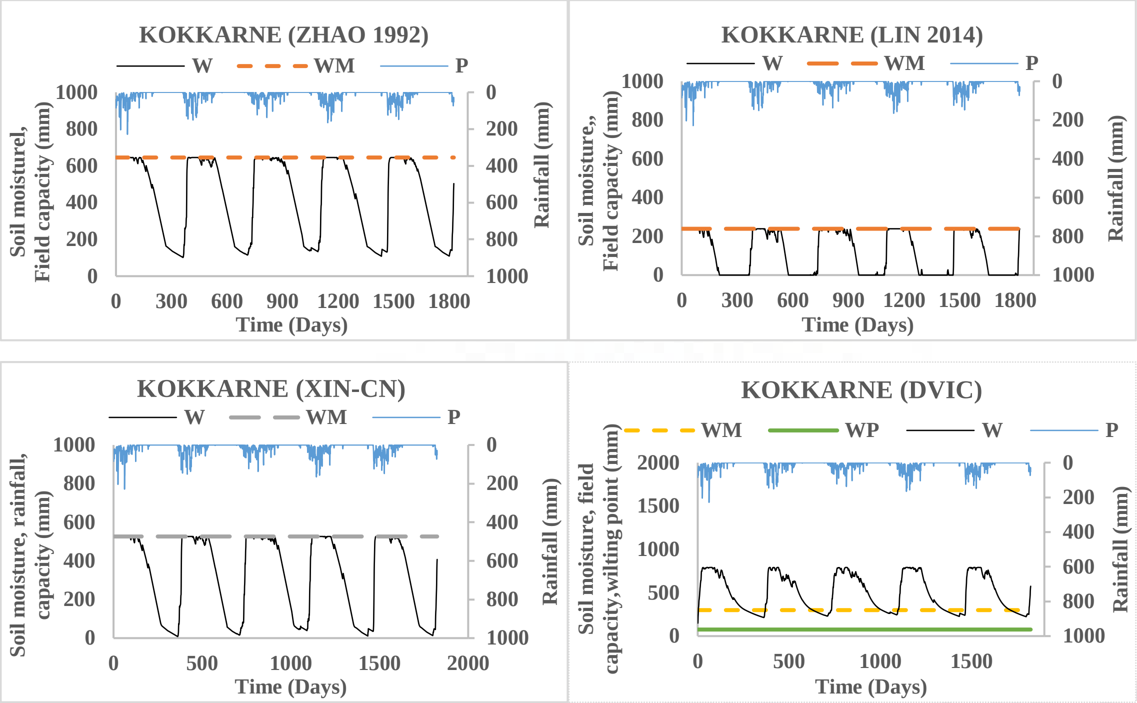
(2)


DASANAKATTE (ZHAO 1992)
W
WM
P
Soil moisture, Field capacity (mm)
0
400
800
1200
Rainfall (mm/day)
0
200
400
600
800
1000
0 300 600 900 1200 1500 1800
Time (Days)
DASANAKATTE (LIN 2014)
W
WM
P
Soil moisture,, Field capacity (mm)
0
200
400
600
800
1000
Rainfall (mm/day)
0 300 600 900 1200 1500 1800
Time (Days)
DASANAKATTE (XIN-CN)
W
WM
P
Soil moisture, Field capacity (mm)
0
200
400
600
800
1000
Rainfall (mm/day)
0 300 600 900 1200 1500 1800
Time (Days)
DASANAKATTE (DVIC)
WM
WP
W
P
Soil moisture, field capacity,wilting point (mm)
0
500
1000
1500
2000
Rainfall (mm/day)
0 300 600 900 1200 1500 1800
Time (Days)

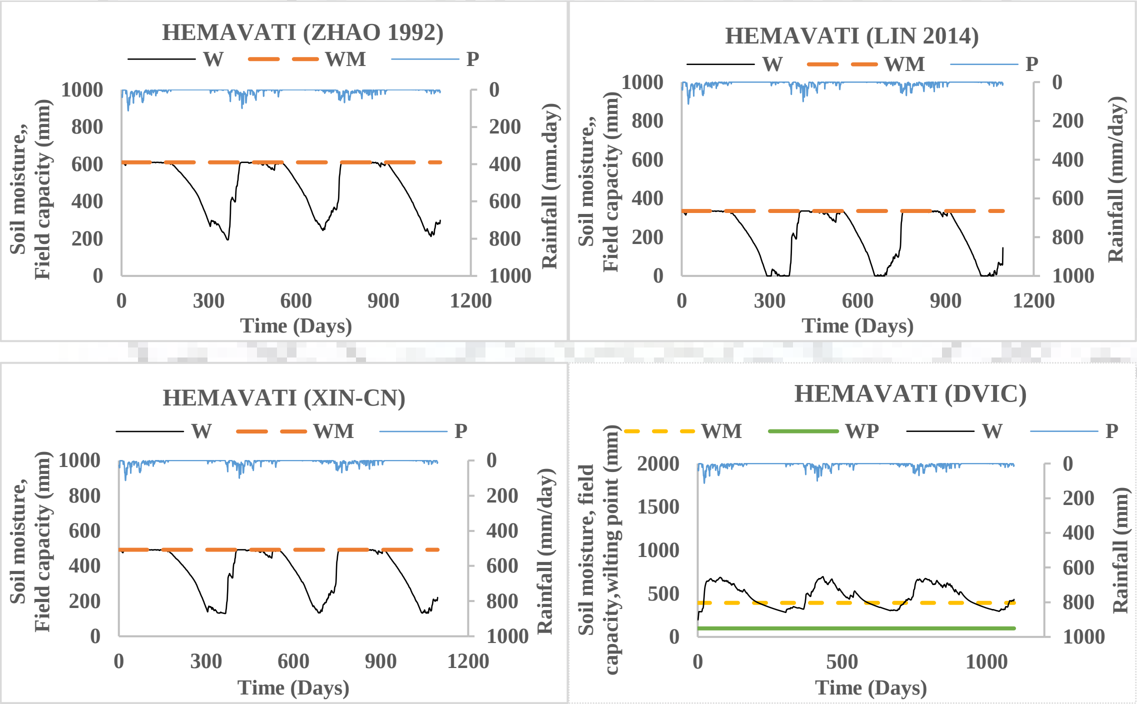
(3)


HALKAL (ZHAO 1992)
W
WM
P
Soil moisture,l, Field capacity (mm)
0
200
400
600
800
1000
Rainfall (mm/day)
0 300 600 900 1200 1500 1800
Time (Days)
HALKAL (LIN 2014)
W
WM
P
Soil moisture,, Field capacity (mm)
0
200
400
600
800
1000
Rainfall (mm/day)
0 300 600 900 1200 1500 1800
Time (Days)
HALKAL (XIN-CN)
W
WM
P
Soil moisture, Field capacity (mm)
0
500
1000
1500
Rainfall (mm/day)
0
200
400
600
800
1000
0 300 600 900 1200 1500 1800
Time (Days)
HALKAL (DVIC)
WM
WP
W
P
Soil moisture, field capacity,wilting point (mm)
0
500
1000
1500
2000
Rainfall (mm)
0 500 1000 1500
Time (Days)

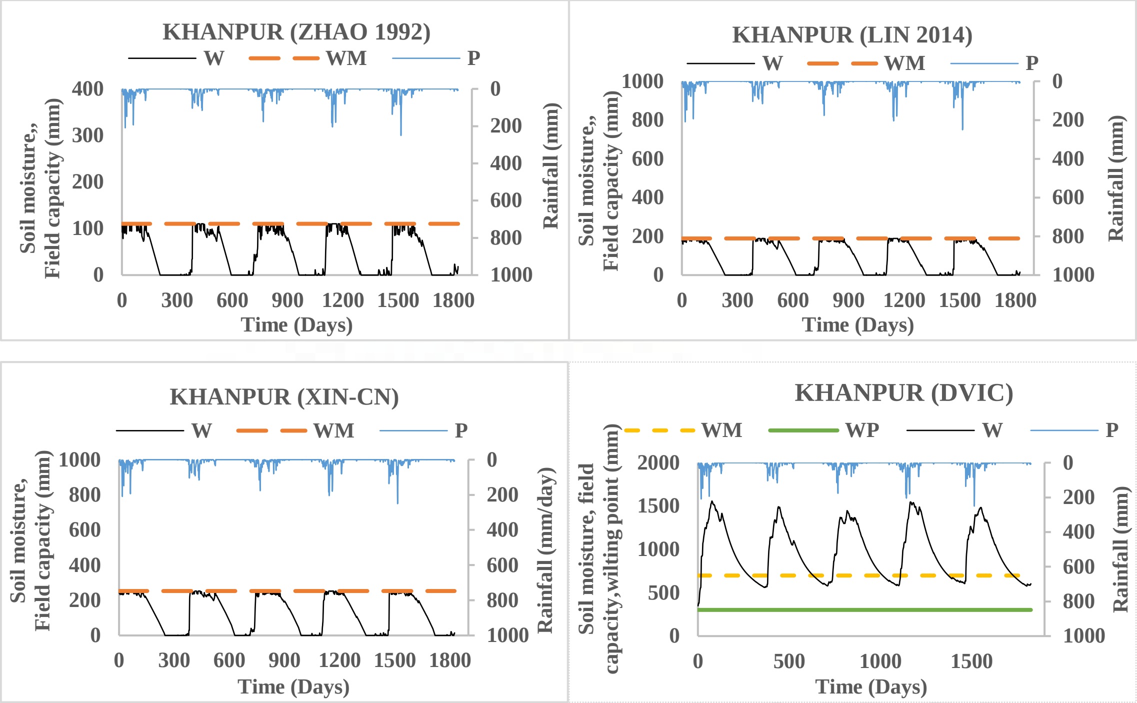
(4)


KOKKARNE (ZHAO 1992)
W
WM
P
Soil moisture, Field capacity (mm)
Rainfall (mm)
Time (Days)
KOKKARNE (LIN 2014)
W
WM
P
Soil moisture,, Field capacity (mm)
Rainfall (mm)
Time (Days)
KOKKARNE (XIN-CN)
W
WM
P
Soil moisture, rainfall, capacity (mm)
Rainfall (mm)
Time (Days)
KOKKARNE (DVIC)
WM
WP
W
P
Soil moisture, field capacity,wilting point (mm)
Rainfall (mm)
Time (Days)

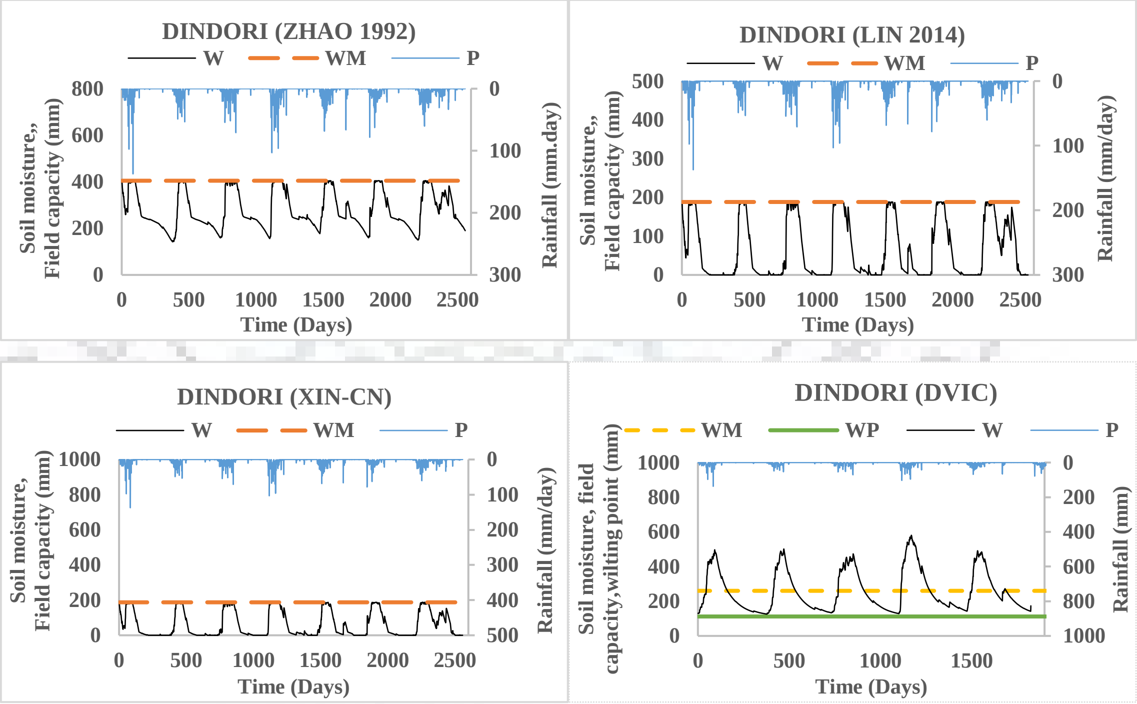
(5)


HEMAVATI (ZHAO 1992)
W
WM
P
Soil moisture,, Field capacity (mm)
Rainfall (mm.day)
Time (Days)
HEMAVATI (LIN 2014)
W
WM
P
Soil moisture,, Field capacity (mm)
Rainfall (mm/day)
Time (Days)
HEMAVATI (XIN-CN)
W
WM
P
Soil moisture, Field capacity (mm)
Rainfall (mm/day)
Time (Days)
HEMAVATI (DVIC)
WM
WP
W
P
Soil moisture, field capacity,wilting point (mm)
Rainfall (mm)
Time (Days)

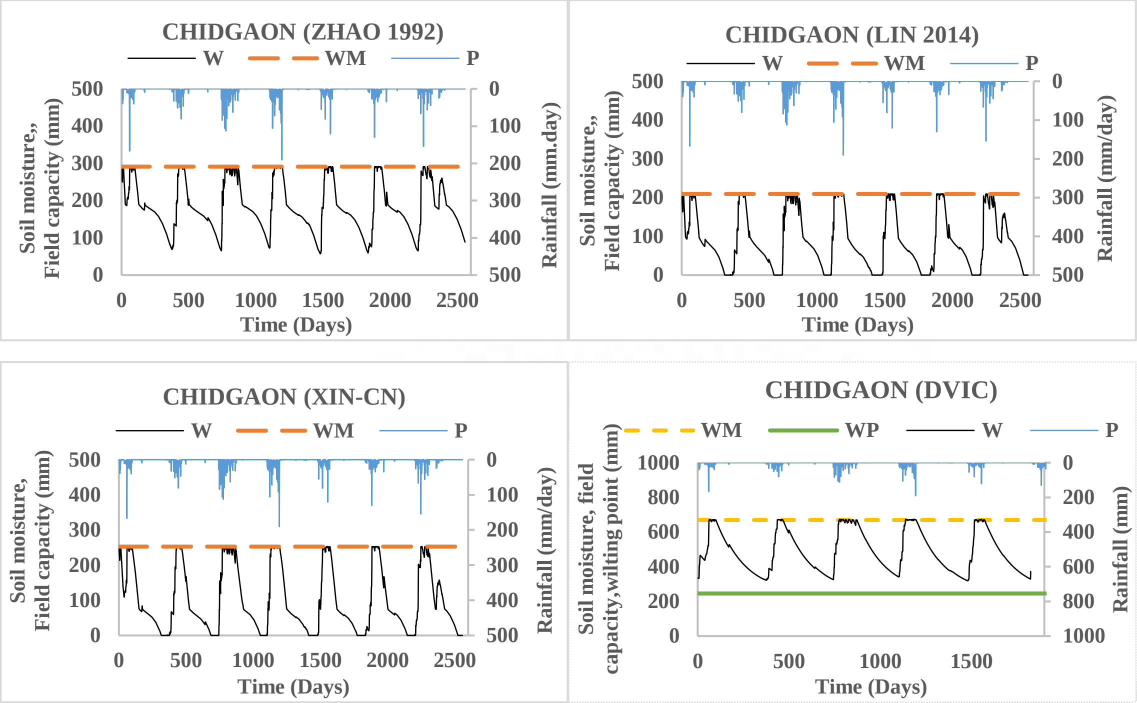
(6)


KHANPUR (ZHAO 1992)
W
WM
P
Soil moisture,, Field capacity (mm)
0
100
200
300
400
Rainfall (mm)
0
200
400
600
800
1000
Time (Days)
0
300
600
900
1200
1500
1800
KHANPUR (LIN 2014)
W
WM
P
Soil moisture,, Field capacity (mm)
0
200
400
600
800
1000
Rainfall (mm)
Time (Days)
KHANPUR (XIN-CN)
W
WM
P
Soil moisture, Field capacity (mm)
Rainfall (mm/day)
Time (Days)
KHANPUR (DVIC)
WM
WP
W
P
Soil moisture, field capacity,wilting point (mm)
0
500
1000
1500
2000
Rainfall (mm)
Time (Days)
0
500
1000
1500

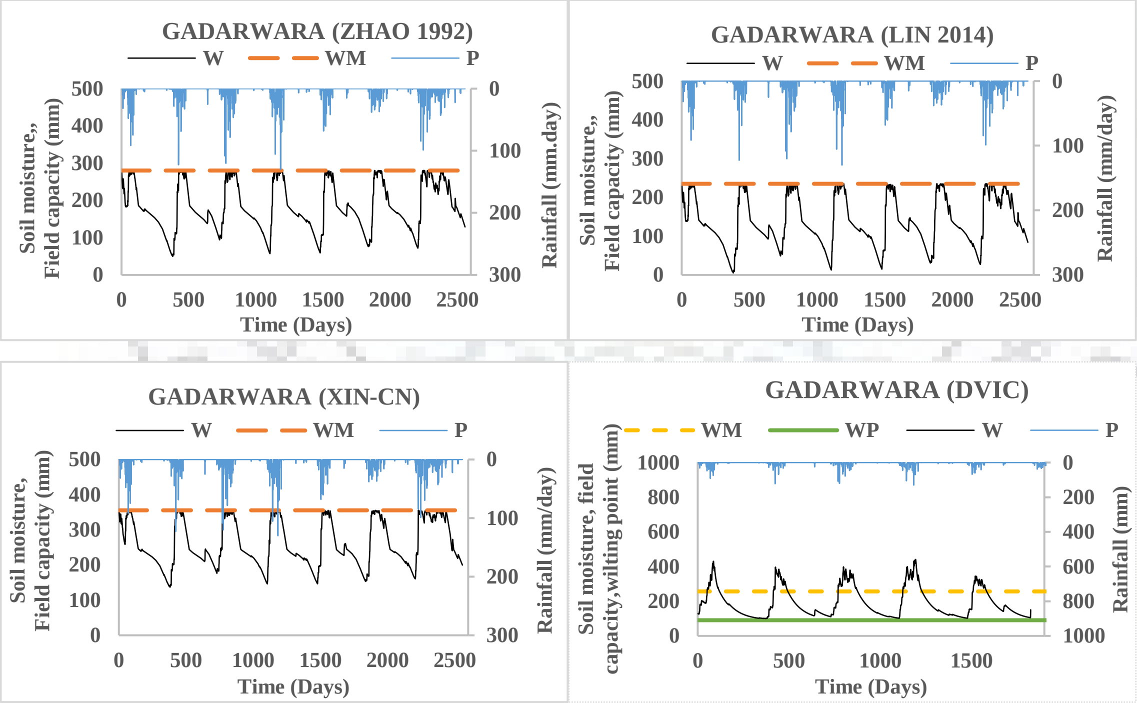
(7)


DINDORI (ZHAO 1992)
W
WM
P
Soil moisture,, Field capacity (mm)
0
200
400
600
800
Rainfall (mm.day)
0
100
200
300
Time (Days)
0
500
1000
1500
2000
2500
DINDORI (LIN 2014)
W
WM
P
Soil moisture,, Field capacity (mm)
0
100
200
300
400
500
Rainfall (mm/day)
Time (Days)
DINDORI (XIN-CN)
W
WM
P
Soil moisture, Field capacity (mm)
0
200
400
600
800
1000
Rainfall (mm/day)
0
100
200
300
400
500
Time (Days)
DINDORI (DVIC)
WM
WP
W
P
Soil moisture, field capacity,wilting point (mm)
Rainfall (mm)
0
200
400
600
800
1000
Time (Days)
0
500
1000
1500

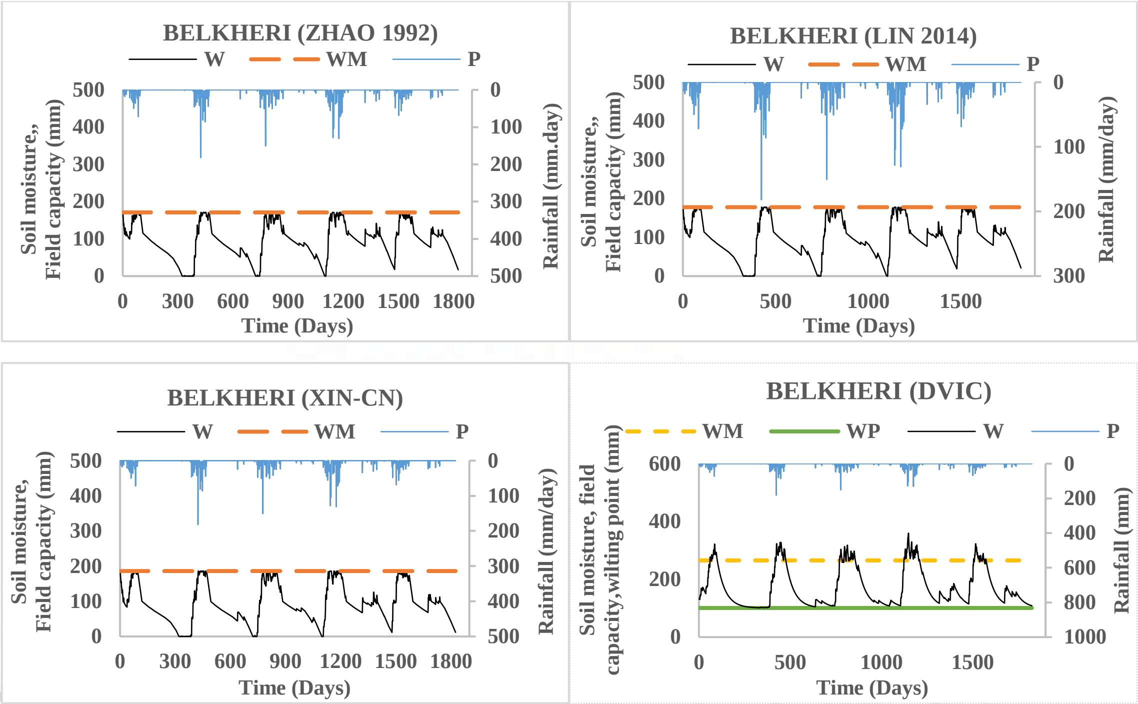
(8)


CHIDGAON (ZHAO 1992)
W
WM
P
Soil moisture,, Field capacity (mm)
Rainfall (mm.day)
0
100
200
300
400
500
0
500
1000
1500
2000
2500
Time (Days)
CHIDGAON (LIN 2014)
W
WM
P
Soil moisture,, Field capacity (mm)
Rainfall (mm/day)
Time (Days)
CHIDGAON (XIN-CN)
W
WM
P
Soil moisture, Field capacity (mm)
Rainfall (mm/day)
Time (Days)
CHIDGAON (DVIC)
WM
WP
W
P
Soil moisture, field capacity,wilting point (mm)
Rainfall (mm)
0
200
400
600
800
1000
0
500
1000
1500
Time (Days)

