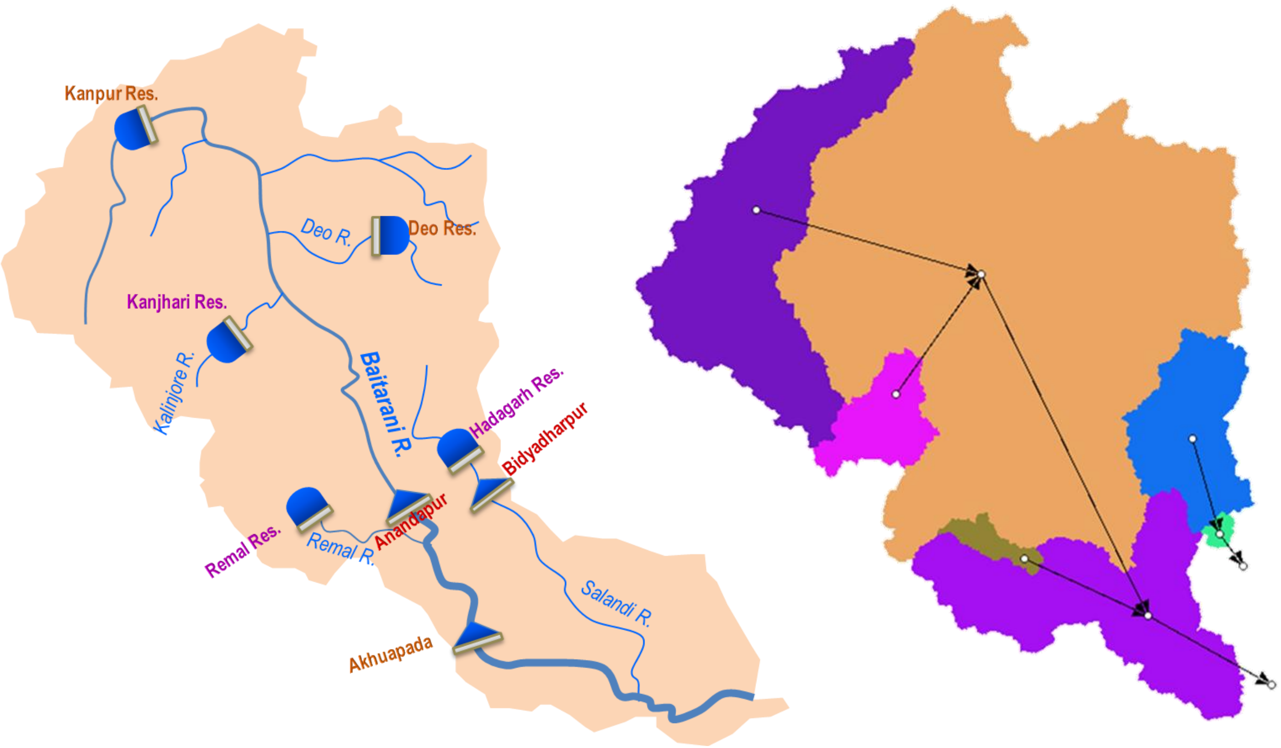
Hydrological Modelling of Brahmani Baitarani River Basin using eWater Source Platform



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NATIONAL INSTITUTE OF HYDROLOGY

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Hydrological Modelling of Brahmani Baitarani River Basin using eWater Source Platform

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1 INTRODUCTION

Water is a key driver of economic and social development of society while it also has a basic function in maintaining the integrity of the natural environment. However water is only one of a number of vital natural resources and it is imperative that water issues are not considered in isolation. Water managers, whether in the State or Central government, have to make difficult decisions on water allocation. More and more they have to apportion diminishing supplies between ever-increasing demands. Drivers such as demographic and climatic changes further increase the stress on water resources. The traditional fragmented approach is no longer viable and a more holistic approach to water management is essential.

This is the rationale for the Integrated Water Resources Management (IWRM) approach that has now been accepted internationally as the way forward for efficient, equitable and sustainable development and management of the world's limited water resources and for coping with conflicting demands. The integrated approach co-ordinates water resources management across sectors and interest groups, and at different scales, from local to international. It emphasises involvement in national policy and law making processes, establishing good governance and creating effective institutional and regulatory arrangements as routes to more equitable and sustainable decisions. A range of tools, such as social and environmental assessments, economic instruments, and information and monitoring systems, support this process

There are great differences in water availability from region to region as well as there are variability of supply through time as a result both of seasonal variation and inter-annual variation. All too often the magnitude of variability and the timing and duration of periods of high and low supply are not predictable; this equates to unreliability of the resource which poses great challenges to water managers in particular and to societies as a whole. Most developed countries have, in large measure, artificially overcome natural variability by supply-side infrastructure to assure reliable supply and reduce risks, albeit at high cost and often with negative impacts on the environment and sometimes on human health and livelihoods. Many less developed countries, and some developed countries, are now finding that supply-side solutions alone are not adequate to address the ever increasing demands from demographic, economic and climatic pressures; waste-water treatment, water recycling and demand management measures are being introduced to counter the challenges of inadequate supply.

The Murray-Darling Basin in Australia was subjected to widespread environmental degradation. In response to this problem, the Murray-Darling Basin Commission was established in January 1988 under the Murray-Darling Basin Agreement, focusing on protecting and improving water quality. The key lesson is that the participatory approach used with its Community Advisory Committee has helped the Commission to be successful in winning and maintaining community interest, involvement and support. to sustain the water resources of the basin and its natural environment very large-scale interstate IWRM organisation for transboundary water resources management using negotiation and legislative tools was adopted. It is a strong example of salinity management, water caps (reduction of further extractions), water quality management strategies (including point source and diffuse source pollutants) in a sub-humid environment. Further, the cross-border approach has been replicated elsewhere in Australia with the establishment of the Lake Eyre Basin Agreement. The skills and approaches being developed in the Murray-Darling have been used to assist the Mekong River Commission, Vietnam, through exchange of experience and high-level staff interaction.

In the India-Australia Water Science and Technology Partnership programme, Australia is collaborating with the Ministry of Water Resources to pilot the source river basin modelling platform in India. The MoWR, GOI is planning to develop an Integrated Water Resources Management (IWRM) plan for Brahmani Baitarani basin using the eWater source river basin modelling platform. The eWater source is Australia's first national river basin scale water modelling system. The source modelling platform has been developed to take a holistic approach to water management including human and ecological impacts. This includes integrating policy, addressing water savings and sharing for a whole river and connected groundwater systems including cities, agricultural and environmental demands.

Hence, the present study has been formulated to develop a rainfall runoff model for Brahmani Baitarani river basin in source platform and test its applicability by generating hydrological time series. The specific objectives of the study area:

a) Statistical and trend analysis of rainfall and river discharge in Brahmani Baitarani river basin.
b) Development of rainfall runoff model for Brahmani Baitarani river basin using eWater source platform.
c) Investigation of implications of different rainfall inputs on rainfall–runoff simulation.
d) Test the applicability of the eWater source modelling platform in Brahmani Baitarani river basin by generating hydrological time series.

2 LITERATURE REVIEW

2.1 Trend analysis

The detection of trends in hydrologic data, in particular rainfall and streamflow, is essential for the assessment of the impacts of climate variability and change on water resources of a region (Marius et al. 2012). Detection trend in long time series of hydrological data is of paramount scientific and practical significance. Water resources system have been designed and operate based on the assumption of stationary hydrology. If this assumption is incorrect then the existing procedures for designing levees, dam, reservoirs and other structure will have to be revised. Without revision, there is a danger that system are over or under design and either do not serve their purpose adequately or are over costly. Changes in streamflow data generally occur gradually (a trend) or abruptly (a step change). The change may affect any aspect of the data including the mean, median or variance (Kundzewicz et al. 2004). A number of different statistics are available to describe the characteristics and to test for any change in the flow regime for each streamflow gauging station. Many techniques are available to analyse trends in hydrologic data. Statistically, the aim is to identify a trend as the increase or decrease of streamflow over time. Many studies has been done by researchers all around the world to detect the trend and it consequences which is practically important in forecasting future planning for water resources and flood protection system. Ercan & Serdar (2003) had computed the 31 years period of monthly streamflow over Turkey to detect the identification of significant trends in the western and south eastern part of the country. Time series of flow data was analyze using four non-parametric trend statistical analysis method. They conclude that trends of streamflow patterns have occurred as a consequences of climate change.

Kundzewicz et al. (2005) had done an analysis of worldwide data set of daily mean flow records by using Mann Kendall test, a non parametric distribution-free method. The study found that most of the basin show statistically significant changes in streamflow. As the conclusion, the relation between climate change and flooding generally cannot be proof. The decreasing or increasing of streamflow trend might be influence by the local event such as very highly intensity local storm, reservoir activity and flood control structure.