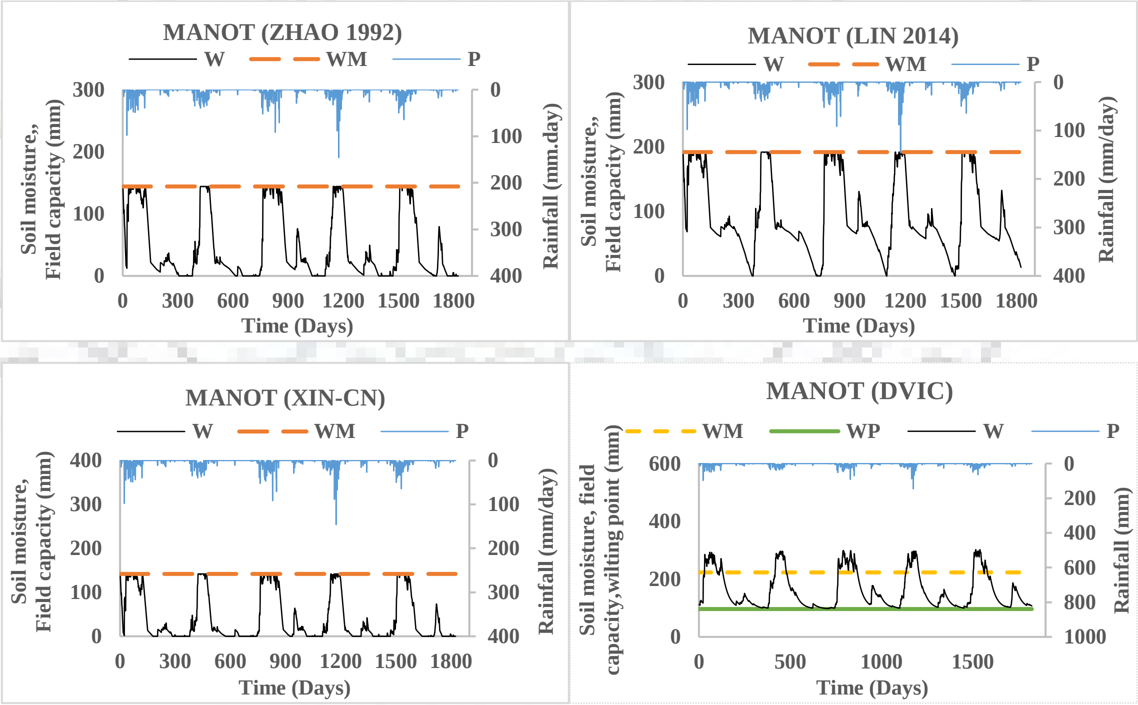
(9)


GADARWARA (ZHAO 1992)
W
WM
P
Soil moisture,, Field capacity (mm)
Rainfall (mm.day)
0
100
200
300
400
500
0
500
1000
1500
2000
2500
Time (Days)
GADARWARA (LIN 2014)
W
WM
P
Soil moisture,, Field capacity (mm)
Rainfall (mm/day)
Time (Days)
GADARWARA (XIN-CN)
W
WM
P
Soil moisture, Field capacity (mm)
Rainfall (mm/day)
Time (Days)
GADARWARA (DVIC)
WM
WP
W
P
Soil moisture, field capacity,wilting point (mm)
Rainfall (mm)
0
200
400
600
800
1000
0
500
1000
1500
Time (Days)

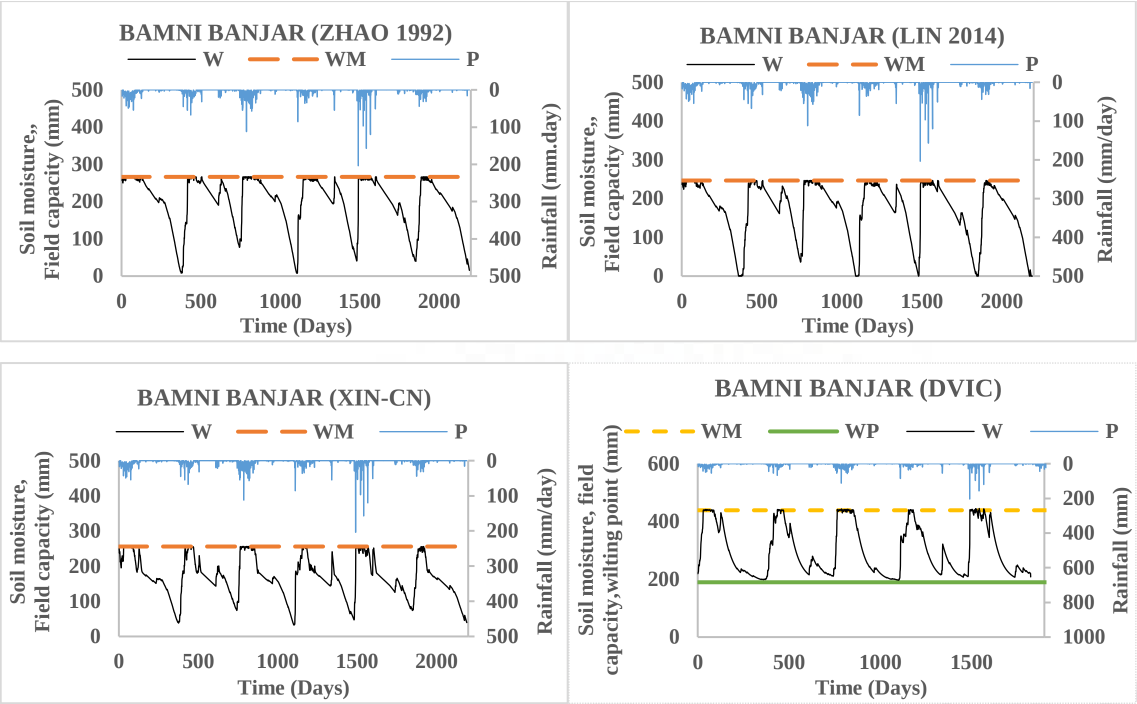
(10)


BELKHERI (ZHAO 1992)
W
WM
P
Soil moisture,, Field capacity (mm)
Rainfall (mm.day)
500
400
300
200
100
0
0
100
200
300
400
500
0
300
600
900
1200
1500
1800
Time (Days)
BELKHERI (LIN 2014)
W
WM
P
Soil moisture,, Field capacity (mm)
Rainfall (mm/day)
500
400
300
200
100
0
0
100
200
300
0
500
1000
1500
Time (Days)
BELKHERI (XIN-CN)
W
WM
P
Soil moisture, Field capacity (mm)
Rainfall (mm/day)
500
400
300
200
100
0
0
100
200
300
400
500
0
300
600
900
1200
1500
1800
Time (Days)
BELKHERI (DVIC)
WM
WP
W
P
Soil moisture, field capacity,wilting point (mm)
Rainfall (mm)
600
400
200
0
0
200
400
600
800
1000
0
500
1000
1500
Time (Days)

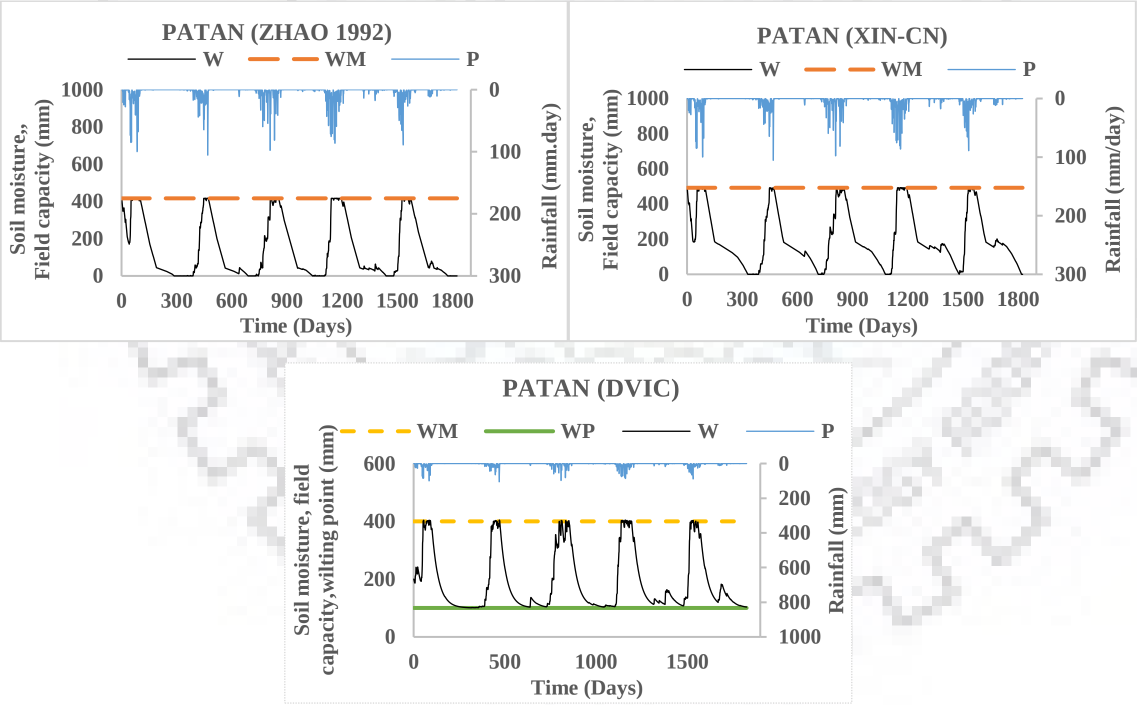
(11)


MANOT (ZHAO 1992)
W
WM
P
Soil moisture,, Field capacity (mm)
Rainfall (mm.day)
300
200
100
0
0
100
200
300
400
0
300
600
900
1200
1500
1800
Time (Days)
MANOT (LIN 2014)
W
WM
P
Soil moisture,, Field capacity (mm)
Rainfall (mm/day)
300
200
100
0
0
100
200
300
400
0
300
600
900
1200
1500
1800
Time (Days)
MANOT (XIN-CN)
W
WM
P
Soil moisture, Field capacity (mm)
Rainfall (mm/day)
400
300
200
100
0
0
100
200
300
400
0
300
600
900
1200
1500
1800
Time (Days)
MANOT (DVIC)
WM
WP
W
P
Soil moisture, field capacity,wilting point (mm)
Rainfall (mm)
600
400
200
0
0
200
400
600
800
1000
0
500
1000
1500
Time (Days)

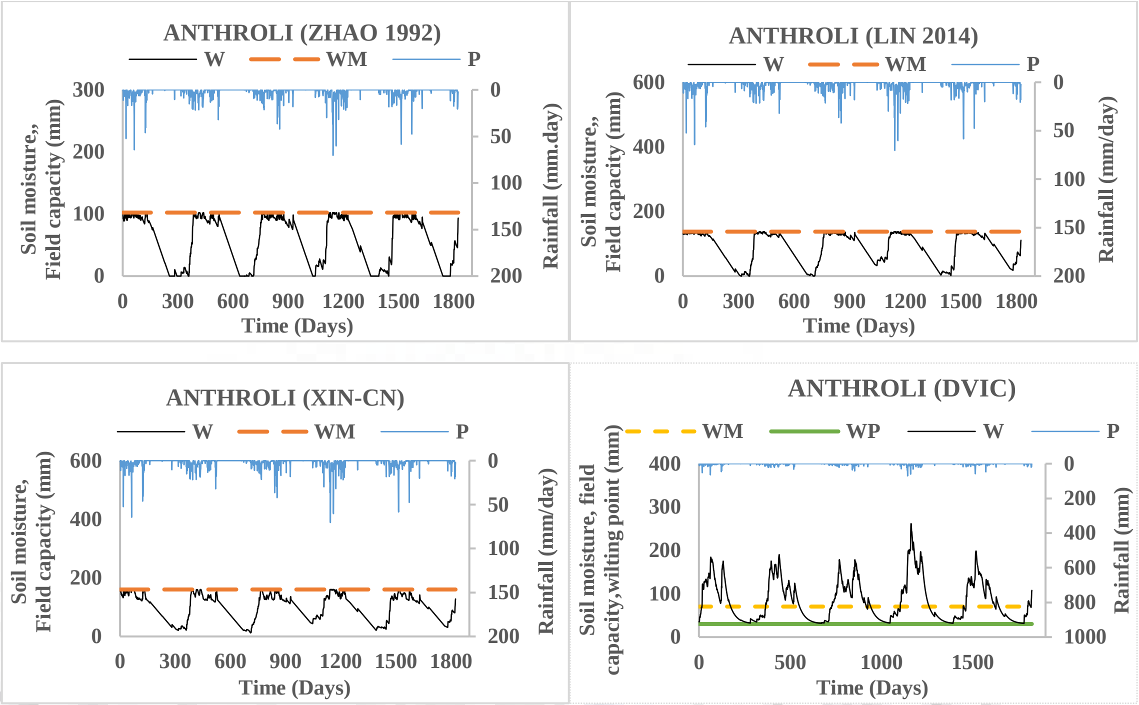
(12)


BAMNI BANJAR (ZHAO 1992)
W
WM
P
Soil moisture,, Field capacity (mm)
Rainfall (mm.day)
0
100
200
300
400
500
0
500
1000
1500
2000
Time (Days)
BAMNI BANJAR (LIN 2014)
W
WM
P
Soil moisture,, Field capacity (mm)
Rainfall (mm/day)
Time (Days)
BAMNI BANJAR (XIN-CN)
W
WM
P
Soil moisture, Field capacity (mm)
Rainfall (mm/day)
Time (Days)
BAMNI BANJAR (DVIC)
WM
WP
W
P
Soil moisture, field capacity,wilting point (mm)
Rainfall (mm)
0
200
400
600
800
1000
0
500
1000
1500
Time (Days)

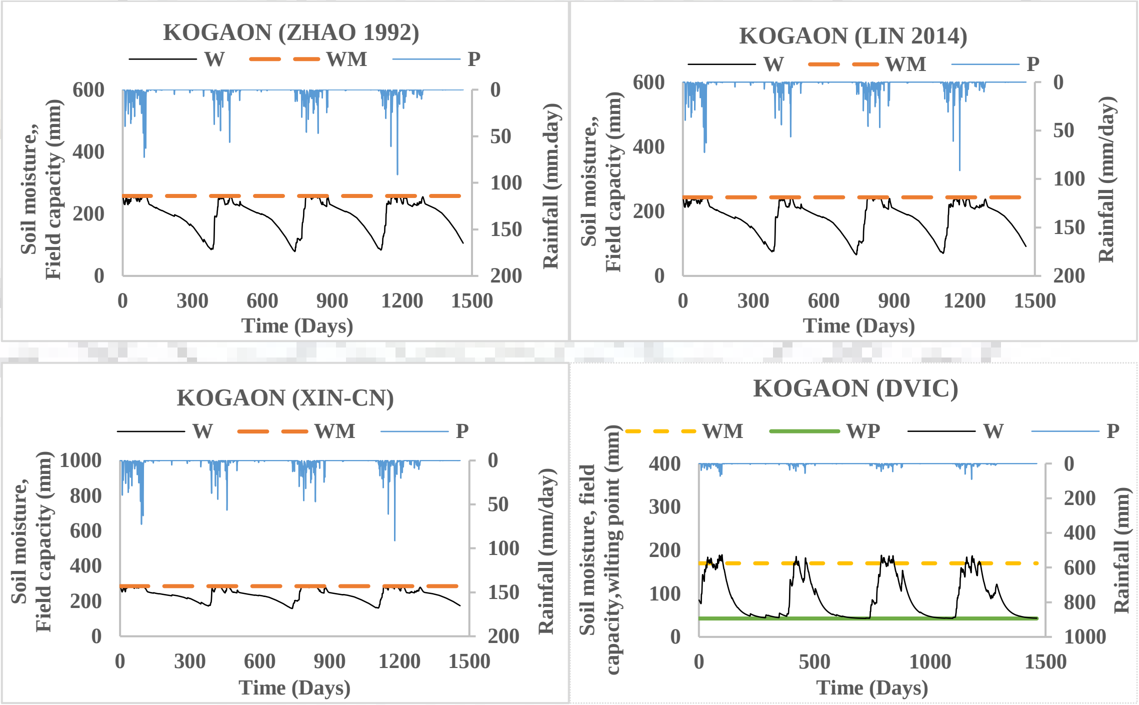
(13)


PATAN (ZHAO 1992)
W
WM
P
Soil moisture,, Field capacity (mm)
Rainfall (mm.day)
0
200
400
600
800
1000
0
100
200
300
0
300
600
900
1200
1500
1800
Time (Days)
PATAN (XIN-CN)
W
WM
P
Soil moisture, Field capacity (mm)
Rainfall (mm/day)
Time (Days)
PATAN (DVIC)
WM
WP
W
P
Soil moisture, field capacity,wilting point (mm)
Rainfall (mm)
0
200
400
600
800
1000
0
500
1000
1500
Time (Days)

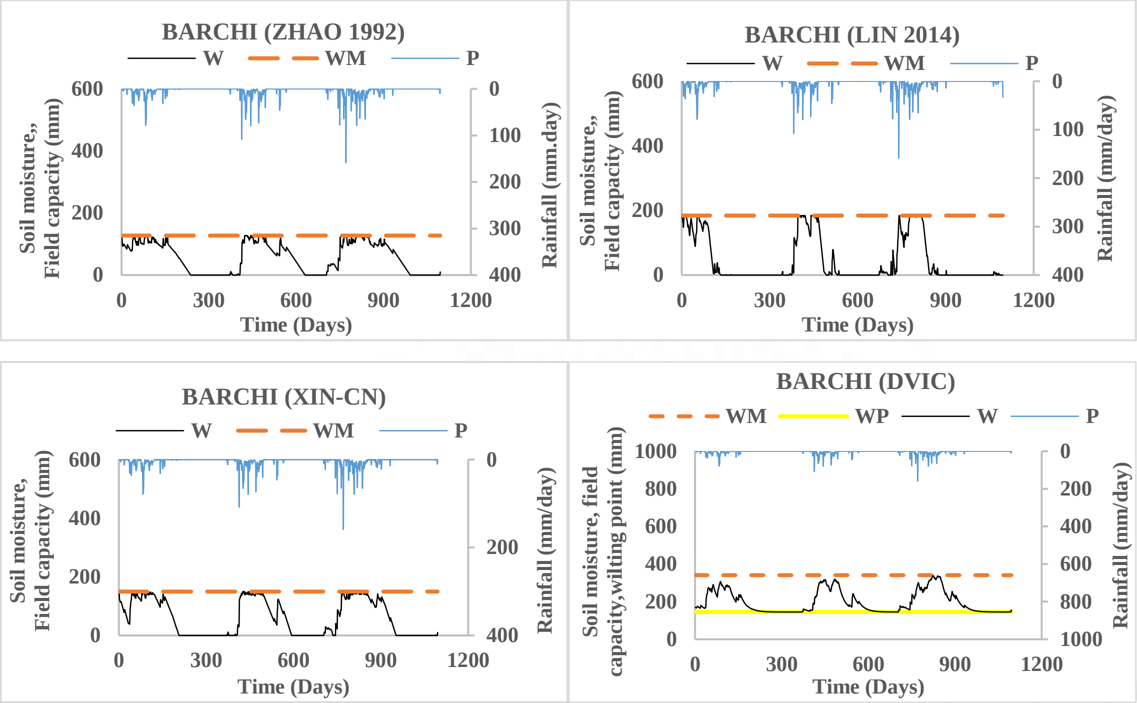
(14)


ANTHROLI (ZHAO 1992)
W
WM
P
Soil moisture,, Field capacity (mm)
Rainfall (mm.day)
Time (Days)
ANTHROLI (LIN 2014)
Soil moisture,, Field capacity (mm)
Rainfall (mm/day)
ANTHROLI (XIN-CN)
Soil moisture, Field capacity (mm)
Rainfall (mm/day)
ANTHROLI (DVIC)
WP
Soil moisture, field capacity,wilting point (mm)
Rainfall (mm)

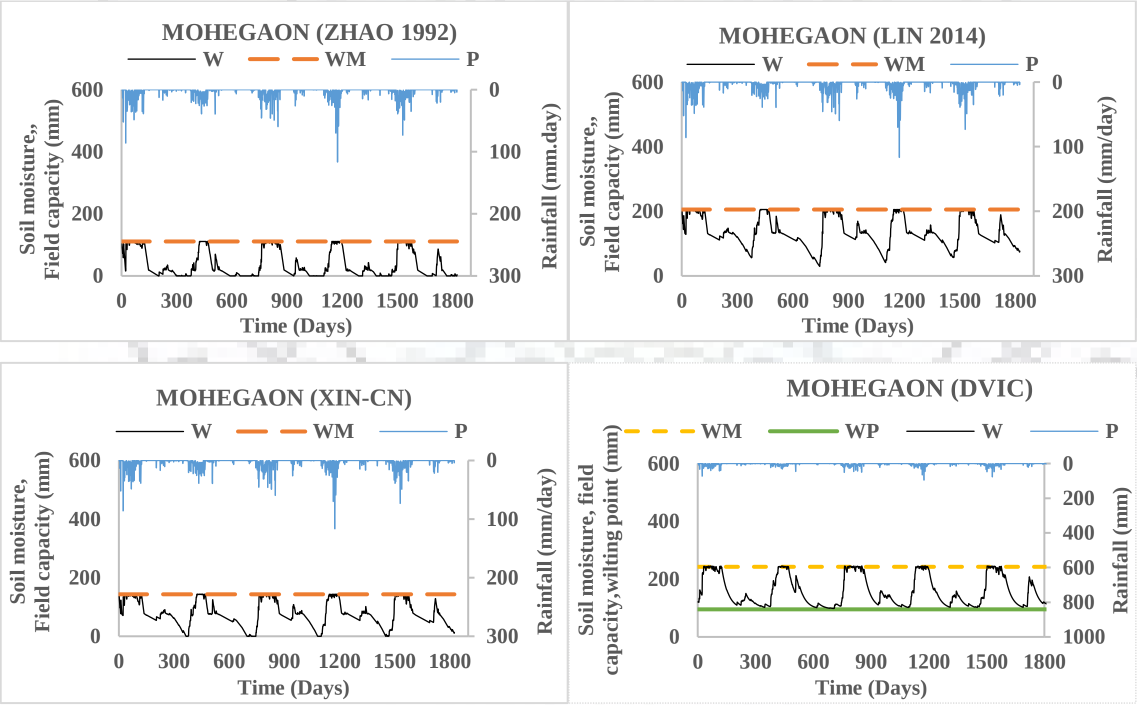
(15)


KOGAON (ZHAO 1992)
W
WM
P
Soil moisture,, Field capacity (mm)
Rainfall (mm.day)
Time (Days)
KOGAON (LIN 2014)
Soil moisture,, Field capacity (mm)
Rainfall (mm/day)
KOGAON (XIN-CN)
Soil moisture, Field capacity (mm)
Rainfall (mm/day)
KOGAON (DVIC)
WP
Soil moisture, field capacity,wilting point (mm)
Rainfall (mm)