Birsan et al. (2011) had done a research on Romanian catchment to detect the trend of the streamflow in a period of 30 years using non parametric trend test. They found that there are a significant changes in trend of streamflow due to climatic variables in Romania.

Abghari et al. (2012) has conducted a study in west of Iran to observe the impact of precipitation to the streamflow trend. Five non parametric trend tests were applied for the trend analysis. At the end of the study, they conclude that stream flow and precipitation have a significant positive correlation for most of the month during the past 40 years.

Nune et al. (2012) applied TREND software in order to detect trend in time series data of annual streamflow and rainfall for their study of Himayat Sagar catchment, India. Using the software, non parametric trend analysis test has been use to analyze the data. As a result, they found that the trends observed in the streamflow are not correlated to the changes in precipitation but mostly due to the variation of land use and water management.

2.2 Rainfall runoff modelling

Reliable estimates of stream flow generated from catchments are required as part of the information sets that help policy makers make informed decisions on water planning and management. Development of mathematical models relating the precipitation incident upon a catchment to the streamflow discharge of the catchment has been a major focus of surface water hydrology for decades. Numerous methods and models have been developed by different researchers to simulate the rainfall runoff process. Based on the problem statement and on the complexities involved, these models are categorized as empirical, black-box, conceptual or physically-based distributed models. Despite the fact that the physics governing the path of a drop of water through a catchment to the stream involves complex relationships, evidence indicates that the information content in a rainfall-runoff record is sufficient to support models of only very limited complexity. Moreover, though a variety of rainfall runoff models are available, selection of a suitable rainfall runoff model depends of various factors like data availability, size of the catchment, type of study etc.

Sherman (1932) first proposed the unit hydrograph (UH) concept. The UH of a watershed is defined as the direct runoff hydrograph resulting from a unit volume of excess rainfall of constant intensity and uniformly distributed over the drainage area. The UH approach is applied for several engineering designs and environmental studies (Roy and Banerjee, 2010; Reshma et al 2010, Bhunya et al., 2011). Detailed descriptions of UH types and formulas can be found in several literatures (Chow et al 1988; Davie, 2008). Ogunlela and Kasali (2002) applied four methods of unit hydrographs generation to develop unit hydrograph for an ungaged watershed. The outcome of the study revealed that both Snyder and SCS methods were not significantly different from each other. Salami (2009) evaluated three methods (Snyder, SCS and Gray methods) of storm hydrograph development for the catchment of lower Niger River basin at downstream of Jebba Dam. The statistical analysis, conducted at the 5% level of significance indicate significant differences in the methods except for Snyder and SCS methods which have relatively close values.

Rainfall runoff models can be represented by a range of approaches, in order of increasing complexity as:

a) simple empirical methods (e.g., curve number and regression equations);
b) large scale energy-water balance equations (e.g., Budyko curve);
c) conceptual rainfall-runoff models (e.g. SIMHYD, Sacramento, AWBM)
d) landscape daily hydrological models (e.g., VIC, WaterDyn);
e) fully distributed physically based hydrological models which explicitly model hillslope and catchment processes (e.g., SHE, TOPOG).

These categories have been used for ease of description, and there is overlap between these model types. Although these approaches vary in terms of the complexity with which they represent the rainfall-runoff transformation processes, all of them conceptualise the real processes using some sets of mathematical equations (and hence are all conceptual models of the physical environment). Similarly, conceptual rainfall-runoff models run in distributed mode can be classed as being landscape daily hydrological models. The rainfall-runoff models presently available in source are: Sacramento (sixteen parameters), SIMHYD (7 parameter), SMARG, GR4J (modèle du Génie Rural à 4 paramètres Journalier) (four parameters), IHACRES (six parameters), AWBM (3 parameter), SURM. These models will be configured to run the rainfall-runoff models at the catchment scale.

2.3 Model Performance Testing

There are many performance measures used to consider the acceptability of a rainfall-runoff model. In all cases visual assessment and statistical results of some sort will be assessed to identify the ability of the model to reproduce the flows it is calibrated or validated against. All may contribute to best practice and which measures are more appropriate will be directed by the modelling objective. A number of commonly used visual assessment techniques are outlined in Table 2.1. Statistical performance measures and their relevance in various study types are listed in Table 2.2.