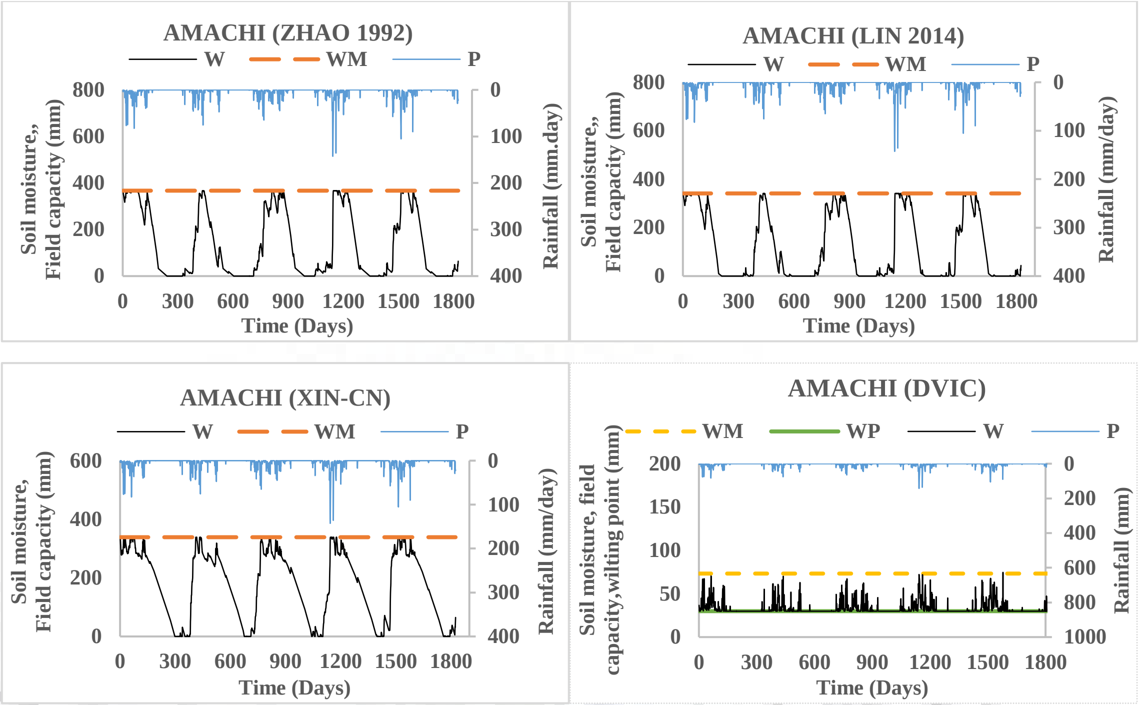
(16)


BARCHI (ZHAO 1992)
W
WM
P
Soil moisture,, Field capacity (mm)
Rainfall (mm.day)
600
400
200
0
0
100
200
300
400
0
300
600
900
1200
Time (Days)
BARCHI (LIN 2014)
W
WM
P
Soil moisture,, Field capacity (mm)
Rainfall (mm/day)
600
400
200
0
0
100
200
300
400
0
300
600
900
1200
Time (Days)
BARCHI (XIN-CN)
W
WM
P
Soil moisture, Field capacity (mm)
Rainfall (mm/day)
600
400
200
0
0
200
400
0
300
600
900
1200
Time (Days)
BARCHI (DVIC)
WM
WP
W
P
Soil moisture, field capacity,wilting point (mm)
Rainfall (mm/day)
1000
800
600
400
200
0
0
200
400
600
800
1000
0
300
600
900
1200
Time (Days)

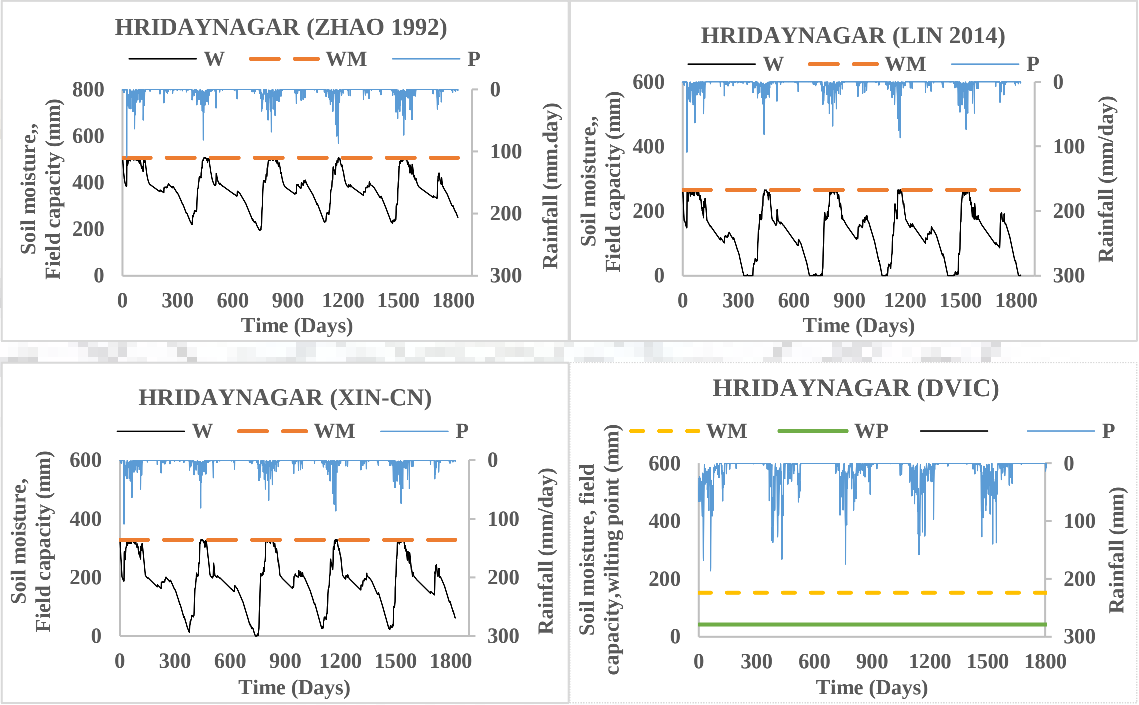
(17)


MOHEGAON (ZHAO 1992)
W
WM
P
Soil moisture,, Field capacity (mm)
Rainfall (mm.day)
600
400
200
0
0
100
200
300
0
300
600
900
1200
1500
1800
Time (Days)
MOHEGAON (LIN 2014)
W
WM
P
Soil moisture,, Field capacity (mm)
Rainfall (mm/day)
600
400
200
0
0
100
200
300
0
300
600
900
1200
1500
1800
Time (Days)
MOHEGAON (XIN-CN)
W
WM
P
Soil moisture, Field capacity (mm)
Rainfall (mm/day)
600
400
200
0
0
100
200
300
0
300
600
900
1200
1500
1800
Time (Days)
MOHEGAON (DVIC)
WM
WP
W
P
Soil moisture, field capacity,wilting point (mm)
Rainfall (mm)
600
400
200
0
0
200
400
600
800
1000
0
300
600
900
1200
1500
1800
Time (Days)

(18)


AMACHI (ZHAO 1992)
W
WM
P
Soil moisture,, Field capacity (mm)
Rainfall (mm.day)
0
200
400
600
800
100
300
Time (Days)
900
1200
1500
1800
AMACHI (LIN 2014)
Rainfall (mm/day)
AMACHI (XIN-CN)
Soil moisture, Field capacity (mm)
AMACHI (DVIC)
WP
Soil moisture, field capacity,wilting point (mm)
Rainfall (mm)
50
150
1000

(19)


HRIDAYNAGAR (ZHAO 1992)
W
WM
P
Soil moisture,, Field capacity (mm)
Rainfall (mm.day)
0
200
400
600
800
100
300
Time (Days)
900
1200
1500
1800
HRIDAYNAGAR (LIN 2014)
Rainfall (mm/day)
HRIDAYNAGAR (XIN-CN)
Soil moisture, Field capacity (mm)
HRIDAYNAGAR (DVIC)
WP
Soil moisture, field capacity,wilting point (mm)
Rainfall (mm)

(20)


भारतीय प्रौद्योगिकी संस्थान रुड़की
INDIAN INSTITUTE OF TECHNOLOGY ROORKEE

APPENDIX-V

COMPARATIVE MODEL EVALUATION ON YEARLY BASIS BETWEEN ORIGINAL XINANJIANG MODEL AND ITS MODIFIED VERSIONS WITH PROPOSED MODIFIED VERSIONS OF THE XINANJIANG MODEL

Name of catchment - Haladi

Area (km^2) = 505

Climatic condition - Wet; Runoff Coefficient = 0.93

Table 1. Comparative Model Evaluation on Yearly basis between Original Xinanjiang Model and its modified versions with proposed modified versions of Xinanjiang model

During Calibration

Year	Observed Values		Existing versions of the Xinanjiang model																Proposed versions of the Xinanjiang model							
			ZHAO(1992)				NIRUPAMA(1996)				HU (2005)				LIN (2014)				XIN-CN				DVIC			
	P (mm)	Qo (mm)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)
1985-86	4397	4105	0.88	0.88	6.95	2.13	0.88	0.88	6.98	2.47	0.80	0.81	8.81	1.99	0.87	0.88	7.10	2.53	0.88	0.89	6.81	2.03	0.92	0.92	5.77	2.32
1986-87	4473	4177	0.82	0.83	5.58	0.79	0.82	0.83	5.63	2.63	0.87	0.87	4.79	-3.15	0.82	0.82	5.63	2.71	0.83	0.83	5.42	0.79	0.89	0.90	4.34	4.06
1987-88	3357	3137	0.74	0.78	3.16	-0.24	0.72	0.78	3.25	2.57	0.78	0.80	2.88	-3.68	0.73	0.78	3.21	2.49	0.74	0.79	3.10	-0.23	0.74	0.83	3.11	5.54
1988-89	4142	3921	0.90	0.90	3.17	0.55	0.90	0.90	3.17	1.99	0.85	0.86	3.89	-3.42	0.90	0.90	3.22	2.08	0.90	0.91	3.17	0.55	0.92	0.92	2.80	3.55
1989-90	4184	4117	0.71	0.73	3.18	-10.73	0.69	0.72	3.24	-8.07	0.80	0.82	2.59	-15.52	0.70	0.73	3.21	-8.71	0.73	0.75	3.04	-10.59	0.80	0.82	2.60	-8.11
Mean	**4111**	**3892**	**0.81**	**0.82**	**4.41**	**-1.50**	**0.80**	**0.82**	**4.45**	**0.32**	**0.82**	**0.83**	**4.59**	**-4.76**	**0.80**	**0.82**	**4.47**	**0.22**	**0.82**	**0.83**	**4.31**	**-1.49**	**0.85**	**0.88**	**3.72**	**1.47**

During Validation

Year	Observed Values		Existing versions of the Xinanjiang model																Proposed versions of the Xinanjiang model							
			ZHAO(1992)				NIRUPAMA(1996)				HU (2005)				LIN (2014)				XIN-CN				DVIC			
	P (mm)	Qo (mm)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)
1990-91	5859	5574	0.80	0.87	7.18	-0.27	0.81	0.87	7.12	0.52	0.77	0.83	7.76	-0.25	0.81	0.86	7.06	0.61	0.82	0.87	6.88	0.00	0.77	0.84	7.80	-0.50
1991-92	4272	4058	0.77	0.85	4.77	3.26	0.77	0.85	4.79	4.40	0.86	0.91	3.72	-0.39	0.78	0.85	4.69	4.48	0.79	0.85	4.55	2.78	0.81	0.90	4.32	5.69
1992-93	5280	4985	0.61	0.72	6.72	0.71	0.60	0.72	6.76	2.26	0.70	0.76	5.89	-1.87	0.62	0.72	6.65	2.24	0.64	0.73	6.47	0.86	0.66	0.78	6.27	4.10
1993-94	4590	4854	0.53	0.66	4.92	-11.84	0.53	0.66	4.93	-9.96	0.60	0.69	4.53	-14.57	0.54	0.66	4.88	-10.13	0.57	0.68	4.69	-11.84	0.59	0.73	4.60	-8.29
Mean	**5000**	**4868**	**0.68**	**0.78**	**5.90**	**-2.04**	**0.68**	**0.78**	**5.90**	**-0.70**	**0.73**	**0.80**	**5.48**	**-4.27**	**0.69**	**0.77**	**5.82**	**-0.70**	**0.71**	**0.78**	**5.65**	**-2.05**	**0.71**	**0.81**	**5.75**	**0.25**

Name of catchment - Jadkal

Area (km^2) = 90

Climatic condition - Wet; Runoff Coefficient = 0.92

Table 2. Comparative Model Evaluation on Yearly basis between Original Xinanjiang Model and its modified versions with proposed modified versions of Xinanjiang model

Year	Observed Values		Existing versions of the Xinanjiang model																Proposed versions of the Xinanjiang model							
	During Calibration																									
			ZHAO(1992)				NIRUPAMA(1996)				HU (2005)				LIN (2014)				XIN-CN				DVIC			
	P (mm)	Qo (mm)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)
1985-86	4553	4324	0.84	0.85	8.48	1.68	0.84	0.85	8.49	1.32	0.78	0.78	10.10	-1.64	0.84	0.85	8.46	1.82	0.85	0.85	8.33	1.85	0.85	0.86	8.15	1.09
1986-87	4216	3897	0.77	0.78	8.80	0.17	0.78	0.78	8.66	-1.17	0.74	0.76	9.38	-12.44	0.77	0.78	8.81	0.74	0.78	0.79	8.74	-1.10	0.87	0.90	6.59	6.02
1987-88	4137	3878	0.86	0.87	4.11	1.53	0.87	0.87	4.08	0.19	0.82	0.83	4.72	-11.87	0.86	0.86	4.14	1.87	0.87	0.87	4.04	-0.12	0.87	0.87	4.06	7.35
1988-89	5473	5285	0.92	0.92	3.64	-3.35	0.92	0.92	3.67	-4.09	0.88	0.88	4.50	-11.21	0.92	0.92	3.66	-2.75	0.93	0.94	3.37	-4.12	0.91	0.91	3.91	0.88
1989-90	4828	4447	0.83	0.83	4.14	0.17	0.83	0.84	4.07	-1.43	0.82	0.83	4.19	-11.26	0.82	0.83	4.18	0.40	0.85	0.85	3.81	-0.06	0.91	0.91	2.97	4.56
Mean	**4641**	**4366**	**0.84**	**0.85**	**5.83**	**0.04**	**0.85**	**0.85**	**5.79**	**-1.04**	**0.81**	**0.82**	**6.58**	**-9.68**	**0.84**	**0.85**	**5.85**	**0.42**	**0.86**	**0.86**	**5.66**	**-0.71**	**0.88**	**0.89**	**5.14**	**3.98**

Year	Observed Values		Existing versions of the Xinanjiang model																Proposed versions of the Xinanjiang model							
	During Validation																									
			ZHAO(1992)				NIRUPAMA(1996)				HU (2005)				LIN (2014)				XIN-CN				DVIC			
	P (mm)	Qo (mm)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)
1990-91	6493	6270	0.85	0.85	11.36	1.01	0.85	0.85	11.38	0.64	0.81	0.81	12.82	-1.88	0.85	0.85	11.34	1.39	0.87	0.87	10.58	1.09	0.84	0.85	11.60	0.19
1991-92	5310	5022	0.93	0.93	4.94	0.31	0.93	0.93	4.89	-0.46	0.90	0.90	5.74	-8.45	0.92	0.92	5.03	0.43	0.94	0.94	4.60	-0.77	0.92	0.92	5.22	5.01
1992-93	6373	5936	0.95	0.96	3.49	2.78	0.95	0.96	3.51	1.86	0.89	0.89	5.42	-5.99	0.95	0.96	3.50	3.09	0.97	0.97	3.02	1.92	0.91	0.92	4.80	6.33
1993-94	5463	5015	0.84	0.88	4.19	2.95	0.84	0.88	4.19	1.19	0.82	0.84	4.54	-5.83	0.84	0.88	4.18	3.22	0.88	0.90	3.59	1.45	0.81	0.86	4.59	8.28
Mean	**5910**	**5561**	**0.89**	**0.91**	**6.00**	**1.76**	**0.89**	**0.91**	**5.99**	**0.81**	**0.86**	**0.86**	**7.13**	**-5.54**	**0.89**	**0.90**	**6.01**	**2.03**	**0.92**	**0.92**	**5.45**	**0.92**	**0.87**	**0.89**	**6.55**	**4.95**

Name of catchment - Dasanakatte

Area (km^2) = 135

Climatic condition - Wet; Runoff Coefficient = 0.90

Table 3. Comparative Model Evaluation on Yearly basis between Original Xinanjiang Model and its modified versions with proposed modified versions of Xinanjiang model

During Calibration

Year	Observed Values		Existing versions of the Xinanjiang model																Proposed versions of the Xinanjiang model							
			ZHAO(1992)				NIRUPAMA(1996)				HU (2005)				LIN (2014)				XIN-CN				DVIC			
	P (mm)	Qo (mm)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)
1985-86	4926	4101	0.82	0.85	8.27	12.45	0.82	0.85	8.27	12.82	0.76	0.77	9.62	12.69	0.82	0.85	8.23	12.64	0.82	0.84	8.22	13.01	0.87	0.88	7.01	3.87
1986-87	4447	3937	0.77	0.79	7.97	-0.62	0.77	0.79	7.98	-0.35	0.72	0.75	8.74	-4.35	0.76	0.77	8.18	0.99	0.77	0.79	7.98	-0.32	0.82	0.83	7.11	2.37
1987-88	3526	3050	0.89	0.89	2.35	-1.48	0.89	0.89	2.35	-1.45	0.87	0.87	2.54	-5.18	0.89	0.89	2.38	-0.04	0.88	0.88	2.42	-1.05	0.90	0.91	2.21	4.03
1988-89	4326	3895	0.90	0.90	2.95	-0.56	0.90	0.90	2.94	-0.31	0.85	0.85	3.60	-3.64	0.90	0.90	2.95	0.08	0.89	0.89	3.02	-0.32	0.90	0.91	2.92	1.91
1989-90	4193	3886	0.83	0.84	2.79	-13.51	0.83	0.84	2.79	-13.41	0.81	0.83	2.97	-17.14	0.83	0.84	2.80	-12.27	0.83	0.85	2.77	-13.08	0.82	0.83	2.85	-9.43
Mean	**4284**	**3774**	**0.84**	**0.85**	**4.87**	**-0.74**	**0.84**	**0.85**	**4.87**	**-0.54**	**0.80**	**0.81**	**5.49**	**-3.52**	**0.84**	**0.85**	**4.91**	**0.28**	**0.84**	**0.85**	**4.88**	**-0.35**	**0.86**	**0.87**	**4.42**	**0.55**

During Validation

Year	Observed Values		Existing versions of the Xinanjiang model																Proposed versions of the Xinanjiang model							
			ZHAO(1992)				NIRUPAMA(1996)				HU (2005)				LIN (2014)				XIN-CN				DVIC			
	P (mm)	Qo (mm)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)
1990-91	5683	4537	0.84	0.85	8.31	15.68	0.84	0.85	8.34	16.08	0.80	0.81	9.33	15.93	0.83	0.84	8.57	15.06	0.84	0.85	8.25	16.23	0.72	0.72	10.98	7.63
1991-92	4124	3506	0.74	0.78	5.57	7.53	0.74	0.78	5.55	7.85	0.81	0.82	4.75	3.09	0.74	0.78	5.57	8.37	0.75	0.79	5.38	7.94	0.73	0.79	5.60	10.03
1992-93	5027	4407	0.77	0.81	5.26	2.99	0.77	0.81	5.24	3.16	0.85	0.85	4.34	0.52	0.77	0.81	5.24	3.55	0.79	0.81	5.12	3.23	0.75	0.80	5.57	6.16
1993-94	5545	4813	0.75	0.77	5.77	4.15	0.75	0.77	5.77	4.19	0.70	0.71	6.36	1.63	0.75	0.77	5.74	5.04	0.74	0.76	5.83	4.23	0.74	0.78	5.89	6.56
Mean	**5095**	**4316**	**0.78**	**0.80**	**6.23**	**7.59**	**0.78**	**0.80**	**6.23**	**7.82**	**0.79**	**0.80**	**6.20**	**5.29**	**0.77**	**0.80**	**6.28**	**8.01**	**0.78**	**0.80**	**6.15**	**7.91**	**0.74**	**0.77**	**7.01**	**7.60**

Name of catchment - Halkal

Area (km^2) = 108

Climatic condition - Wet; Runoff Coefficient = 0.89

Table 4 Comparative Model Evaluation on Yearly basis between Original Xinanjiang Model and its modified versions with proposed modified versions of Xinanjiang model

Year	During Calibration																									
	Observed Values		Existing versions of the Xinanjiang model																Proposed versions of the Xinanjiang model							
			ZHAO(1992)				NIRUPAMA(1996)				HU (2005)				LIN (2014)				XIN-CN				DVIC			
	P (mm)	Qo (mm)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)
1985-86	4553	4013	0.86	0.91	6.51	5.75	0.86	0.91	6.50	5.84	0.91	0.91	5.25	5.45	0.87	0.91	6.20	1.03	0.87	0.91	6.25	5.85	0.89	0.91	5.76	-6.60
1986-87	4216	3603	0.94	0.94	3.74	-5.41	0.94	0.94	3.73	-5.10	0.89	0.90	4.98	-8.46	0.93	0.94	4.03	-10.43	0.94	0.96	3.60	-5.22	0.95	0.96	3.27	-0.51
1987-88	4137	3466	0.85	0.85	3.80	-0.97	0.84	0.84	3.82	-0.35	0.85	0.86	3.69	-6.04	0.85	0.85	3.79	-8.94	0.85	0.85	3.76	-1.00	0.90	0.90	3.10	3.38
1988-89	5473	4730	0.92	0.92	3.44	-0.83	0.92	0.92	3.45	-0.86	0.87	0.87	4.47	-4.43	0.91	0.92	3.65	-5.04	0.93	0.93	3.40	-1.09	0.94	0.94	3.11	0.53
1989-90	4828	4047	0.91	0.91	2.67	-2.92	0.91	0.91	2.69	-2.69	0.86	0.87	3.31	-7.12	0.92	0.93	2.57	-10.31	0.92	0.92	2.48	-2.89	0.94	0.94	2.27	0.87
Mean	**4641**	**3972**	**0.90**	**0.91**	**4.03**	**-0.88**	**0.89**	**0.90**	**4.04**	**-0.63**	**0.88**	**0.88**	**4.34**	**-4.12**	**0.90**	**0.91**	**4.05**	**-6.74**	**0.90**	**0.91**	**3.90**	**-0.87**	**0.92**	**0.93**	**3.50**	**-0.47**
Year	During Validation																									
	Observed Values		Existing versions of the Xinanjiang model																Proposed versions of the Xinanjiang model							
			ZHAO(1992)				NIRUPAMA(1996)				HU (2005)				LIN (2014)				XIN-CN				DVIC			
	P (mm)	Qo (mm)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)
1990-91	6531	5982	0.86	0.86	10.55	2.88	0.86	0.86	10.55	2.83	0.81	0.81	12.39	2.54	0.86	0.86	10.51	-1.54	0.89	0.89	9.22	2.87	0.87	0.87	10.19	-5.39
1991-92	5310	4778	0.92	0.93	5.00	-4.28	0.92	0.93	5.03	-3.91	0.90	0.91	5.69	-6.35	0.92	0.93	5.22	-6.76	0.92	0.94	4.99	-4.03	0.94	0.95	4.30	-1.13
1992-93	6648	6269	0.85	0.85	6.97	-5.90	0.85	0.85	6.96	-5.73	0.77	0.77	8.65	-8.90	0.82	0.82	7.60	-10.61	0.84	0.84	7.17	-6.77	0.81	0.81	7.70	-4.71
1993-94	5463	5033	0.90	0.92	4.33	-7.08	0.90	0.92	4.33	-6.81	0.87	0.89	5.01	-10.10	0.89	0.92	4.60	-13.19	0.90	0.93	4.33	-6.46	0.91	0.93	4.13	-4.01
Mean	**5988**	**5516**	**0.88**	**0.89**	**6.71**	**-3.60**	**0.88**	**0.89**	**6.72**	**-3.41**	**0.84**	**0.85**	**7.94**	**-5.70**	**0.87**	**0.88**	**6.98**	**-8.03**	**0.89**	**0.90**	**6.43**	**-3.60**	**0.88**	**0.89**	**6.58**	**-3.81**