Table 2.1: Plots for assessing model performance

Plot	Assessment and Purpose
Daily and monthly plots (linear and log)	Used to check the general size, shape and timing of hydrographs. Linear plots will better show medium and high flows and log plots low flows. Baseflow and recession characteristics can be reviewed. If recessions are frequently too flat then this can indicate that the interflow and baseflow are not represented correctly.
Scatter Plot	Scatter plots show the ability of the model to match flows on actual time steps. They show the flow ranges where the model is more accurate. Linear and log plots will show the variability across the various flow ranges. Often a line of best fit is shown to indicate the bias of the model in estimating flows.
Ranked Plots	Commonly referred to as frequency of excedence or flow duration graphs, they show the percentage of time a flow is exceeded over the modelled period. They show whether the modelled output can replicate the observed flow regime. Flow duration curves are effective diagnostics to ensure that both the variability and the seasonal pattern are captured.
Cumulative mass or cumulative residual mass curves	Scatter plots and flow duration curves do not examine the time sequence of events. A model could appear to be replicating the flow regime however the replication of regimes during wet and dry periods may not be adequate. A cumulative residual mass curve is a cumulative plot of residuals (flow value - mean of all values). A residual, and therefore slope of the curve, will be positive during wet periods as flows are higher than average and during dry periods the slope will be negative. If the curves diverge there may be a data issue. If they diverge consistently in all wet or all dry periods it is likely that model

	parameterisation for wet periods or dry periods may not be appropriate.
Plotting average daily or monthly flows (average of all Days, average of all Januaries)	A simple diagnostic to ensuring that the model can replicate seasonality characteristics.

Table 2.2: Statistical performance measures (metrics) and their relevance in various study types (Y – Yes, N – No)

Metric	**Purpose**					
	Runoff Yield	**Climate change**	**Landuse change**	**Low flow**	**Water quality**	**Peak flow / floods**
Difference in total runoff	Y	Y	Y	N	N	Y
Difference in total runoff over different seasons of the year*	Y	Y	Y	Y	Y	Y
Difference in total runoff contained within high, medium and low parts of the flow duration curve	Y	Y	Y	Y	Y	Y (high flows)
Difference in proportion of time that cease to flow occurs	N	Y	Y	Y	Y	N
Difference in the slope of logarithm of flow versus time for baseflow recession periods	N	N	Y	Y	Y	N
Mean square error between observed and modelled runoff	Y	Y	Y	N	N	Y
Coefficient of determination (often referred to as r^2)	Y	Y	Y	N	N	Y
Nash Sutcliffe coefficient of efficiency on daily flows	Y	Y	Y	N	N	Y
Nash Sutcliffe coefficient of efficiency on monthly accumulated flows	Y	Y	Y	N	N	N
Nash Sutcliffe coefficient of						

efficiency calculated using logarithm transformed flows	N	Y	Y	Y	Y	N

2.4 Calibration and validation

Model calibration is a process of optimising or systematically adjusting model parameter values to get a set of parameters which provides the best estimate of the observed streamflow. Virtually all rainfall runoff models must be calibrated to produce reliable estimates of streamflow because there has been little evidence identified of strong links between physical characteristics of catchments and the parameters of rainfall runoff models (Beven, 1989). Models should always be calibrated to observed data to demonstrate that the model can produce observed flow time series with an acceptable level of accuracy. The acceptable level of accuracy will depend upon the statistics of the flow data to be reproduced, which is determined by the purpose that the model will be applied for.

A model may be available that has been previously calibrated for a catchment as part of another study. In this situation, the calibration performance of the model should be re-tested before it is applied because the purpose for developing the model may be different between the earlier and later applications, which may influence the calibration objectives. When calibrating a model it should always be kept in mind that there are always going to be tradeoffs, for example between getting wet, dry, and average conditions correct, and those tradeoffs will be driven by the purposes the model will be used for.

Model validation is a process of using the calibrated model parameters to simulate runoff over an independent period outside the calibration period (if enough data is available) to determine the suitability of the calibrated model for predicting runoff over any period outside the calibration period. If there is not enough data available, the validation may be performed by testing shorter periods within the full record. Model validation is one of the most important steps in rainfall-runoff modelling as the performance of the calibrated model in the validation period provides us confidence in the modelling results when the calibrated model is used for simulating streamflow outside the measured streamflow period or when the model is used for predicting streamflow under future climate change scenarios.