Name of catchment - Kokkarne

Area (km^2) = 343

Climatic condition - Wet; Runoff Coefficient = 0.79

Table 5. Comparative Model Evaluation on Yearly basis between Original Xinanjiang Model and its modified versions with proposed modified versions of Xinanjiang model

During Calibration

Year	Observed Values		Existing versions of the Xinanjiang model																Proposed versions of the Xinanjiang model							
			ZHAO(1992)				NIRUPAMA(1996)				HU (2005)				LIN (2014)				XIN-CN				DVIC			
	P (mm)	Qo (mm)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)
1985-86	4938	3932	0.85	0.88	7.66	8.73	0.85	0.88	7.66	8.46	0.79	0.80	9.16	9.93	0.87	0.89	7.11	5.35	0.86	0.89	7.43	9.51	0.88	0.90	6.85	4.28
1986-87	4556	3522	0.93	0.93	3.94	-3.30	0.93	0.93	3.98	-3.53	0.84	0.85	5.81	-6.49	0.88	0.88	4.97	-0.61	0.93	0.93	3.85	-2.41	0.93	0.93	4.00	6.98
1987-88	3752	2539	0.88	0.88	2.60	1.30	0.88	0.88	2.59	0.36	0.84	0.84	2.98	-2.08	0.89	0.89	2.47	2.57	0.90	0.90	2.43	2.58	0.92	0.93	2.18	17.13
1988-89	4804	3955	0.88	0.88	3.59	-3.49	0.88	0.88	3.59	-3.70	0.85	0.85	4.06	-7.49	0.88	0.88	3.58	-0.38	0.89	0.89	3.53	-2.83	0.86	0.87	3.91	4.22
1989-90	5178	4113	0.91	0.93	2.77	-10.73	0.91	0.93	2.76	-10.96	0.86	0.88	3.50	-12.03	0.89	0.92	3.00	-6.17	0.91	0.93	2.80	-9.82	0.92	0.93	2.58	-1.77
Mean	**4646**	**3612**	**0.89**	**0.90**	**4.11**	**-1.50**	**0.89**	**0.90**	**4.12**	**-1.87**	**0.84**	**0.84**	**5.10**	**-3.63**	**0.88**	**0.89**	**4.23**	**0.15**	**0.90**	**0.91**	**4.01**	**-0.59**	**0.90**	**0.91**	**3.90**	**6.17**

During Validation

Year	Observed Values		Existing versions of the Xinanjiang model																Proposed versions of the Xinanjiang model							
			ZHAO(1992)				NIRUPAMA(1996)				HU (2005)				LIN (2014)				XIN-CN				DVIC			
	P (mm)	Qo (mm)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)
1990-91	5741	4742	0.89	0.89	7.45	3.28	0.89	0.89	7.49	3.00	0.88	0.88	7.69	3.99	0.88	0.88	7.76	-0.47	0.88	0.89	7.60	3.87	0.88	0.88	7.74	-0.67
1991-92	4956	4005	0.92	0.92	4.35	-3.64	0.92	0.92	4.29	-3.78	0.85	0.85	6.07	-5.56	0.90	0.90	4.82	-1.98	0.93	0.93	4.13	-2.80	0.91	0.92	4.54	8.72
1992-93	5605	4271	0.93	0.93	3.38	4.85	0.93	0.93	3.34	4.67	0.84	0.84	5.10	1.80	0.92	0.93	3.51	6.23	0.94	0.94	3.20	6.11	0.94	0.95	3.02	12.89
1993-94	6207	5015	0.87	0.87	4.42	-2.12	0.87	0.87	4.41	-2.18	0.76	0.76	6.03	-3.68	0.88	0.88	4.25	-0.58	0.87	0.87	4.45	-1.25	0.89	0.89	4.13	6.40
Mean	**5627**	**4508**	**0.90**	**0.90**	**4.90**	**0.59**	**0.90**	**0.90**	**4.88**	**0.43**	**0.83**	**0.83**	**6.22**	**-0.86**	**0.90**	**0.90**	**5.09**	**0.80**	**0.91**	**0.91**	**4.85**	**1.48**	**0.91**	**0.91**	**4.86**	**6.84**

Name of catchment - Hemavati

Area (km^2) = 600

Climatic condition - Wet; Runoff Coefficient = 0.78

Table 6. Comparative Model Evaluation on Yearly basis between Original Xinanjiang Model and its modified versions with proposed modified versions of Xinanjiang model

Year	Observed Values		Existing versions of the Xinanjiang model																Proposed versions of the Xinanjiang model							
During Calibration																										
			ZHAO(1992)				NIRUPAMA(1996)				HU (2005)				LIN (2014)				XIN-CN				DVIC			
	P (mm)	Qo (mm)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)
1975-76	2938	2553	0.80	0.81	5.49	-0.37	0.81	0.81	5.39	-0.75	0.80	0.80	5.57	-0.20	0.81	0.81	5.38	-2.07	0.82	0.82	5.30	-0.39	0.84	0.86	4.92	-15.10
1976-77	2651	1718	0.93	0.93	1.68	-5.09	0.92	0.92	1.78	-5.00	0.88	0.89	2.15	-1.68	0.92	0.92	1.79	-4.20	0.92	0.92	1.78	-2.55	0.92	0.93	1.76	8.67
1977-78	2676	1894	0.91	0.91	1.32	-1.64	0.91	0.91	1.34	-2.27	0.89	0.89	1.46	-0.48	0.91	0.91	1.34	-3.61	0.92	0.92	1.26	-1.45	0.90	0.90	1.40	5.20
Mean	**2755**	**2055**	**0.88**	**0.88**	**2.83**	**-2.37**	**0.88**	**0.88**	**2.84**	**-2.67**	**0.86**	**0.86**	**3.06**	**-0.79**	**0.88**	**0.88**	**2.84**	**-3.29**	**0.89**	**0.89**	**2.78**	**-1.46**	**0.89**	**0.90**	**2.69**	**-0.41**

Year	Observed Values		Existing versions of the Xinanjiang model																Proposed versions of the Xinanjiang model							
During Validation																										
			ZHAO(1992)				NIRUPAMA(1996)				HU (2005)				LIN (2014)				XIN-CN				DVIC			
	P (mm)	Qo (mm)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)
1978-79	2942	2937	0.86	0.90	5.00	-14.65	0.85	0.89	5.05	-14.81	0.77	0.82	6.29	-14.42	0.85	0.90	5.09	-16.11	0.84	0.89	5.31	-14.68	0.82	0.92	5.66	-27.75
1979-80	3064	2062	0.90	0.93	3.37	0.65	0.90	0.93	3.36	1.29	0.86	0.89	4.03	4.33	0.91	0.93	3.28	1.62	0.90	0.92	3.41	2.72	0.90	0.91	3.43	12.38
Mean	**3003**	**2499**	**0.88**	**0.92**	**4.19**	**-7.00**	**0.88**	**0.91**	**4.21**	**-6.76**	**0.82**	**0.86**	**5.16**	**-5.05**	**0.88**	**0.92**	**4.19**	**-7.25**	**0.87**	**0.91**	**4.36**	**-5.98**	**0.86**	**0.92**	**4.55**	**-7.69**

Name of catchment - Khanpur

Area (km^2) = 320

Climatic condition - Average; Runoff Coefficient = 0.60

Table 7. Comparative Model Evaluation on Yearly basis between Original Xinanjiang Model and its modified versions with proposed modified versions of Xinanjiang model

Year	During Calibration																									
	Observed Values		Existing versions of the Xinanjiang model																Proposed versions of the Xinanjiang model							
			ZHAO(1992)				NIRUPAMA(1996)				HU (2005)				LIN (2014)				XIN-CN				DVIC			
	P (mm)	Qo (mm)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)
1985-86	3420	1665	0.66	0.68	6.08	23.08	0.67	0.70	5.98	28.78	0.65	0.69	6.15	44.75	0.70	0.73	5.69	30.15	0.65	0.73	6.13	46.67	0.84	0.85	4.10	14.81
1986-87	2796	1736	0.56	0.60	5.83	-8.42	0.54	0.57	5.96	-6.99	0.75	0.82	4.40	-13.31	0.58	0.63	5.69	-5.12	0.82	0.91	3.78	-4.24	0.75	0.83	4.43	-11.31
1987-88	2938	1475	0.60	0.66	2.76	14.48	0.61	0.66	2.72	13.43	0.78	0.80	2.04	-3.95	0.68	0.72	2.48	18.12	0.83	0.87	1.78	17.58	0.75	0.81	2.19	13.86
1988-89	3911	2499	0.76	0.76	3.76	4.28	0.75	0.75	3.84	6.51	0.77	0.80	3.62	-1.35	0.71	0.73	4.11	8.71	0.86	0.86	2.83	8.39	0.78	0.81	3.59	3.56
1989-90	3250	1788	0.61	0.65	2.90	18.46	0.63	0.68	2.81	18.72	0.58	0.64	3.00	-8.04	0.59	0.67	2.98	20.00	0.82	0.83	1.97	19.08	0.58	0.67	2.99	10.69
Mean	**3263**	**1833**	**0.64**	**0.67**	**4.27**	**10.38**	**0.64**	**0.67**	**4.26**	**12.09**	**0.71**	**0.75**	**3.84**	**3.62**	**0.65**	**0.70**	**4.19**	**14.37**	**0.80**	**0.84**	**3.30**	**17.50**	**0.74**	**0.79**	**3.46**	**6.32**

Year	During Validation																									
	Observed Values		Existing versions of the Xinanjiang model																Proposed versions of the Xinanjiang model							
			ZHAO(1992)				NIRUPAMA(1996)				HU (2005)				LIN (2014)				XIN-CN				DVIC			
	P (mm)	Qo (mm)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)
1990-91	3507	2307	0.58	0.59	8.65	-2.33	0.59	0.60	8.56	-0.45	0.62	0.63	8.29	5.86	0.58	0.59	8.65	-3.66	0.78	0.79	6.35	14.21	0.63	0.70	8.13	-19.88
1991-92	3455	2318	0.69	0.70	5.99	-0.63	0.67	0.67	6.17	0.83	0.78	0.80	5.02	-10.54	0.74	0.74	5.53	3.13	0.87	0.90	3.92	-1.10	0.82	0.83	4.54	-3.58
1992-93	3547	2506	0.63	0.63	4.73	-9.22	0.64	0.64	4.68	-9.48	0.83	0.85	3.20	-14.60	0.73	0.75	4.00	-5.82	0.88	0.91	2.65	-7.80	0.84	0.86	3.11	-13.19
1993-94	3788	2444	0.64	0.66	5.06	-1.45	0.65	0.68	4.96	-0.54	0.63	0.66	5.12	-9.43	0.69	0.72	4.68	1.14	0.73	0.77	4.41	1.61	0.68	0.72	4.78	-3.65
Mean	**3574**	**2394**	**0.64**	**0.65**	**6.11**	**-3.41**	**0.64**	**0.65**	**6.09**	**-2.41**	**0.72**	**0.74**	**5.41**	**-7.18**	**0.69**	**0.70**	**5.72**	**-1.30**	**0.82**	**0.84**	**4.33**	**1.73**	**0.74**	**0.78**	**5.14**	**-10.08**

Name of catchment - Dindori

Area (km^2) = 2292

Climatic condition - Average; Runoff Coefficient = 0.51

Table 8. Comparative Model Evaluation on Yearly basis between Original Xinanjiang Model and its modified versions with proposed modified versions of Xinanjiang model

During Calibration

Year	Observed Values		Existing versions of the Xinanjiang model																Proposed versions of the Xinanjiang model							
			ZHAO(1992)				NIRUPAMA(1996)				HU (2005)				LIN (2014)				XIN-CN				DVIC			
	P (mm)	Qo (mm)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)
1991-92	1114	488	0.85	0.85	2.81	21.19	0.88	0.88	2.57	22.09	0.35	0.36	5.88	28.29	0.81	0.83	3.16	17.61	0.91	0.92	2.17	20.01	0.93	0.93	1.91	11.14
1992-93	979	416	0.80	0.80	1.16	7.09	0.77	0.77	1.24	-1.49	0.59	0.62	1.64	-15.78	0.80	0.80	1.14	8.99	0.74	0.75	1.29	13.65	0.83	0.84	1.07	-5.26
1993-94	1124	508	0.83	0.83	1.01	-2.33	0.80	0.80	1.11	-14.28	0.56	0.58	1.62	-9.14	0.84	0.84	0.99	-6.64	0.83	0.84	1.01	-7.56	0.88	0.88	0.85	-5.54
1994-95	1750	993	0.78	0.79	1.63	-4.59	0.83	0.84	1.44	-7.08	0.59	0.59	2.23	-7.23	0.80	0.82	1.56	-2.51	0.89	0.89	1.17	0.86	0.81	0.81	1.53	-7.11
1995-96	1142	496	0.54	0.61	0.90	-4.49	0.50	0.53	0.94	-15.60	0.52	0.53	0.92	-8.52	0.58	0.61	0.86	-6.29	0.69	0.70	0.74	-6.24	0.65	0.67	0.79	-8.24
1996-97	1116	548	0.66	0.70	1.18	-24.19	0.69	0.75	1.14	-26.47	0.46	0.49	1.49	-20.45	0.67	0.70	1.17	-13.84	0.66	0.70	1.19	-15.78	0.67	0.73	1.16	-16.89
1997-98	1517	612	- 0.13	0.45	1.03	-15.14	-0.02	0.48	0.98	-20.23	0.45	0.53	0.72	-5.43	-0.26	0.44	1.09	-9.27	0.16	0.53	0.89	-10.49	0.20	0.55	0.87	-1.96
Mean	**1249**	**580**	**0.66**	**0.72**	**1.39**	**-3.21**	**0.64**	**0.72**	**1.35**	**-9.01**	**0.50**	**0.53**	**2.07**	**-5.47**	**0.61**	**0.72**	**1.42**	**-1.71**	**0.70**	**0.76**	**1.21**	**-0.79**	**0.71**	**0.77**	**1.17**	**-4.84**

During Validation

Year	Observed Values		Existing versions of the Xinanjiang model																Proposed versions of the Xinanjiang model							
			ZHAO(1992)				NIRUPAMA(1996)				HU (2005)				LIN (2014)				XIN-CN				DVIC			
	P (mm)	Qo (mm)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)
2001-02	1356	536	0.13	0.69	2.89	34.83	0.06	0.64	3.01	35.51	0.51	0.52	2.18	-3.80	0.02	0.65	3.06	30.21	0.53	0.82	2.11	37.34	0.59	0.74	1.99	15.51
2002-03	913	330	0.16	0.62	1.44	-6.89	-0.04	0.39	1.60	-23.03	0.60	0.67	0.99	-1.49	0.11	0.57	1.48	-12.48	0.48	0.63	1.14	-11.32	0.37	0.67	1.25	-3.54
2003-04	1480	885	0.77	0.78	1.70	-16.20	0.51	0.52	2.48	-21.93	0.43	0.46	2.67	-27.60	0.49	0.51	2.53	-17.98	0.67	0.69	2.04	-16.46	0.76	0.77	1.76	-21.16
2004-05	1295	569	0.38	0.51	1.77	-12.18	0.61	0.63	1.41	-24.23	0.37	0.42	1.79	6.61	0.63	0.66	1.36	-15.85	0.64	0.65	1.34	-14.62	0.59	0.62	1.44	-4.38
Mean	**1261**	**580**	**0.36**	**0.65**	**1.95**	**-0.11**	**0.29**	**0.55**	**2.13**	**-8.42**	**0.48**	**0.52**	**1.91**	**-6.57**	**0.31**	**0.60**	**2.11**	**-4.03**	**0.58**	**0.70**	**1.66**	**-1.27**	**0.58**	**0.70**	**1.61**	**-3.39**

Name of catchment - Chidgaon

Area (km^2) = 1729

Climatic condition - Average; Runoff Coefficient = 0.50

Table 9. Comparative Model Evaluation on Yearly basis between Original Xinanjiang Model and its modified versions with proposed modified versions of Xinanjiang model

Year	During Calibration																									
	Observed Values		Existing versions of the Xinanjiang model																Proposed versions of the Xinanjiang model							
			ZHAO(1992)				NIRUPAMA(1996)				HU (2005)				LIN (2014)				XIN-CN				DVIC			
	P (mm)	Qo (mm)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)
1991-92	884	273	0.69	0.80	3.09	78.94	0.72	0.82	2.92	82.01	0.22	0.31	4.87	82.59	0.66	0.76	3.22	59.65	0.69	0.75	3.09	65.59	0.89	0.90	1.83	24.60
1992-93	960	280	0.33	0.42	3.01	75.96	0.29	0.39	3.09	77.16	0.35	0.36	2.97	64.47	0.34	0.43	2.98	68.11	0.32	0.41	3.02	63.41	0.44	0.47	2.75	46.91
1993-94	1470	825	0.64	0.66	3.62	-8.93	0.64	0.66	3.60	-5.52	0.24	0.24	5.27	1.32	0.65	0.67	3.57	-12.26	0.67	0.68	3.49	-9.03	0.58	0.60	3.90	-3.43
1994-95	1667	1267	0.84	0.88	3.19	-14.22	0.84	0.88	3.16	-13.24	0.41	0.43	6.10	-10.22	0.83	0.87	3.27	-17.15	0.87	0.90	2.85	-18.31	0.84	0.87	3.13	-13.65
1995-96	1025	414	0.37	0.78	1.59	36.45	0.36	0.78	1.60	42.47	0.53	0.56	1.38	25.25	0.36	0.77	1.60	29.77	0.43	0.80	1.51	24.68	0.71	0.87	1.08	12.13
1996-97	1040	634	0.69	0.73	1.71	-16.25	0.69	0.74	1.72	-14.21	0.48	0.51	2.22	-15.91	0.70	0.73	1.69	-18.02	0.66	0.79	1.81	-23.04	0.39	0.39	2.41	-28.53
1997-98	1219	722	0.82	0.90	1.94	-25.40	0.83	0.91	1.88	-23.30	0.33	0.39	3.75	-18.24	0.83	0.92	1.87	-27.00	0.89	0.97	1.52	-27.62	0.69	0.86	2.55	-29.32
Mean	**1181**	**631**	**0.63**	**0.74**	**2.59**	**18.08**	**0.62**	**0.74**	**2.57**	**20.77**	**0.37**	**0.40**	**3.79**	**18.47**	**0.62**	**0.74**	**2.60**	**11.87**	**0.65**	**0.76**	**2.47**	**10.81**	**0.65**	**0.71**	**2.52**	**1.24**

Year	During Validation																									
	Observed Values		Existing versions of the Xinanjiang model																Proposed versions of the Xinanjiang model							
			ZHAO(1992)				NIRUPAMA(1996)				HU (2005)				LIN (2014)				XIN-CN				DVIC			
	P (mm)	Qo (mm)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)
1998-99	1262	864	0.63	0.66	12.45	-14.06	0.62	0.65	12.57	-12.96	0.39	0.48	15.84	-7.67	0.63	0.67	12.37	-19.69	0.59	0.61	13.04	-14.81	0.63	0.67	12.33	-26.32
1999-00	1625	991	0.52	0.54	4.19	-7.29	0.54	0.55	4.11	-5.18	0.38	0.38	4.77	3.22	0.49	0.51	4.34	-13.34	0.61	0.61	3.79	-10.59	0.54	0.54	4.10	-2.36
2000-01	474	123	0.27	0.31	0.42	-44.56	0.32	0.33	0.41	-27.63	0.63	0.67	0.30	-3.15	0.25	0.30	0.43	-58.07	0.10	0.21	0.47	-71.15	0.16	0.33	0.45	-84.12
2001-02	877	339	0.44	0.45	1.77	-18.03	0.43	0.43	1.79	-15.37	0.28	0.28	2.00	-2.10	0.44	0.46	1.77	-26.28	0.28	0.28	2.01	-33.54	0.41	0.44	1.82	-23.41
2002-03	896	325	0.22	0.28	1.57	-5.86	0.23	0.28	1.55	-3.92	0.20	0.28	1.59	33.49	0.25	0.29	1.54	-13.35	0.34	0.35	1.44	-21.42	0.28	0.31	1.50	-5.40
2003-04	1057	598	0.61	0.62	1.70	-17.70	0.60	0.61	1.72	-16.15	0.29	0.30	2.29	-18.41	0.48	0.49	1.96	-25.48	0.56	0.57	1.80	-25.50	0.52	0.56	1.88	-24.16
2004-05	1063	438	0.91	0.92	0.71	5.46	0.94	0.94	0.58	7.75	0.48	0.49	1.73	9.49	0.92	0.92	0.70	1.10	0.95	0.95	0.55	-7.23	0.95	0.96	0.52	-13.78
Mean	**1036**	**526**	**0.51**	**0.54**	**3.26**	**-14.58**	**0.53**	**0.54**	**3.25**	**-10.49**	**0.38**	**0.41**	**4.07**	**2.12**	**0.49**	**0.52**	**3.30**	**-22.16**	**0.49**	**0.51**	**3.30**	**-26.32**	**0.50**	**0.54**	**3.23**	**-25.65**

Name of catchment - Gadarwara

Area (km^2) = 2270

Climatic condition - Average; Runoff Coefficient = 0.49

Table 10. Comparative Model Evaluation on Yearly basis between Original Xinanjiang Model and its modified versions with proposed modified versions of Xinanjiang model

During Calibration

Year	Observed Values		Existing versions of the Xinanjiang model																Proposed versions of the Xinanjiang model							
			ZHAO(1992)				NIRUPAMA(1996)				HU (2005)				LIN (2014)				XIN-CN				DVIC			
	P (mm)	Qo (mm)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)
1991-92	855	319	0.35	0.62	2.51	44.94	0.35	0.59	2.53	45.94	0.46	0.48	2.29	-0.27	0.40	0.63	2.43	42.02	0.25	0.63	2.71	71.80	0.25	0.46	2.71	39.13
1992-93	940	506	0.28	0.37	2.78	-13.47	0.19	0.34	2.96	-11.56	0.39	0.39	2.57	-14.31	0.28	0.36	2.80	-13.80	0.39	0.42	2.57	-2.85	0.44	0.45	2.46	-7.11
1993-94	1202	622	0.75	0.75	1.45	11.08	0.77	0.77	1.41	11.34	0.51	0.51	2.04	9.58	0.76	0.77	1.41	9.97	0.67	0.68	1.67	17.76	0.85	0.85	1.14	12.20
1994-95	1581	1352	0.55	0.57	3.54	-27.01	0.56	0.58	3.49	-27.36	0.53	0.55	3.62	-23.52	0.55	0.56	3.55	-27.54	0.59	0.63	3.38	-22.62	0.53	0.54	3.62	-23.55
1995-96	769	402	0.52	0.55	1.12	-26.21	0.48	0.49	1.16	-20.64	0.46	0.51	1.18	-26.07	0.52	0.55	1.12	-23.20	0.59	0.61	1.03	-9.72	0.50	0.50	1.15	-17.25
1996-97	841	294	0.55	0.55	0.56	-2.94	0.51	0.51	0.59	-2.16	0.50	0.51	0.60	8.23	0.55	0.55	0.56	-1.69	0.49	0.58	0.60	23.73	0.46	0.50	0.62	18.78
1997-98	1766	578	0.56	0.66	1.18	46.31	0.55	0.66	1.19	53.96	0.37	0.52	1.42	74.89	0.57	0.66	1.17	45.02	0.38	0.57	1.40	75.37	0.44	0.51	1.34	63.39
Mean	**1136**	**582**	**0.51**	**0.58**	**1.88**	**4.67**	**0.49**	**0.56**	**1.90**	**7.07**	**0.46**	**0.50**	**1.96**	**4.08**	**0.52**	**0.58**	**1.86**	**4.40**	**0.48**	**0.59**	**1.91**	**21.92**	**0.50**	**0.54**	**1.86**	**12.23**

During Validation

Year	Observed Values		Existing versions of the Xinanjiang model																Proposed versions of the Xinanjiang model							
			ZHAO(1992)				NIRUPAMA(1996)				HU (2005)				LIN (2014)				XIN-CN				DVIC			
	P (mm)	Qo (mm)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)
1998-99	1066	356	0.68	0.77	1.42	33.79	0.70	0.81	1.37	34.64	0.47	0.49	1.83	1.12	0.70	0.78	1.38	30.33	0.28	0.78	2.13	69.02	0.54	0.62	1.71	36.26
1999-00	1872	1625	0.83	0.87	5.16	-19.32	0.82	0.87	5.28	-19.55	0.70	0.75	6.82	-19.16	0.83	0.87	5.17	-20.15	0.75	0.83	6.17	-18.35	0.85	0.87	4.83	-15.65
2000-01	968	321	0.61	0.61	1.22	14.34	0.61	0.61	1.23	10.31	0.32	0.40	1.61	47.84	0.62	0.62	1.21	16.81	0.51	0.54	1.37	29.94	0.23	0.46	1.71	48.08
2001-02	1158	314	0.12	0.22	2.02	52.28	0.16	0.28	1.97	70.86	-0.23	0.12	2.39	108.04	0.13	0.22	2.01	53.63	0.06	0.22	2.09	86.05	0.23	0.29	1.90	90.51
2002-03	1282	540	0.33	0.48	2.54	41.02	0.33	0.47	2.54	40.50	0.33	0.41	2.53	41.04	0.33	0.48	2.54	41.05	0.43	0.51	2.35	50.42	0.47	0.56	2.27	40.37
2003-04	1214	706	0.10	0.12	2.38	-14.34	0.07	0.10	2.42	-11.70	0.13	0.15	2.33	-7.65	0.10	0.12	2.38	-14.83	0.19	0.21	2.25	-0.36	0.20	0.20	2.25	-7.58
2004-05	890	290	0.59	0.62	0.58	-21.78	0.57	0.60	0.60	-21.61	0.56	0.61	0.60	26.36	0.60	0.62	0.57	-17.68	0.64	0.69	0.54	6.73	0.52	0.54	0.63	17.63
Mean	**1207**	**593**	**0.47**	**0.53**	**2.19**	**12.28**	**0.47**	**0.53**	**2.20**	**14.78**	**0.33**	**0.42**	**2.59**	**28.23**	**0.47**	**0.53**	**2.18**	**12.74**	**0.41**	**0.54**	**2.41**	**31.92**	**0.43**	**0.51**	**2.19**	**29.95**

Name of catchment - Belkheri

Area (km^2) = 1508

Climatic condition - Average; Runoff Coefficient = 0.45

Table 11. Comparative Model Evaluation on Yearly basis between Original Xinanjiang Model and its modified versions with proposed modified versions of Xinanjiang model

Year	During Calibration																									
	Observed Values		Existing versions of the Xinanjiang model																Proposed versions of the Xinanjiang model							
			ZHAO(1992)				NIRUPAMA(1996)				HU (2005)				LIN (2014)				XIN-CN				DVIC			
	P (mm)	Qo (mm)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)
1991-92	633	340	0.54	0.57	3.57	-9.45	0.70	0.71	2.89	17.51	0.38	0.45	4.14	-26.49	0.56	0.59	3.50	-6.18	0.68	0.74	2.96	-11.19	0.68	0.86	2.99	-30.89
1992-93	1206	611	0.85	0.85	2.38	13.12	0.85	0.85	2.37	9.14	0.41	0.42	4.70	7.22	0.84	0.85	2.41	17.69	0.89	0.89	2.03	12.74	0.89	0.89	2.08	12.26
1993-94	1100	430	0.93	0.93	0.90	8.35	0.90	0.90	1.12	15.61	0.39	0.41	2.71	10.84	0.94	0.94	0.83	14.37	0.81	0.82	1.53	7.81	0.95	0.95	0.79	9.60
1994-95	1699	949	0.64	0.75	2.18	0.79	0.65	0.79	2.14	6.37	0.68	0.68	2.07	3.57	0.64	0.74	2.19	1.62	0.85	0.86	1.43	-2.70	0.72	0.80	1.92	2.43
1995-96	841	366	0.36	0.36	1.24	-29.68	0.27	0.31	1.32	-37.84	0.28	0.29	1.31	-23.82	0.36	0.37	1.24	-26.20	0.28	0.31	1.31	-27.27	0.26	0.27	1.33	-31.84
Mean	**1096**	**539**	**0.66**	**0.69**	**2.05**	**-3.37**	**0.67**	**0.71**	**1.97**	**2.16**	**0.43**	**0.45**	**2.99**	**-5.74**	**0.67**	**0.70**	**2.03**	**0.26**	**0.70**	**0.72**	**1.85**	**-4.12**	**0.70**	**0.75**	**1.82**	**-7.69**

Year	During Validation																									
	Observed Values		Existing versions of the Xinanjiang model																Proposed versions of the Xinanjiang model							
			ZHAO(1992)				NIRUPAMA(1996)				HU (2005)				LIN (2014)				XIN-CN				DVIC			
	P (mm)	Qo (mm)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)
1998-99	1188	497	0.58	0.68	2.34	9.08	0.42	0.77	2.73	53.11	0.53	0.55	2.48	16.88	0.50	0.61	2.53	12.12	0.53	0.74	2.47	12.60	0.74	0.74	1.82	-2.77
1999-00	1455	994	0.96	0.96	2.19	-4.95	0.92	0.93	2.96	-4.57	0.52	0.55	7.26	-9.48	0.95	0.96	2.26	-2.58	0.94	0.95	2.68	-9.99	0.93	0.95	2.73	-10.15
2000-01	935	278	0.70	0.74	1.61	32.35	0.74	0.80	1.51	21.22	0.33	0.33	2.44	37.84	0.75	0.80	1.49	33.14	0.60	0.61	1.88	29.47	0.73	0.77	1.54	35.87
2001-02	944	673	0.13	0.24	6.56	-57.39	0.16	0.18	6.47	-52.59	0.07	0.10	6.80	-46.42	0.18	0.40	6.39	-56.29	0.17	0.28	6.42	-62.50	0.14	0.23	6.53	-53.51
2002-03	1117	481	0.67	0.76	1.69	7.02	0.56	0.72	1.94	5.57	0.63	0.63	1.77	14.04	0.69	0.77	1.63	6.48	0.79	0.83	1.32	3.45	0.70	0.77	1.59	8.76
2003-04	1349	594	0.64	0.66	1.60	21.34	0.57	0.64	1.76	27.27	0.43	0.43	2.03	21.68	0.69	0.70	1.48	26.76	0.63	0.64	1.64	20.38	0.72	0.73	1.41	17.96
2004-05	890	314	0.71	0.71	0.89	-14.23	0.59	0.60	1.05	-10.17	0.37	0.37	1.31	3.33	0.63	0.63	1.00	-13.15	0.54	0.54	1.12	-26.88	0.56	0.56	1.09	-8.97
Mean	**1125**	**547**	**0.63**	**0.68**	**2.41**	**-0.97**	**0.57**	**0.66**	**2.63**	**5.69**	**0.41**	**0.42**	**3.44**	**5.41**	**0.63**	**0.70**	**2.40**	**0.93**	**0.60**	**0.66**	**2.50**	**-4.78**	**0.65**	**0.68**	**2.39**	**-1.83**

Name of catchment - Manot

Area (km^2) = 4661

Climatic condition - Average; Runoff Coefficient = 0.45

Table 12. Comparative Model Evaluation on Yearly basis between Original Xinanjiang Model and its modified versions with proposed modified versions of Xinanjiang model

During Calibration

Year	Observed Values		Existing versions of the Xinanjiang model																Proposed versions of the Xinanjiang model							
			ZHAO(1992)				NIRUPAMA(1996)				HU (2005)				LIN (2014)				XIN-CN				DVIC			
	P (mm)	Qo (mm)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)
1981-82	1136	387	0.56	0.61	1.78	12.95	0.58	0.61	1.74	4.29	0.39	0.41	2.10	-3.52	0.55	0.59	1.81	12.12	0.59	0.61	1.72	8.71	0.60	0.60	1.71	3.70
1982-83	1024	375	0.73	0.74	0.98	8.61	0.79	0.79	0.87	8.76	0.70	0.71	1.04	9.36	0.73	0.74	0.98	11.96	0.77	0.78	0.90	11.24	0.76	0.76	0.93	5.36
1983-84	1391	573	0.74	0.80	1.08	4.51	0.70	0.78	1.16	2.30	0.62	0.64	1.31	3.49	0.74	0.79	1.08	1.19	0.80	0.81	0.97	3.27	0.79	0.84	0.97	0.83
1984-95	1303	622	0.91	0.94	0.92	12.56	0.90	0.93	0.94	6.22	0.71	0.72	1.60	-1.94	0.90	0.94	0.93	12.76	0.93	0.95	0.78	10.36	0.91	0.92	0.91	0.67
1985-86	1264	720	0.75	0.83	1.34	-22.59	0.74	0.82	1.36	-26.36	0.57	0.62	1.75	-21.25	0.75	0.84	1.34	-23.51	0.73	0.82	1.39	-22.99	0.73	0.82	1.39	-28.68
Mean	**1224**	**535**	**0.74**	**0.78**	**1.22**	**3.21**	**0.74**	**0.79**	**1.21**	**-0.96**	**0.60**	**0.62**	**1.56**	**-2.77**	**0.73**	**0.78**	**1.23**	**2.90**	**0.76**	**0.79**	**1.15**	**2.12**	**0.76**	**0.79**	**1.18**	**-3.62**

During Validation

Year	Observed Values		Existing versions of the Xinanjiang model																Proposed versions of the Xinanjiang model							
			ZHAO(1992)				NIRUPAMA(1996)				HU (2005)				LIN (2014)				XIN-CN				DVIC			
	P (mm)	Qo (mm)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)
1986-87	1379	715	0.79	0.80	2.95	-31.60	0.75	0.77	3.19	-35.32	0.47	0.57	4.65	-31.80	0.78	0.80	2.98	-31.86	0.82	0.83	2.70	-29.92	0.79	0.82	2.91	-30.92
1987-88	1347	775	0.61	0.79	3.66	-31.98	0.63	0.82	3.58	-33.21	0.37	0.49	4.66	-32.22	0.61	0.79	3.67	-31.00	0.57	0.78	3.84	-33.93	0.61	0.83	3.64	-34.58
1988-89	1309	637	0.86	0.86	1.19	-2.49	0.88	0.88	1.11	-7.39	0.63	0.63	1.91	-8.72	0.86	0.86	1.17	-3.74	0.83	0.83	1.31	-2.07	0.84	0.85	1.25	-4.58
1989-90	1219	279	0.55	0.65	0.58	37.61	0.54	0.65	0.58	21.30	0.25	0.45	0.74	26.84	0.56	0.66	0.57	37.31	0.49	0.67	0.61	32.60	0.36	0.55	0.69	40.93
Mean	**1313**	**602**	**0.70**	**0.78**	**2.10**	**-7.12**	**0.70**	**0.78**	**2.12**	**-13.66**	**0.43**	**0.54**	**2.99**	**-11.48**	**0.70**	**0.78**	**2.10**	**-7.32**	**0.68**	**0.78**	**2.12**	**-8.33**	**0.65**	**0.76**	**2.12**	**-7.29**

Name of catchment - Bamni Banjar

Area (km^2) = 1864

Climatic condition - Average; Runoff Coefficient = 0.37

Table 13. Comparative Model Evaluation on Yearly basis between Original Xinanjiang Model and its modified versions with proposed modified versions of Xinanjiang model

During Calibration

Year	Observed Values		Existing versions of the Xinanjiang model																Proposed versions of the Xinanjiang model							
			ZHAO(1992)				NIRUPAMA(1996)				HU (2005)				LIN (2014)				XIN-CN				DVIC			
	P (mm)	Qo (mm)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)
2001-02	1382	511	0.50	0.56	2.21	35.65	0.53	0.57	2.15	34.14	0.72	0.75	1.64	24.94	0.51	0.56	2.17	34.67	0.65	0.71	1.83	32.95	0.78	0.82	1.46	17.35
2002-03	1023	326	0.54	0.56	1.36	-4.53	0.58	0.59	1.31	-11.43	0.59	0.67	1.29	-11.68	0.57	0.58	1.32	-2.73	0.56	0.58	1.33	-3.10	0.48	0.57	1.45	-24.93
2003-04	1575	752	0.73	0.73	1.33	7.26	0.73	0.73	1.32	1.25	0.71	0.71	1.36	1.35	0.73	0.74	1.31	2.23	0.80	0.80	1.15	9.25	0.79	0.79	1.17	5.53
2004-05	996	398	0.68	0.74	0.73	-17.53	0.65	0.73	0.77	-32.33	0.67	0.76	0.74	-30.65	0.67	0.74	0.74	-20.74	0.68	0.77	0.73	-29.76	0.56	0.72	0.86	-46.96
2005-06	1650	787	0.93	0.94	0.68	16.65	0.94	0.95	0.59	11.05	0.74	0.74	1.28	2.87	0.94	0.95	0.59	12.97	0.90	0.90	0.78	7.89	0.89	0.89	0.83	2.75
2006-07	611	374	0.23	0.33	0.98	-46.56	0.17	0.32	1.02	-68.26	0.22	0.50	0.99	-66.89	0.20	0.32	1.00	-60.18	0.32	0.49	0.93	-54.37	0.03	0.39	1.10	-85.38
Mean	**1206**	**524**	**0.60**	**0.64**	**1.22**	**-1.51**	**0.60**	**0.65**	**1.19**	**-10.93**	**0.61**	**0.69**	**1.22**	**-13.34**	**0.60**	**0.65**	**1.19**	**-5.63**	**0.65**	**0.71**	**1.13**	**-6.19**	**0.59**	**0.70**	**1.15**	**-21.94**

During Validation

Year	Observed Values		Existing versions of the Xinanjiang model																Proposed versions of the Xinanjiang model							
			ZHAO(1992)				NIRUPAMA(1996)				HU (2005)				LIN (2014)				XIN-CN				DVIC			
	P (mm)	Qo (mm)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)
2007-08	720	305 -	0.31	0.13	1.96	-4.85	-0.17	0.13	1.85	-10.72	0.37	0.49	1.36	-43.02	-0.14	0.15	1.82	-7.95	0.44	0.46	1.28	-31.13	0.09	0.33	1.63	-75.50
2008-09	900	253	0.32	0.52	0.96	20.91	0.35	0.52	0.94	7.18	0.67	0.76	0.67	15.47	0.35	0.52	0.94	13.03	0.63	0.67	0.71	-0.71	0.71	0.72	0.62	-5.25
2009-10	918	146	0.36	0.69	0.67	118.8	0.28	0.73	0.71	117.67	0.46	0.48	0.61	40.00	0.34	0.72	0.68	119.1	0.54	0.63	0.57	61.93	0.76	0.78	0.41	24.20
2010-11	1220	256	0.04	0.53	0.81	84.64	0.14	0.53	0.78	71.16	0.14	0.68	0.77	78.73	0.10	0.52	0.79	79.98	0.23	0.70	0.73	91.64	0.32	0.64	0.69	74.61
2011-12	1166	398	0.64	0.69	0.62	24.76	0.64	0.67	0.63	13.27	0.79	0.82	0.48	15.18	0.64	0.66	0.63	15.55	0.77	0.80	0.50	19.88	0.78	0.78	0.49	10.82
Mean	**985**	**272**	**0.33**	**0.51**	**1.00**	**48.85**	**0.25**	**0.52**	**0.98**	**39.71**	**0.49**	**0.65**	**0.78**	**21.27**	**0.26**	**0.51**	**0.97**	**43.94**	**0.52**	**0.65**	**0.76**	**28.32**	**0.53**	**0.65**	**0.77**	**5.78**

Name of catchment - Patan

Area (km^2) = 3950

Climatic condition - Average; Runoff Coefficient = 0.37

Table 14. Comparative Model Evaluation on Yearly basis between Original Xinanjiang Model and its modified versions with proposed modified versions of Xinanjiang model

During Calibration

Year	Observed Values		Existing versions of the Xinanjiang model																Proposed versions of the Xinanjiang model							
			ZHAO(1992)				NIRUPAMA(1996)				HU (2005)				LIN (2014)				XIN-CN				DVIC			
	P (mm)	Qo (mm)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)
1991-92	1283	460	0.75	0.83	2.07	32.44	0.80	0.83	1.86	15.70	0.75	0.79	2.08	26.56	-	-	-	-	0.87	0.88	1.51	16.13	0.82	0.83	1.74	14.73
1992-93	1225	462	0.81	0.82	1.31	-17.17	0.80	0.81	1.34	-13.18	0.77	0.80	1.43	-10.79	-	-	-	-	0.83	0.83	1.26	-16.17	0.79	0.80	1.39	-10.26
1993-94	1298	366	0.73	0.75	0.68	-8.08	0.72	0.73	0.70	-14.87	0.79	0.79	0.61	-18.77	-	-	-	-	0.73	0.76	0.68	-35.58	0.76	0.76	0.65	-14.45
1994-95	1946	908	0.85	0.86	1.17	-8.59	0.85	0.86	1.19	-6.21	0.90	0.90	0.98	0.41	-	-	-	-	0.87	0.87	1.12	-8.62	0.89	0.90	1.02	-2.72
1995-96	1288	393	0.62	0.78	0.80	10.39	0.63	0.77	0.79	5.25	0.83	0.83	0.53	-12.97	-	-	-	-	0.70	0.74	0.70	-19.37	0.68	0.79	0.72	-2.23
Mean	**1408**	**518**	**0.75**	**0.81**	**1.21**	**1.80**	**0.76**	**0.80**	**1.18**	**-2.66**	**0.81**	**0.82**	**1.13**	**-3.11**	-	-	-	-	**0.80**	**0.82**	**1.05**	**-12.72**	**0.79**	**0.82**	**1.10**	**-2.99**

During Validation

Year	Observed Values		Existing versions of the Xinanjiang model																Proposed versions of the Xinanjiang model							
			ZHAO(1992)				NIRUPAMA(1996)				HU (2005)				LIN (2014)				XIN-CN				DVIC			
	P (mm)	Qo (mm)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)
1999-00	1558	752	0.83	0.85	2.24	-5.51	0.77	0.79	2.58	-12.84	0.84	0.84	2.15	-11.21	-	-	-	-	0.81	0.84	2.32	-13.85	0.87	0.89	1.93	-18.33
2000-01	984	211	0.17	0.19	1.00	-34.42	0.24	0.25	0.96	-30.01	0.35	0.79	0.88	11.47	-	-	-	-	0.48	0.75	0.79	-59.12	0.74	0.82	0.56	-9.65
2001-02	1205	378	0.29	0.38	0.91	-51.81	0.42	0.50	0.83	-49.71	0.52	0.65	0.75	-46.01	-	-	-	-	0.37	0.48	0.86	-59.99	0.58	0.68	0.70	-43.54
2002-03	1127	434	0.54	0.56	1.21	-34.35	0.62	0.64	1.10	-27.47	0.78	0.80	0.82	-19.84	-	-	-	-	0.70	0.75	0.98	-36.65	0.87	0.88	0.63	-14.66
2003-04	1652	747	0.82	0.86	0.93	-25.36	0.82	0.87	0.93	-25.90	0.86	0.87	0.82	-16.26	-	-	-	-	0.84	0.87	0.87	-30.39	0.78	0.86	1.02	-22.86
2004-05	1227	290	0.78	0.79	0.41	-30.08	0.78	0.78	0.41	-18.94	0.74	0.79	0.44	3.86	-	-	-	-	0.83	0.86	0.36	-27.77	0.79	0.83	0.40	2.27
Mean	**1292**	**469**	**0.57**	**0.61**	**1.12**	**-30.26**	**0.61**	**0.64**	**1.14**	**-27.48**	**0.68**	**0.79**	**0.98**	**-13.00**	-	-	-	-	**0.67**	**0.76**	**1.03**	**-37.96**	**0.77**	**0.83**	**0.87**	**-17.80**

Name of catchment - Anthroli

Area (km^2) = 503

Climatic condition - Average; Runoff Coefficient = 0.37

Table 15. Comparative Model Evaluation on Yearly basis between Original Xinanjiang Model and its modified versions with proposed modified versions of Xinanjiang model

During Calibration

Year	Observed Values		Existing versions of the Xinanjiang model																Proposed versions of the Xinanjiang model							
			ZHAO(1992)				NIRUPAMA(1996)				HU (2005)				LIN (2014)				XIN-CN				DVIC			
	P (mm)	Qo (mm)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)
1985-86	756	256	0.48	0.59	1.18	15.54	0.63	0.68	1.00	15.28	0.66	0.68	0.95	23.95	0.50	0.58	1.16	17.44	0.50	0.63	1.16	21.78	0.71	0.74	0.88	-13.43
1986-87	709	148	0.29	0.30	0.57	19.01	0.22	0.22	0.60	12.10	0.46	0.48	0.50	12.77	0.30	0.32	0.57	29.62	0.49	0.55	0.48	3.65	0.50	0.51	0.48	22.87
1987-88	733	200	0.09	0.17	0.70	-5.19	0.05	0.15	0.72	-24.72	0.16	0.17	0.68	-8.79	0.16	0.19	0.68	4.68	-0.14	0.11	0.79	-30.41	0.14	0.17	0.68	-7.99
1988-89	1012	342	0.83	0.87	0.58	31.56	0.81	0.87	0.61	37.04	0.78	0.78	0.66	14.85	0.82	0.88	0.59	43.56	0.88	0.89	0.50	28.83	0.90	0.92	0.45	15.38
1989-90	826	287	0.77	0.81	0.60	-14.49	0.75	0.78	0.63	-20.25	0.63	0.69	0.76	-9.57	0.74	0.79	0.63	-3.27	0.73	0.86	0.65	-35.83	0.75	0.81	0.62	-15.91
Mean	**807**	**247**	**0.49**	**0.55**	**0.73**	**9.29**	**0.49**	**0.54**	**0.71**	**3.89**	**0.54**	**0.56**	**0.71**	**6.64**	**0.50**	**0.55**	**0.73**	**18.41**	**0.49**	**0.61**	**0.72**	**-2.40**	**0.60**	**0.63**	**0.62**	**0.18**