Validation has often been achieved using a “split sample” process, whereby a period of observed data (say the first two-thirds of the available record) are used for calibration and the remaining one-third are used for validation. The model that was calibrated using the calibration data set is run for the validation period without changing the model parameters and the goodness of fit statistics are computed for the validation period. The split sample approach assumes that both the catchment and the climatic conditions that it is subject to are stationary in nature across the entire period that recorded data is available for. Evidence of stationarity (or non-stationarity) in catchment conditions that would affect the hydrological response during the period of recorded data should be checked using independent data sources (such as aerial photography, satellite imagery, land use, topographic or other spatial information).

Transposition of model parameter values from gauged to ungauged catchments may be tested using a spatial variant on split sample validation. Under this approach, component models from a gauged catchment with the calibrated parameter values for that catchment can be applied to another gauged catchment to test the uncertainty and bias introduced from transposition. Uncertainty ranges can be established by testing contributions flow series produced by model outputs with parameter sets adopted from several different gauged catchments. Examples of the performance of these transposition approaches are discussed in Viney *et al.* (2009) and Chiew (2010).

Generally the same metrics used to assess the performance of the model during calibration are also used to assess model performance during validation. The model performance during validation is almost always poorer than during calibration because model parameters are deliberately not specifically fitted to the data for the validation period.

3 STUDY AREA AND DATA

3.1 Study area

The Brahmani Baitarni basin (Figure 3.1) extends over states of Odisha, Jharkhand and Chhattisgarh with catchment area of about 51,822 km^2. The basin is bounded by the Chhotanagpur Plateau on the north, by the ridge separating it from Mahanadi basin on the west and the south and by the Bay of Bengal on the east. The Brahmani known as South Koel in its upper reaches rises near Nagri village of Jharkhand at an elevation of about 600 m and has length of about 800 km. In its tail reach, the river is known as Maipura. The Baitarni rises near Dumuria village in the hill ranges of Kendujhar district of Odisha at an elevation of about 900 m and has a length of about 355 km. The river is known as Dhamra in its lower reaches. Brahmani and Baitarni form common delta area before falling into the Bay of Bengal. The lower reaches of the basin near the deltaic area are subject to floods. Moreover Mahanadi, Brahmani and Baitarani are interconnected near their delta, worst flood occur when there is simultaneous heavy rains in all the three catchments. Floods are also caused from cyclonic storms since the coastal areas of the basin are cyclone-prone. The industrial development potential of this basin is very high due to its rich mineral resources (iron ore, copper, bauxite etc.) and power potential (548 MW at 60% load factor). Rourkela is an important industrial centre located in this basin. There various other industries (Iron and steel, Thermal power plant, fertilizers etc) existing the basin and more than 50 small to large industries are planned to set up in the upper and middle reaches of the basin. Hence, in future there will be very high water demands from industrial sectors.