During Validation

Year	Observed Values		Existing versions of the Xinanjiang model																Proposed versions of the Xinanjiang model							
			ZHAO(1992)				NIRUPAMA(1996)				HU (2005)				LIN (2014)				XIN-CN				DVIC			
	P (mm)	Qo (mm)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)
1990-91	889	253	0.49	0.51	1.33	5.71	0.61	0.66	1.16	10.88	0.55	0.62	1.25	27.06	0.48	0.51	1.34	20.63	0.60	0.63	1.17	27.46	0.52	0.64	1.29	-14.69
1991-92	1151	418	0.54	0.67	1.10	26.06	0.46	0.65	1.18	30.95	0.49	0.61	1.15	7.23	0.51	0.66	1.13	33.70	0.51	0.67	1.13	26.50	0.25	0.60	1.39	13.46
1992-93	1156	392	0.16	0.26	1.18	19.51	0.09	0.26	1.22	16.03	0.33	0.34	1.05	-4.02	0.23	0.28	1.13	22.38	0.41	0.47	0.98	4.73	0.28	0.32	1.09	-3.20
1993-94	1093	345	0.67	0.68	0.81	28.39	0.51	0.54	0.98	23.71	0.55	0.57	0.94	5.20	0.67	0.69	0.81	36.63	0.60	0.60	0.89	17.14	0.60	0.61	0.89	7.10
Mean	**1072**	**352**	**0.47**	**0.53**	**1.11**	**19.92**	**0.42**	**0.53**	**1.14**	**20.39**	**0.48**	**0.54**	**1.10**	**8.87**	**0.47**	**0.54**	**1.10**	**28.34**	**0.53**	**0.59**	**1.04**	**18.96**	**0.41**	**0.54**	**1.17**	**0.67**

Name of catchment - Kogaon

Area (km^2) = 3919

Climatic condition - Dry; Runoff Coefficient = 0.35

Table 16. Comparative Model Evaluation on Yearly basis between Original Xinanjiang Model and its modified versions with proposed modified versions of Xinanjiang model

During Calibration																										
Year	Observed Values		Existing versions of the Xinanjiang model																Proposed versions of the Xinanjiang model							
			ZHAO(1992)				NIRUPAMA(1996)				HU (2005)				LIN (2014)				XIN-CN				DVIC			
	P (mm)	Qo (mm)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)
1993-94	883	540	0.63	0.66	4.61	-6.90	0.62	0.65	4.64	-3.59	0.39	0.44	5.93	-8.37	0.63	0.66	4.60	-5.81	0.61	0.65	4.73	1.90	0.69	0.76	4.24	-18.88
1994-95	578	200	0.12	0.28	2.03	-2.51	0.17	0.29	1.98	-4.30	0.35	0.36	1.75	40.27	0.05	0.26	2.11	-1.81	0.20	0.33	1.94	14.73	0.29	0.36	1.83	-3.36
1995-96	814	342	0.64	0.68	0.93	0.05	0.67	0.70	0.88	-3.34	0.65	0.66	0.91	7.72	0.65	0.68	0.91	0.26	0.69	0.74	0.85	19.03	0.75	0.75	0.77	-5.08
1996-97	807	319	0.94	0.96	0.61	-6.73	0.96	0.97	0.54	-8.83	0.36	0.38	2.07	21.74	0.93	0.96	0.68	-8.75	0.90	0.93	0.82	9.37	0.93	0.96	0.71	-14.10
Mean	**771**	**350**	**0.58**	**0.65**	**2.05**	**-4.02**	**0.61**	**0.65**	**2.01**	**-5.02**	**0.44**	**0.46**	**2.67**	**15.34**	**0.57**	**0.64**	**2.08**	**-4.03**	**0.60**	**0.66**	**2.09**	**11.26**	**0.67**	**0.71**	**1.89**	**-10.36**

During Validation																										
Year	Observed Values		Existing versions of the Xinanjiang model																Proposed versions of the Xinanjiang model							
			ZHAO(1992)				NIRUPAMA(1996)				HU (2005)				LIN (2014)				XIN-CN				DVIC			
	P (mm)	Qo (mm)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)
2002-03	852	389	0.53	0.63	5.28	47.81	0.50	0.61	5.44	50.03	0.44	0.44	5.80	62.98	0.55	0.64	5.19	48.44	0.58	0.65	4.98	50.52	0.52	0.61	5.35	25.80
2003-04	881	399	0.34	0.41	2.82	-11.11	0.33	0.41	2.85	-10.80	0.27	0.28	2.96	25.29	0.31	0.38	2.88	-13.71	0.44	0.48	2.61	10.80	0.02	0.34	3.44	-0.89
2004-05	744	267	0.09	0.27	2.52	10.25	0.03	0.25	2.60	8.31	0.19	0.21	2.38	34.59	0.05	0.25	2.59	12.91	0.23	0.33	2.33	36.13	0.27	0.33	2.27	-0.08
Mean	**826**	**352**	**0.32**	**0.44**	**3.54**	**15.65**	**0.29**	**0.42**	**3.63**	**15.85**	**0.30**	**0.31**	**3.71**	**40.95**	**0.30**	**0.42**	**3.55**	**15.88**	**0.42**	**0.49**	**3.31**	**32.48**	**0.27**	**0.43**	**3.69**	**8.28**

Name of catchment - Barchi

Area (km^2) = 14.5

Climatic condition - Dry; Runoff Coefficient = 0.35

Table 17. Comparative Model Evaluation on Yearly basis between Original Xinanjiang Model and its modified versions with proposed modified versions of Xinanjiang model

	During Calibration																									
Year	Observed Values		Existing versions of the Xinanjiang model																Proposed versions of the Xinanjiang model							
			ZHAO(1992)				NIRUPAMA(1996)				HU (2005)				LIN (2014)				XIN-CN				DVIC			
	P (mm)	Qo (mm)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)
1989-90	1013	226	0.43	0.34	2.40	75.37	-0.20	0.42	1.69	101.98	0.15	0.23	1.42	-52.37	-0.38	0.38	1.81	107.9	-1.07	0.35	2.21	80.38	-0.55	0.34	1.92	31.69
1990-91	1457	615	0.41	0.43	2.28	-24.01	0.38	0.39	2.33	-9.91	0.76	0.77	1.44	-13.85	0.39	0.40	2.31	-11.55	0.71	0.74	1.58	-6.55	0.57	0.57	1.94	-6.67
1991-92	1796	667	0.59	0.60	1.54	14.75	0.49	0.51	1.71	27.96	0.59	0.59	1.55	-18.81	0.48	0.50	1.73	21.60	0.72	0.75	1.27	30.39	0.47	0.53	1.74	18.56
Mean	**1422**	**503**	**0.48**	**0.46**	**2.07**	**22.04**	**0.22**	**0.44**	**1.91**	**40.01**	**0.50**	**0.53**	**1.47**	**-28.34**	**0.16**	**0.43**	**1.95**	**39.33**	**0.12**	**0.61**	**1.69**	**34.74**	**0.16**	**0.48**	**1.87**	**14.53**

	During Validation																									
Year	Observed Values		Existing versions of the Xinanjiang model																Proposed versions of the Xinanjiang model							
			ZHAO(1992)				NIRUPAMA(1996)				HU (2005)				LIN (2014)				XIN-CN				DVIC			
	P (mm)	Qo (mm)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)
1992-93	1630	668	0.49	0.49	3.35	3.90	0.40	0.41	3.64	16.51	0.55	0.78	3.16	-30.42	0.40	0.41	3.65	18.04	0.77	0.79	2.24	27.81	0.57	0.57	3.09	0.39
1993-94	1159	313	0.47	0.52	1.03	-13.51	0.49	0.56	1.01	-0.98	0.14	0.28	1.32	-40.17	0.24	0.37	1.24	-43.76	0.54	0.56	0.96	-28.51	0.38	0.39	1.12	-18.69
Mean	**1395**	**490**	**0.48**	**0.51**	**2.19**	**-4.81**	**0.45**	**0.49**	**2.33**	**7.77**	**0.35**	**0.53**	**2.24**	**-35.30**	**0.32**	**0.39**	**2.45**	**-12.86**	**0.66**	**0.68**	**1.60**	**-0.35**	**0.48**	**0.48**	**2.11**	**-9.15**

Name of catchment - Mohegaon

Area (km^2) = 5032

Climatic condition - Dry; Runoff Coefficient = 0.35

Table 18. Comparative Model Evaluation on Yearly basis between Original Xinanjiang Model and its modified versions with proposed modified versions of Xinanjiang model

	During Calibration																									
Year	Observed Values		Existing versions of the Xinanjiang model																Proposed versions of the Xinanjiang model							
			ZHAO(1992)				NIRUPAMA(1996)				HU (2005)				LIN (2014)				XIN-CN				DVIC			
	P (mm)	Qo (mm)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)
1981-82	1134	328	0.08	0.54	1.82	32.14	0.03	0.54	1.87	35.00	0.44	0.57	1.42	20.95	0.20	0.59	1.70	30.68	0.26	0.65	1.64	30.17	0.54	0.62	1.28	13.84
1982-83	901	339	0.47	0.48	1.42	-8.66	0.47	0.48	1.42	-7.81	0.61	0.61	1.22	1.03	0.49	0.50	1.39	-0.99	0.57	0.57	1.28	-1.24	0.59	0.60	1.25	-12.94
1983-84	1260	486	0.27	0.59	1.20	8.24	0.25	0.58	1.22	8.26	0.68	0.74	0.80	12.94	0.37	0.60	1.12	5.38	0.60	0.70	0.89	6.07	0.56	0.69	0.93	11.72
1984-85	1150	518	0.88	0.88	1.25	13.88	0.88	0.88	1.24	13.45	0.43	0.45	2.71	3.19	0.89	0.89	1.21	11.28	0.85	0.85	1.40	13.22	0.85	0.89	1.37	0.38
1985-86	1196	579	0.79	0.85	1.20	-18.40	0.79	0.85	1.20	-17.68	0.39	0.42	2.03	-13.63	0.77	0.84	1.24	-22.83	0.73	0.80	1.36	-21.77	0.78	0.85	1.22	-21.53
Mean	**1128**	**450**	**0.50**	**0.67**	**1.38**	**5.44**	**0.48**	**0.67**	**1.39**	**6.24**	**0.51**	**0.56**	**1.64**	**4.90**	**0.54**	**0.68**	**1.33**	**4.70**	**0.60**	**0.71**	**1.31**	**5.29**	**0.66**	**0.73**	**1.21**	**-1.71**

	During Validation																									
Year	Observed Values		Existing versions of the Xinanjiang model																Proposed versions of the Xinanjiang model							
			ZHAO(1992)				NIRUPAMA(1996)				HU (2005)				LIN (2014)				XIN-CN				DVIC			
	P (mm)	Qo (mm)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)
1986-87	1281	471	0.05	0.77	3.96	5.94	0.04	0.77	3.99	6.62	0.50	0.52	2.89	23.40	-0.05	0.77	4.17	17.83	0.31	0.78	3.37	18.99	0.68	0.83	2.31	9.25
1987-88	1289	378	0.03	0.41	2.58	37.39	0.02	0.41	2.58	38.75	0.35	0.38	2.10	37.15	0.00	0.40	2.61	40.02	0.17	0.43	2.38	39.88	0.46	0.53	1.92	22.29
1988-89	1369	550	0.65	0.74	1.68	31.90	0.66	0.75	1.66	30.66	0.29	0.44	2.39	48.58	0.67	0.76	1.62	34.36	0.74	0.80	1.43	35.06	0.13	0.53	2.63	48.23
1989-90	926	227	0.05	0.28	1.19	52.90	-1.25	0.26	1.24	55.34	-0.06	0.48	0.85	85.22	-0.49	0.34	1.01	40.72	-0.39	0.39	0.98	42.17	-0.33	0.41	0.96	86.55
Mean	**1216**	**406**	**0.20**	**0.55**	**2.35**	**32.03**	**-0.13**	**0.55**	**2.37**	**32.84**	**0.27**	**0.46**	**2.06**	**48.59**	**0.03**	**0.57**	**2.35**	**33.23**	**0.21**	**0.60**	**2.04**	**34.03**	**0.24**	**0.58**	**1.96**	**41.58**

Name of catchment - Amachi

Area (km^2) = 87

Climatic condition - Dry; Runoff Coefficient = 0.29

Table 19. Comparative Model Evaluation on Yearly basis between Original Xinanjiang Model and its modified versions with proposed modified versions of Xinanjiang model

During Calibration

Year	Observed Values		Existing versions of the Xinanjiang model																Proposed versions of the Xinanjiang model							
			ZHAO(1992)				NIRUPAMA(1996)				HU (2005)				LIN (2014)				XIN-CN				DVIC			
	P (mm)	Qo (mm)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)
1985-86	1514	446	0.45	0.60	1.71	57.76	0.47	0.60	1.68	52.52	0.60	0.74	1.46	64.65	0.45	0.61	1.70	57.75	0.55	0.68	1.55	63.43	0.52	0.54	1.60	-19.49
1986-87	1254	390	0.13	0.18	1.12	-30.48	0.14	0.19	1.11	-32.80	0.45	0.61	0.89	-37.85	0.14	0.19	1.11	-27.51	0.32	0.36	0.99	-30.84	0.66	0.73	0.70	-30.13
1987-88	1360	305	- 0.06	0.05	0.87	-57.06	-0.10	0.06	0.89	-66.43	0.43	0.61	0.64	-27.43	-0.06	0.05	0.87	-56.82	0.12	0.25	0.79	-52.93	0.49	0.58	0.61	-26.68
1988-89	1801	417	0.73	0.76	0.87	50.27	0.72	0.75	0.89	45.79	0.58	0.65	1.09	62.26	0.72	0.76	0.88	51.58	0.76	0.79	0.83	49.55	0.19	0.32	1.51	35.43
1989-90	1698	494	0.46	0.46	0.92	-0.81	0.46	0.46	0.92	-5.74	0.52	0.58	0.87	-10.27	0.46	0.46	0.92	0.35	0.55	0.55	0.84	1.27	0.52	0.55	0.87	-20.17
Mean	**1525**	**410**	**0.37**	**0.41**	**1.10**	**3.94**	**0.34**	**0.41**	**1.10**	**-1.33**	**0.52**	**0.64**	**0.99**	**10.27**	**0.34**	**0.41**	**1.10**	**5.07**	**0.46**	**0.53**	**1.00**	**6.10**	**0.48**	**0.54**	**1.06**	**-12.21**

During Validation

Year	Observed Values		Existing versions of the Xinanjiang model																Proposed versions of the Xinanjiang model							
			ZHAO(1992)				NIRUPAMA(1996)				HU (2005)				LIN (2014)				XIN-CN				DVIC			
	P (mm)	Qo (mm)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)
1990-91	2042	601	0.21	0.33	3.13	66.80	0.23	0.33	3.08	61.29	0.43	0.67	2.65	76.35	0.21	0.33	3.13	66.85	0.51	0.62	2.47	71.98	0.46	0.66	2.58	-37.64
1991-92	1973	544	0.23	0.29	1.91	41.97	0.23	0.28	1.90	35.18	-1.13	0.41	3.17	81.96	0.23	0.29	1.91	42.51	0.36	0.41	1.74	43.55	0.41	0.49	1.67	-30.02
1992-93	2469	651	0.27	0.36	1.74	50.44	0.36	0.44	1.63	46.48	0.50	0.57	1.45	53.37	0.27	0.37	1.74	51.24	0.64	0.73	1.23	55.55	0.60	0.61	1.30	8.53
1993-94	1953	549	0.23	0.25	1.49	24.72	0.25	0.27	1.47	26.05	0.34	0.41	1.38	-3.67	0.23	0.25	1.49	24.51	0.47	0.56	1.25	25.18	0.41	0.54	1.31	-22.63
Mean	**2109**	**586**	**0.24**	**0.31**	**2.07**	**45.98**	**0.27**	**0.33**	**2.02**	**42.25**	**0.04**	**0.52**	**2.16**	**52.00**	**0.24**	**0.31**	**2.07**	**46.28**	**0.50**	**0.58**	**1.67**	**49.07**	**0.47**	**0.58**	**1.72**	**-20.44**

Name of catchment - Hridaynagar

Area (km^2) = 3370

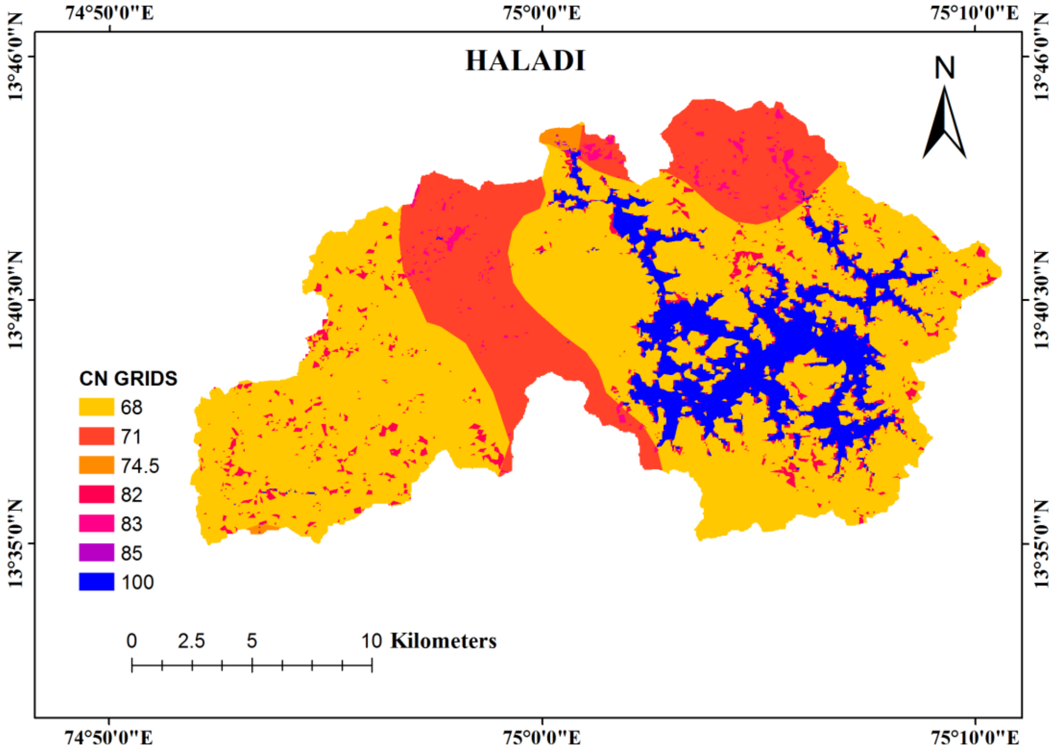
Climatic condition - Dry; Runoff Coefficient = 0.24

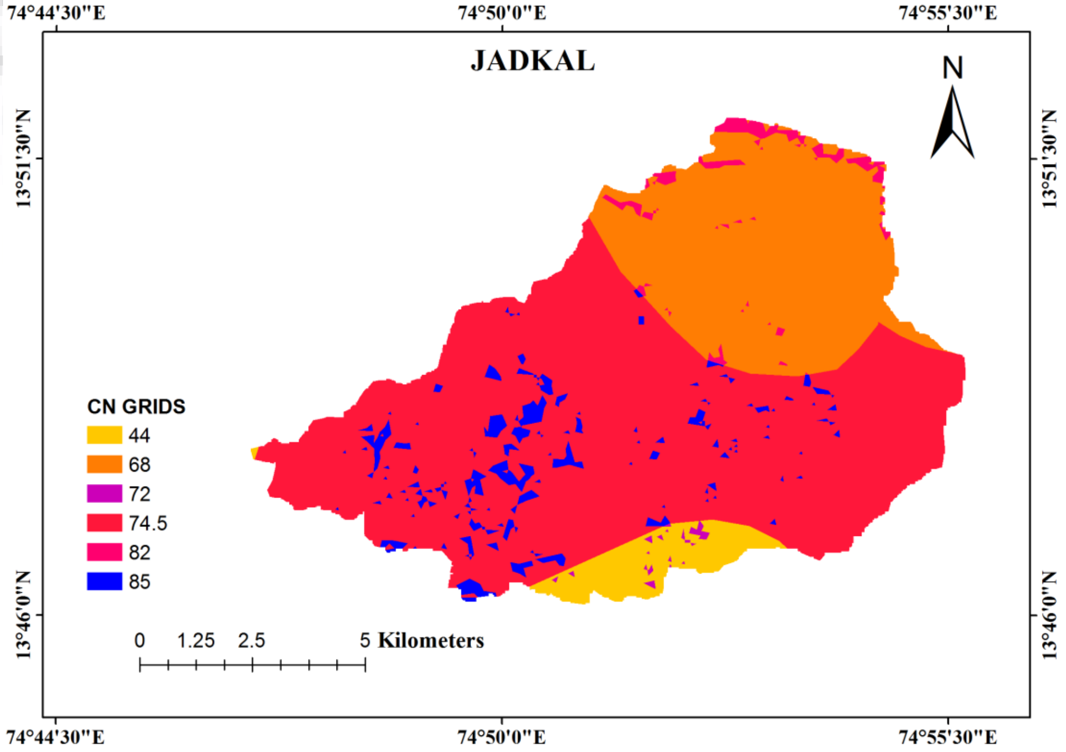
Table 20. Comparative Model Evaluation on Yearly basis between Original Xinanjiang Model and its modified versions with proposed modified versions of Xinanjiang model

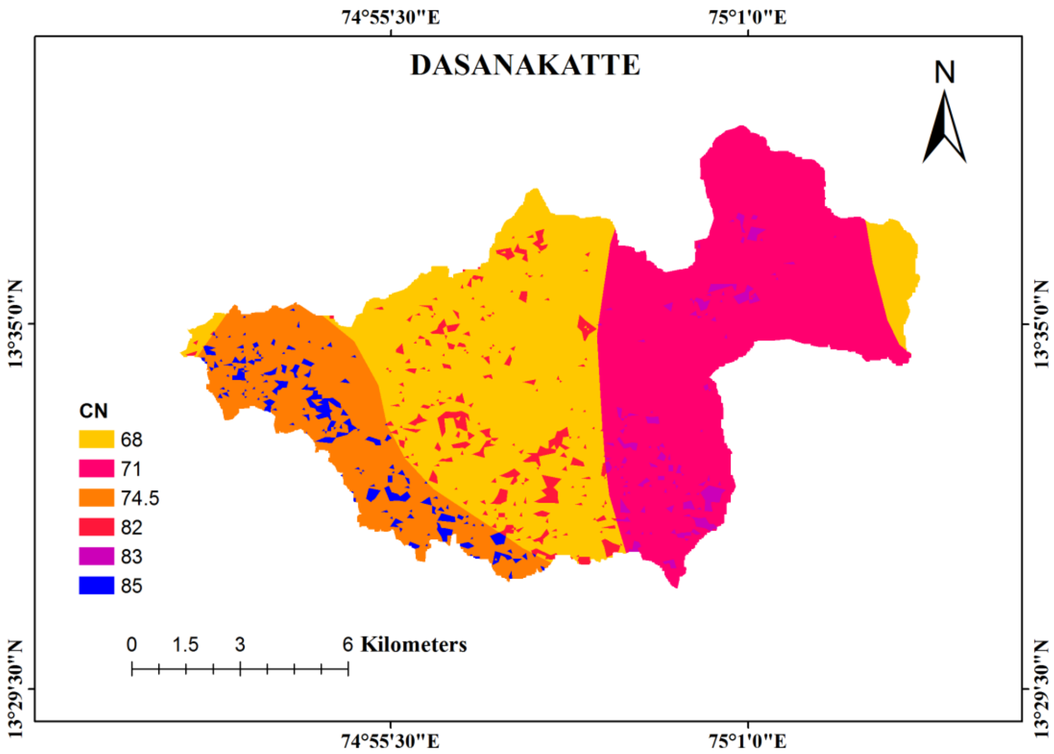
	During Calibration																									
Year	Observed Values		Existing versions of the Xinanjiang model																Proposed versions of the Xinanjiang model							
			ZHAO(1992)				NIRUPAMA(1996)				HU (2005)				LIN (2014)				XIN-CN				DVIC			
	P (mm)	Qo (mm)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)
1981-82	1213	314	0.52	0.53	1.64	9.20	0.28	0.39	2.01	8.41	0.23	0.29	2.08	12.75	0.54	0.55	1.61	9.27	0.49	0.51	1.69	21.31	0.62	0.63	1.46	16.12
1982-83	1020	309	0.45	0.46	2.02	-11.35	0.63	0.79	1.65	-34.43	0.40	0.45	2.11	-15.23	0.44	0.46	2.03	-17.33	0.56	0.66	1.80	-21.72	0.48	0.48	1.96	-14.86
1983-84	1334	375	0.50	0.56	0.94	2.98	0.37	0.41	1.05	-22.35	0.62	0.63	0.82	7.15	0.50	0.56	0.94	-0.55	0.60	0.61	0.84	-3.38	0.70	0.71	0.72	11.42
1984-95	1053	295	0.88	0.88	0.57	12.87	0.80	0.82	0.75	0.40	0.78	0.79	0.77	10.07	0.88	0.88	0.57	8.15	0.86	0.86	0.62	-0.16	0.85	0.86	0.64	11.34
1985-86	1271	255	0.69	0.75	0.43	12.00	0.46	0.62	0.56	-14.83	0.70	0.70	0.42	10.58	0.69	0.76	0.43	11.36	0.75	0.76	0.38	-0.27	0.75	0.77	0.38	16.84
Mean	**1178**	**310**	**0.61**	**0.64**	**1.12**	**5.14**	**0.51**	**0.61**	**1.20**	**-12.56**	**0.55**	**0.57**	**1.24**	**5.06**	**0.61**	**0.64**	**1.12**	**2.18**	**0.65**	**0.68**	**1.07**	**-0.84**	**0.68**	**0.69**	**1.03**	**8.17**

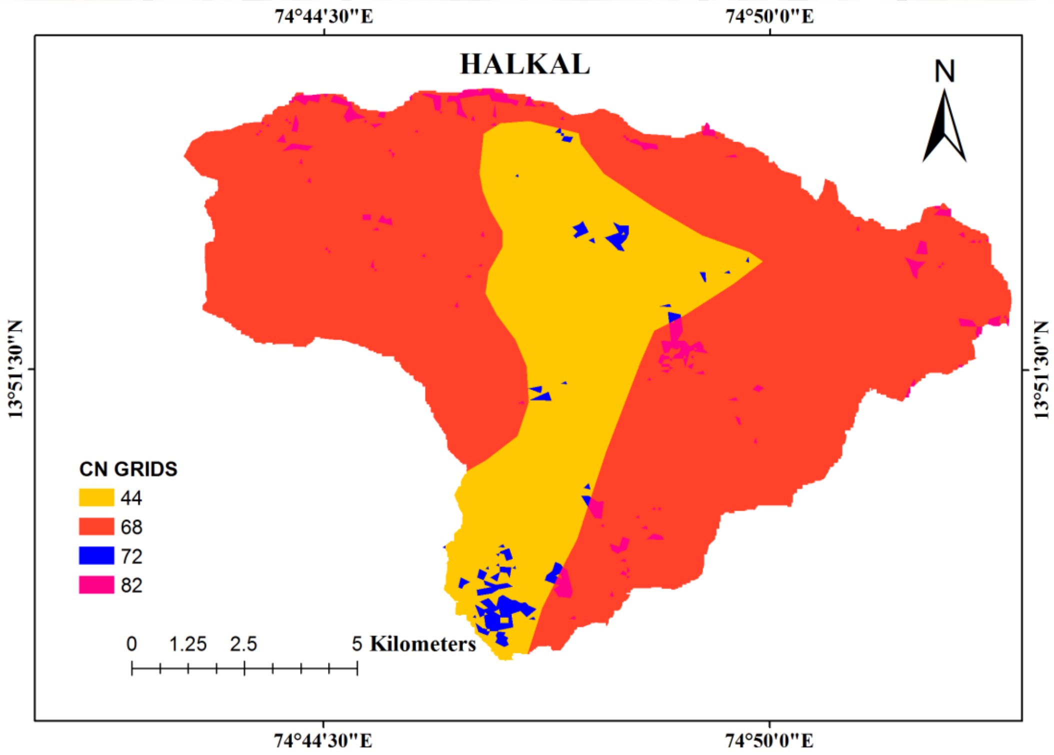
	During Validation																									
Year	Observed Values		Existing versions of the Xinanjiang model																Proposed versions of the Xinanjiang model							
			ZHAO(1992)				NIRUPAMA(1996)				HU (2005)				LIN (2014)				XIN-CN				DVIC			
	P (mm)	Qo (mm)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)	NSE	R^2	RMSE (mm)	RE (%)
1986-87	1243	593	0.44	0.53	3.12	-38.25	0.47	0.55	3.03	-39.46	0.40	0.49	3.22	-38.57	0.48	0.58	3.01	-38.39	0.59	0.72	2.66	-31.86	0.55	0.67	2.80	-34.80
1987-88	1086	179	0.30	0.31	0.77	-16.42	0.27	0.30	0.79	-44.07	0.44	0.45	0.69	8.94	0.64	0.64	0.56	2.23	0.63	0.63	0.57	-19.72	0.59	0.62	0.59	1.89
1988-89	1418	560	0.62	0.65	1.36	-13.27	0.52	0.55	1.53	-23.48	0.54	0.55	1.50	-12.06	0.61	0.64	1.38	-15.92	0.57	0.59	1.44	-10.74	0.50	0.56	1.57	2.50
1989-90	1189	285	0.70	0.76	0.56	-21.91	0.56	0.65	0.68	-42.80	0.59	0.63	0.65	-14.88	0.65	0.65	0.61	-1.78	0.73	0.81	0.53	-26.35	0.65	0.66	0.60	-1.53
Mean	**1234**	**404**	**0.52**	**0.56**	**1.45**	**-22.46**	**0.46**	**0.51**	**1.51**	**-37.45**	**0.49**	**0.53**	**1.52**	**-14.14**	**0.60**	**0.63**	**1.39**	**-13.47**	**0.63**	**0.69**	**1.30**	**-22.17**	**0.57**	**0.63**	**1.39**	**-7.99**

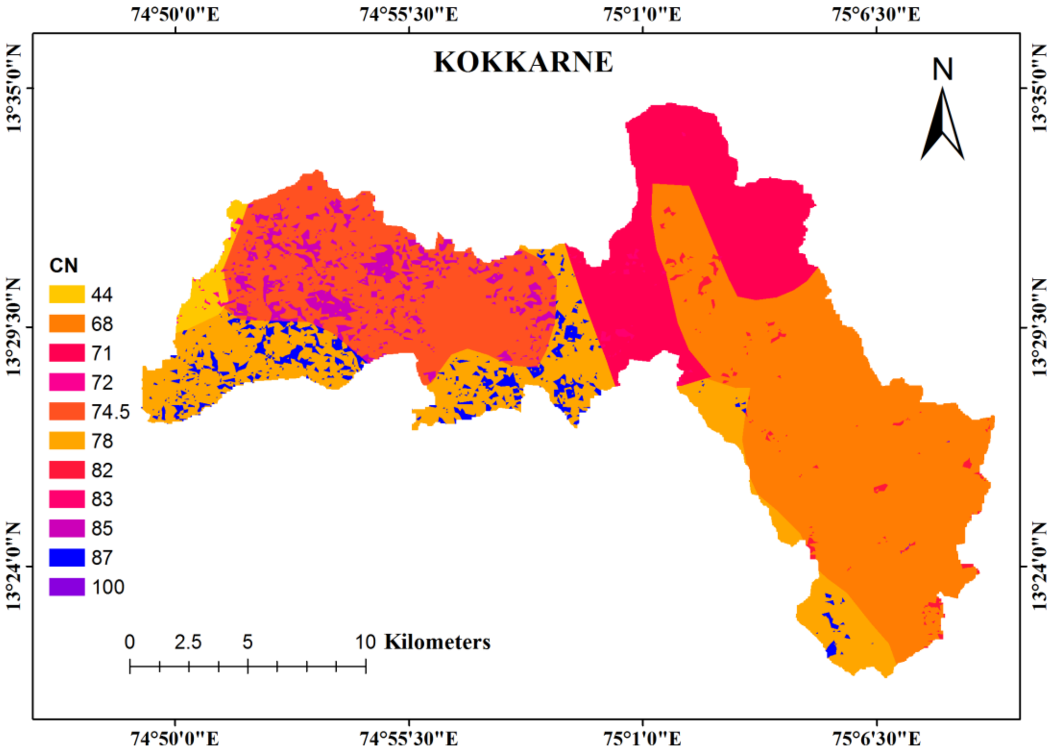
APPENDIX-VI CNGRID MAPS OF THE STUDIED CATCHMENTS

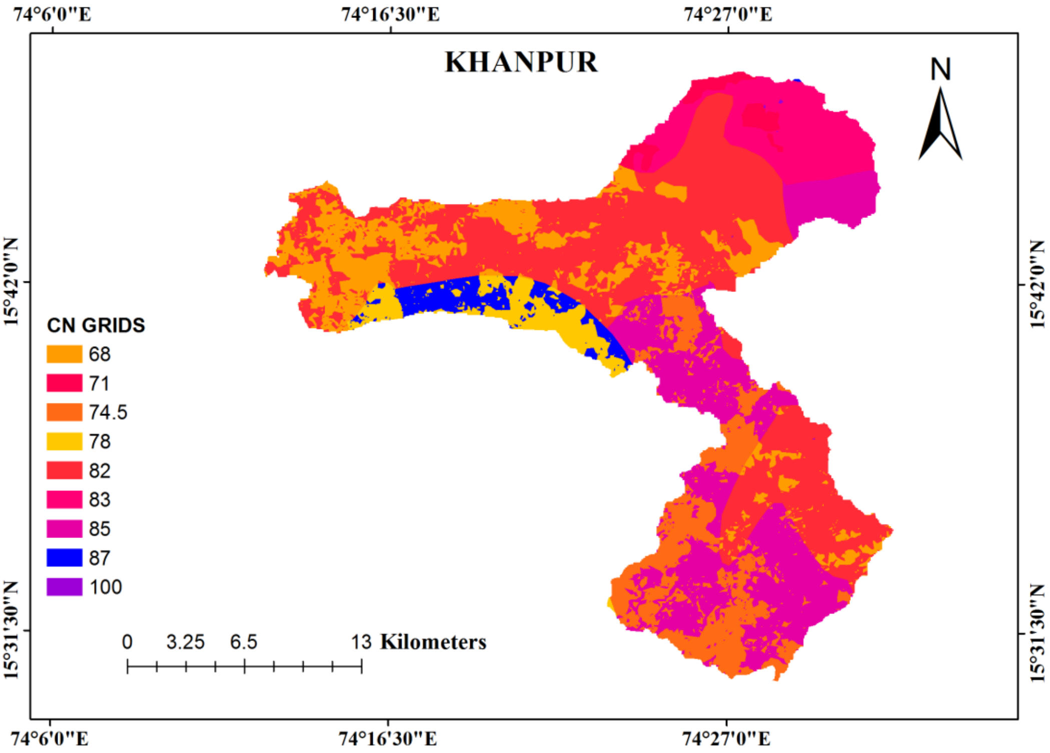


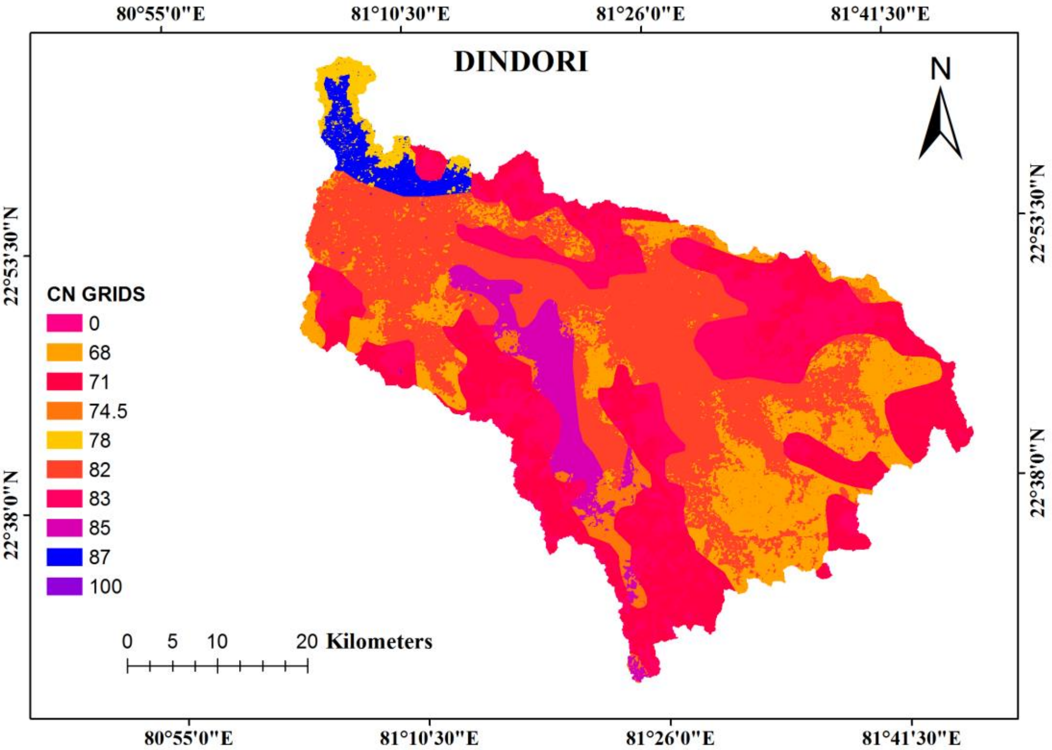


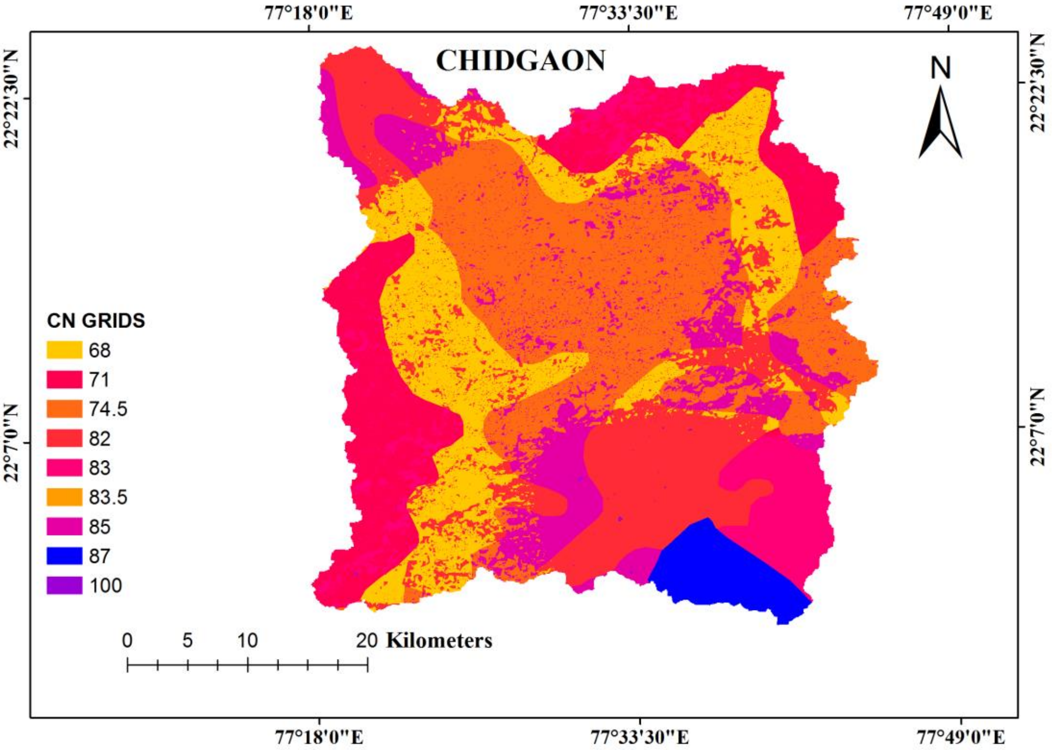

74°55'30"E
75°1'0"E
DASANAKATTE
N
13°35'0"N
13°29'30"N
CN
68
71
74.5
82
83
85
0
1.5
3
6 Kilometers

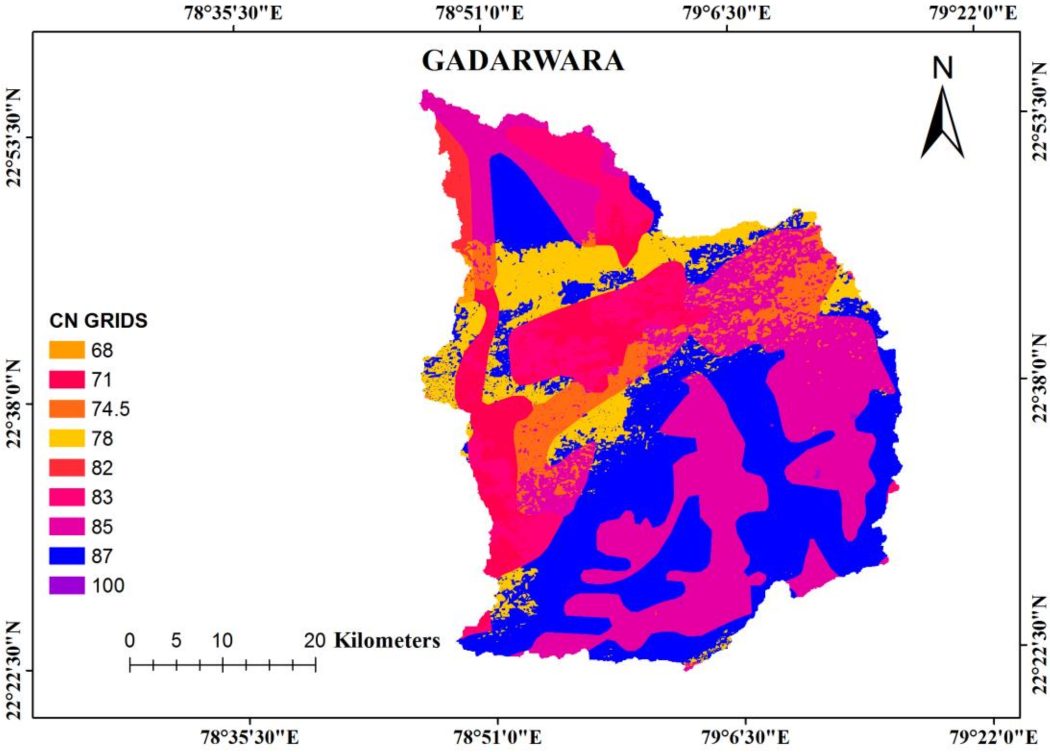

74°44'30"E
74°50'0"E
HALKAL
N
13°51'30"N
CN GRIDS
44
68
72
82
0
1.25
2.5
5 Kilometers


74°50'0"E
74°55'30"E
75°1'0"E
75°6'30"E
KOKKARNE
N
13°35'0"N
13°29'30"N
13°24'0"N
CN
44
68
71
72
74.5
78
82
83
85
87
100
0
2.5
5
10 Kilometers


74°6'0"E
74°16'30"E
74°27'0"E
KHANPUR
N
15°42'0"N
15°31'30"N
CN GRIDS
68
71
74.5
78
82
83
85
87
100
0
3.25
6.5
13 Kilometers


DINDORI
N
80°55'0"E
81°10'30"E
81°26'0"E
81°41'30"E
22°53'30"N
22°38'0"N
CN GRIDS
0
68
71
74.5
78
82
83
85
87
100
0 5 10 20 Kilometers


CHIDGAON
N
77°18'0"E
77°33'30"E
77°49'0"E
22°22'30"N
22°7'0"N
CN GRIDS
68
71
74.5
82
83
83.5
85
87
100
0 5 10 20 Kilometers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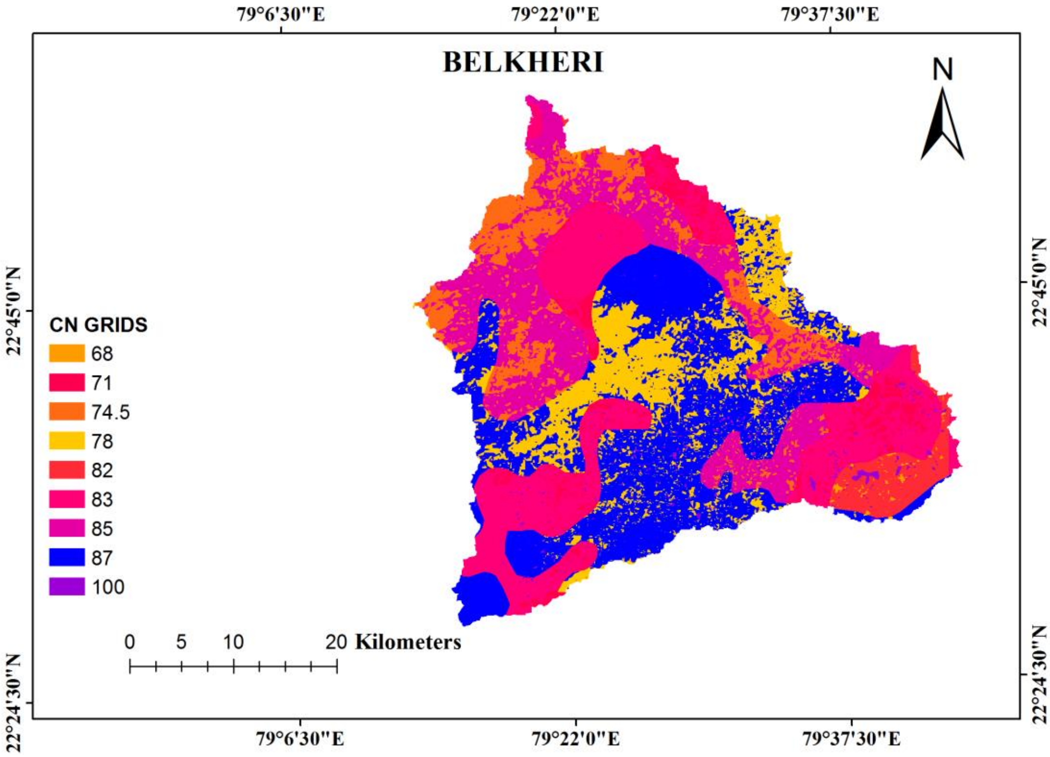
78°51'0"E
79°6'30"E
79°22'0"E
GADARWARA
N
22°53'30"N
22°38'0"N
22°22'30"N
CN GRIDS
68
71
74.5
78
82
83
85
87
100
0 5 10 20 Kilometers


79°6'30"E
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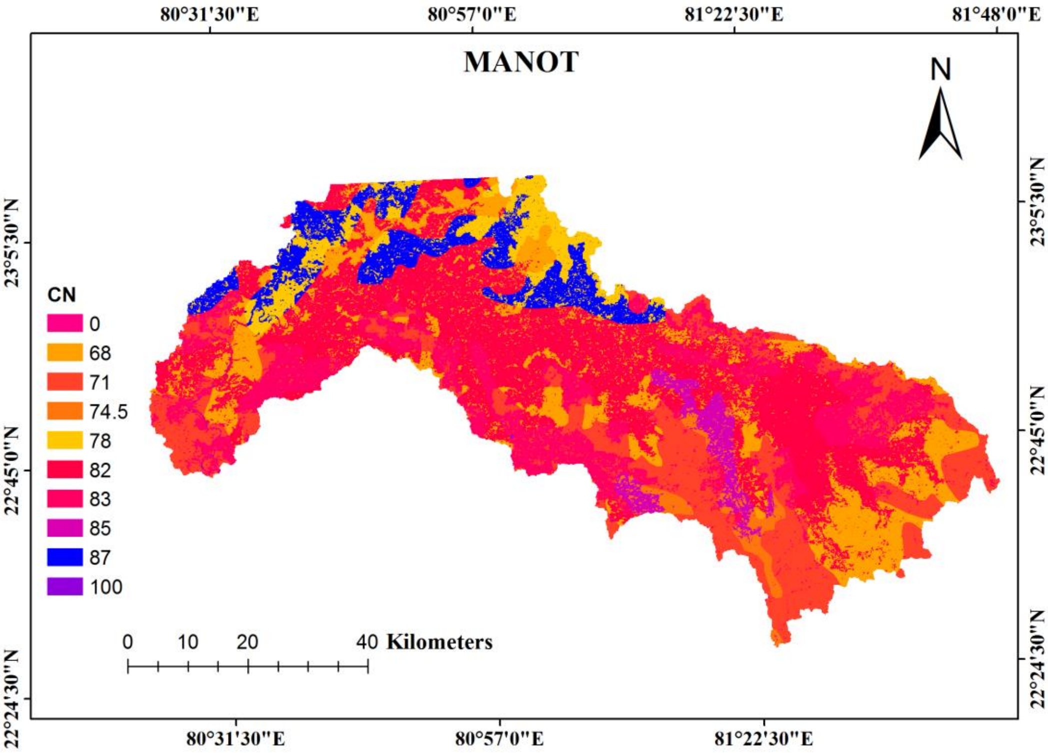
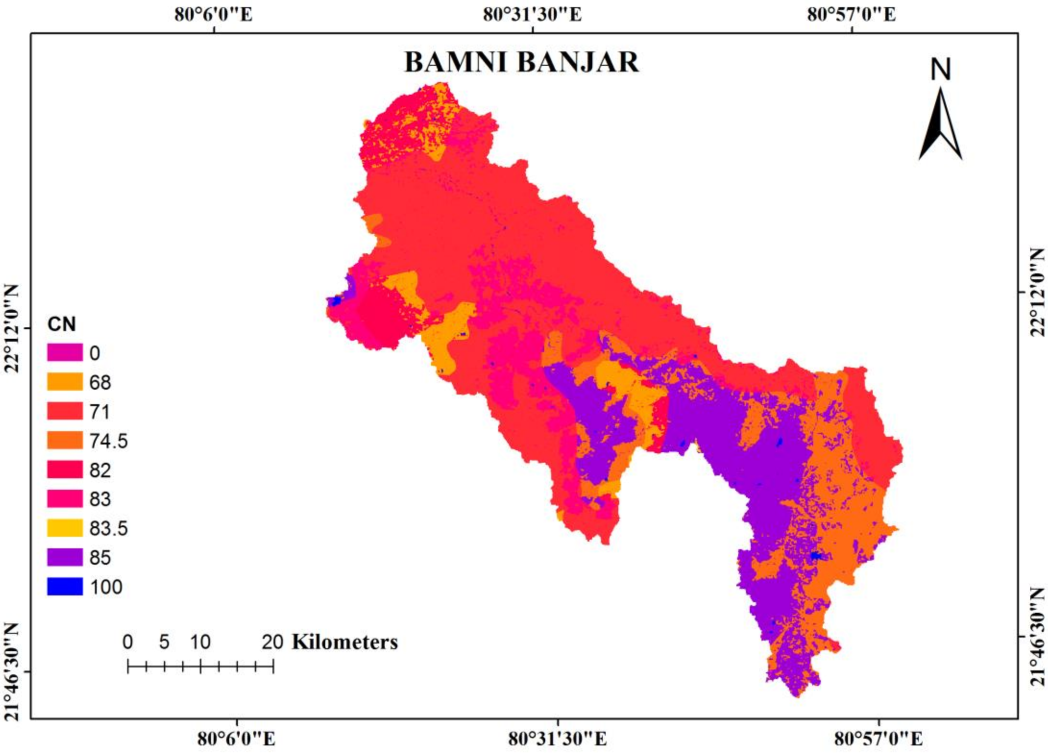
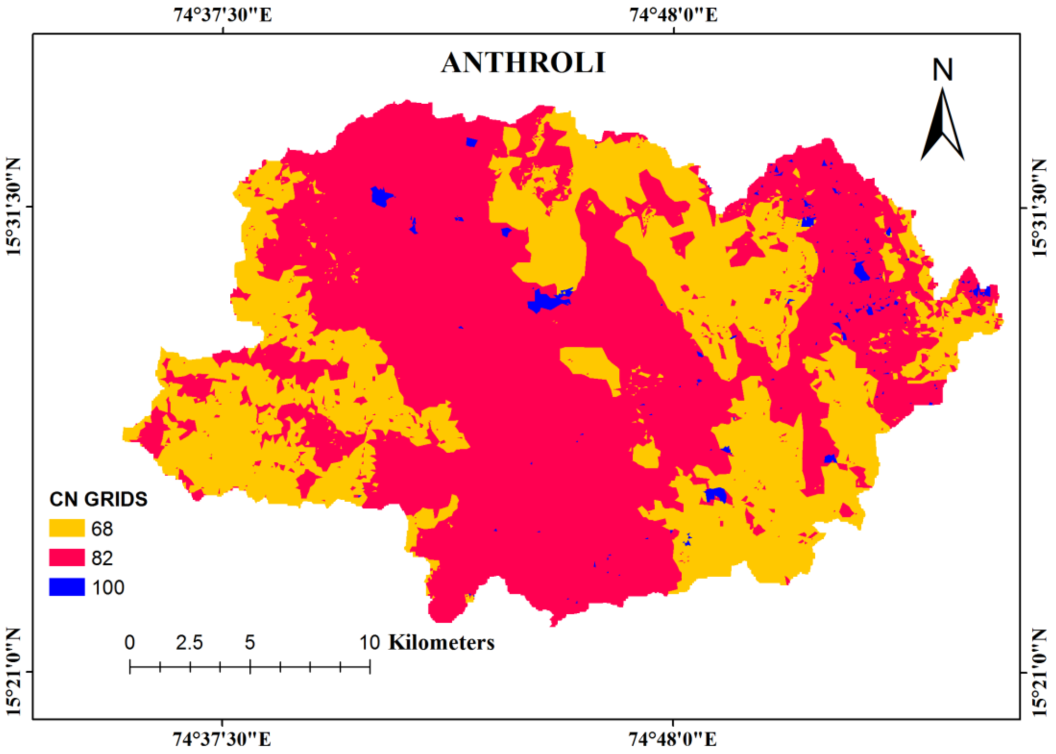
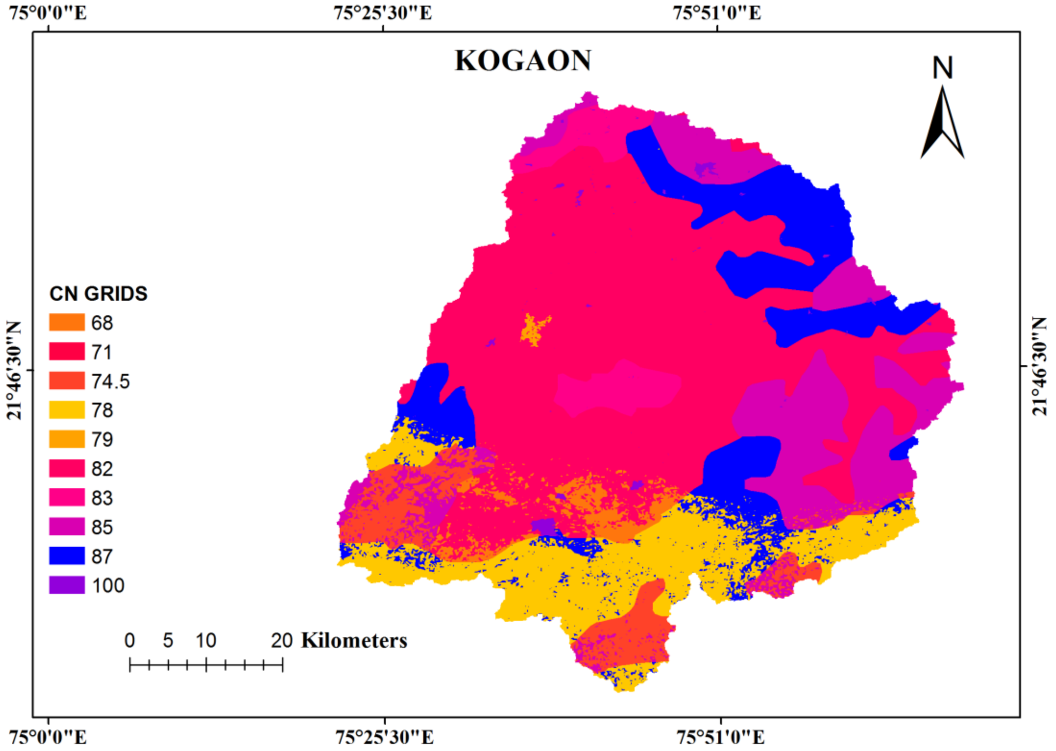
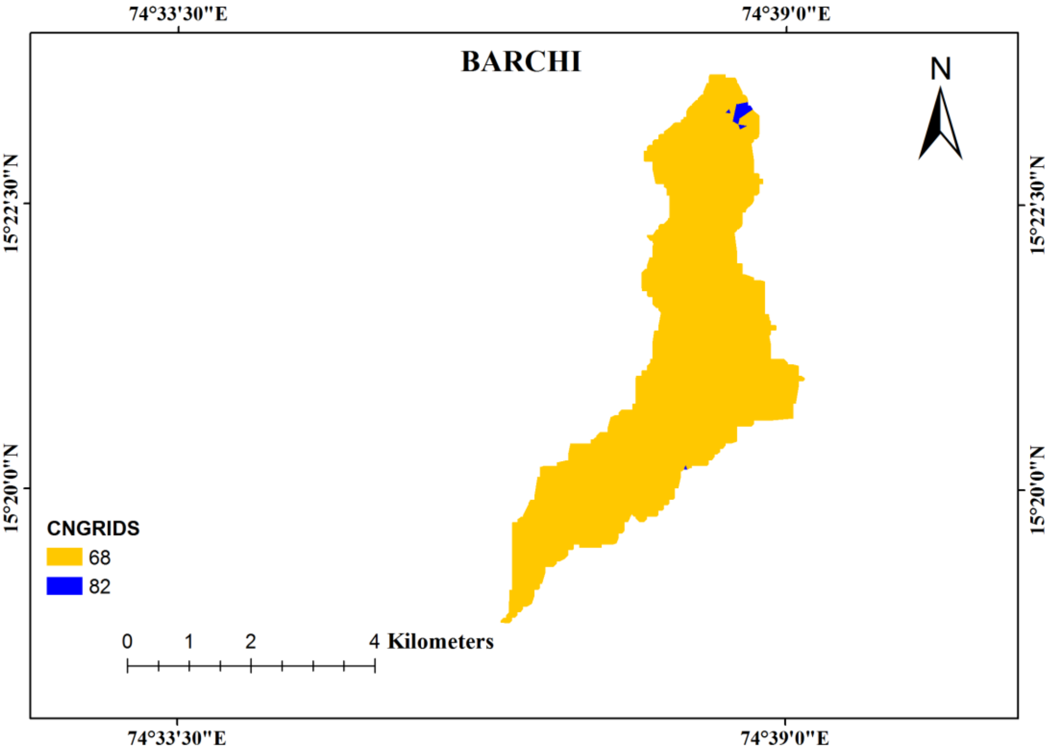
79°37'30"E
BELKHERI
N
22°45'0"N
22°24'30"N
CN GRIDS
68
71
74.5
78
82
83
85
87
100
0 5 10 20 Kilometers

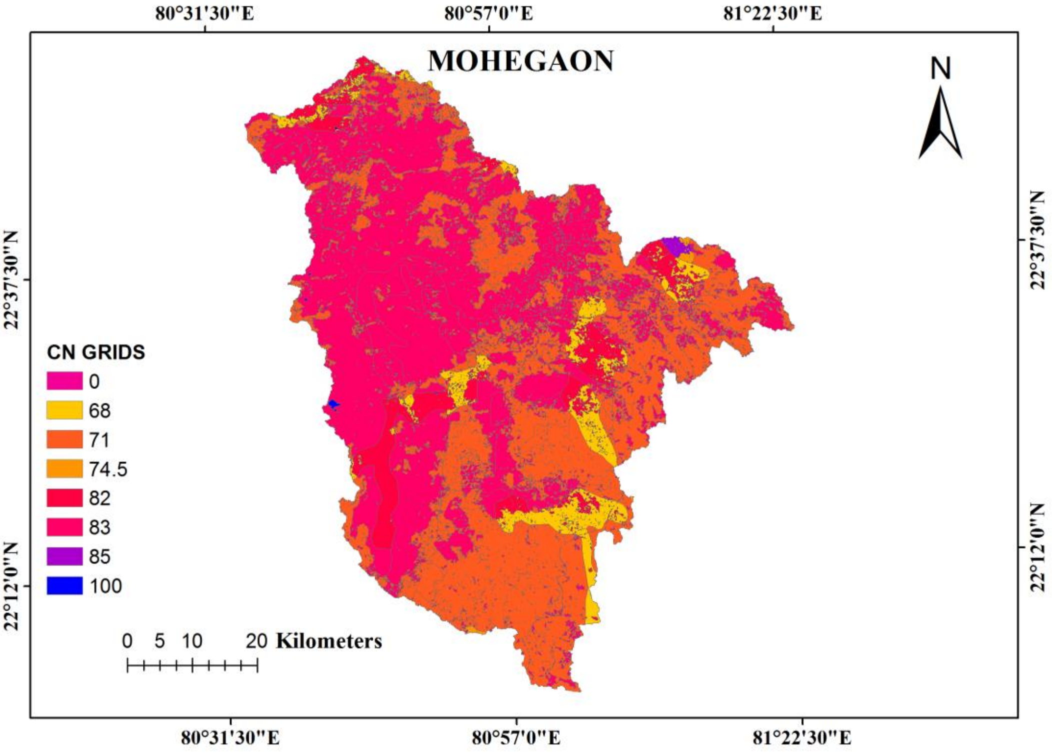

MANOT
80°31'30"E
80°57'0"E
81°22'30"E
81°48'0"E
23°5'30"N
22°45'0"N
22°24'30"N
N
CN
0
68
71
74.5
78
82
83
85
87
100
0 10 20 40 Kilometers


BAMNI BANJAR
80°6'0"E
80°31'30"E
80°57'0"E
22°12'0"N
21°46'30"N
N
CN
0
68
71
74.5
82
83
83.5
85
100
0 5 10 20 Kilometers


74°37'30"E
74°48'0"E
ANTHROLI
N
15°31'30"N
15°21'0"N
CN GRIDS
68
82
100
0 2.5 5 10 Kilometers


75°0'0"E
75°25'30"E
75°51'0"E
KOGAON
N
21°46'30"N
CN GRIDS
68
71
74.5
78
79
82
83
85
87
100
0 5 10 20 Kilometers


74°33'30"E
74°39'0"E
BARCHI
N
15°22'30"N
15°20'0"N
CNGRIDS
68
82
0 1 2 4 Kilometers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80°57'0"E
81°22'30"E
MOHEGAON
N
22°37'30"N
22°12'0"N
CN GRIDS
0
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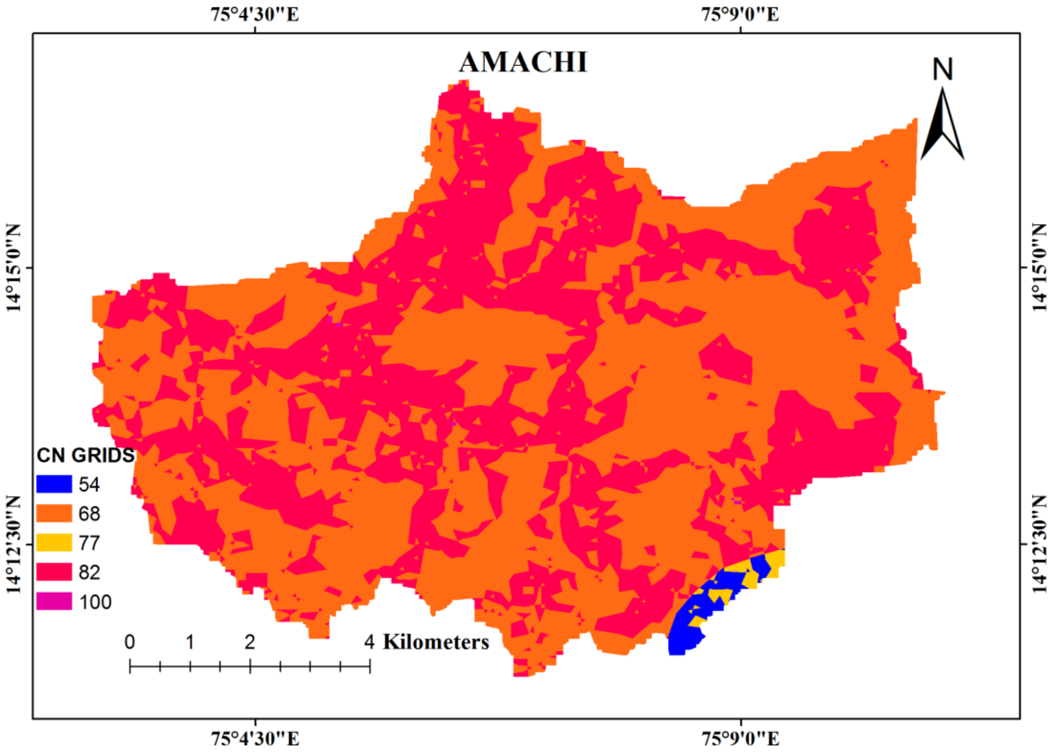
71
74.5
82
83
85
100
0 5 10 20 Kilometers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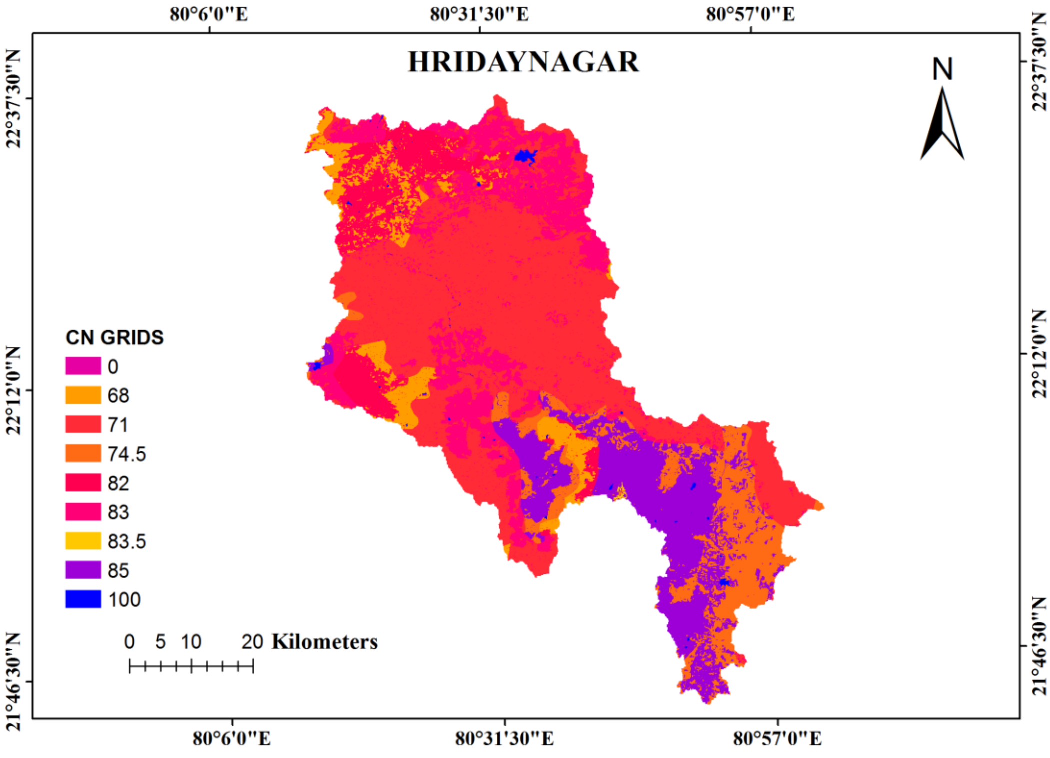
14°15'0"N
14°12'30"N
N
CN GRIDS
54
68
77
82
100
0 1 2 4 Kilometers


HRIDAYNAGAR
80°6'0"E
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80°57'0"E
22°37'30"N
22°12'0"N
21°46'30"N
N
CN GRIDS
0
68
71
74.5
82
83
83.5
85
100
0 5 10 20 Kilometers

PUBLICATION

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