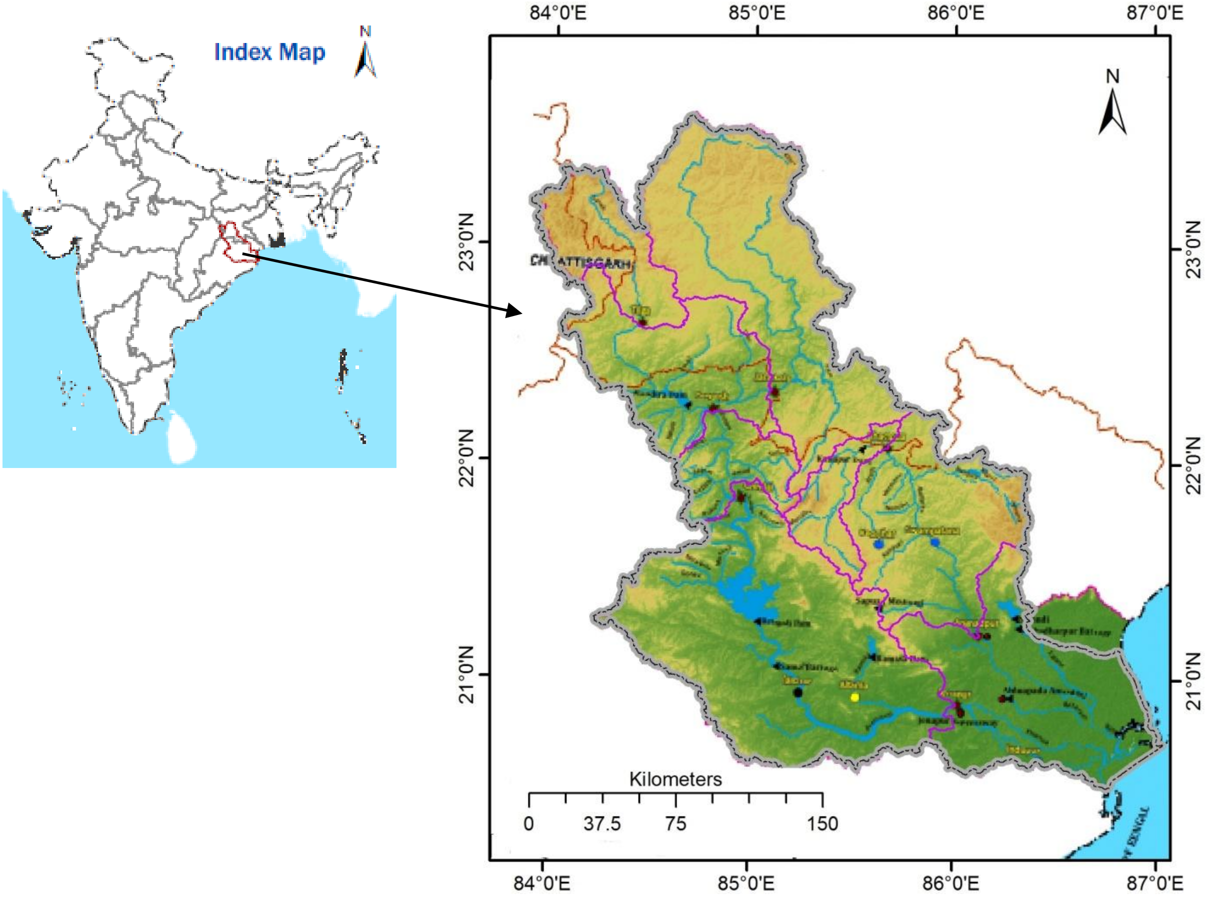


Figure 3.1: Location map of study area

3.2 Data Availability

3.2.1 Topography data

The Digital elevation map (Figure 3.2) is prepared from the SRTM data. The elevation of the basin varies from 1182 m to 0 m. The land use land cover and soil map are shown in Figure 3.3 and Figure 3.4 respectively.

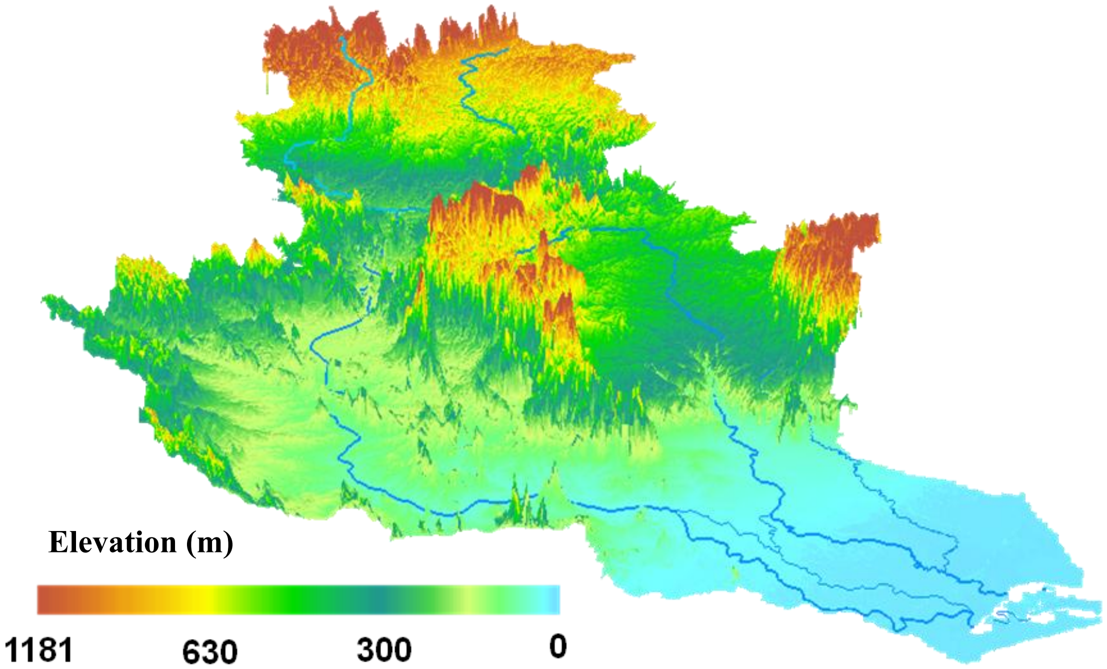
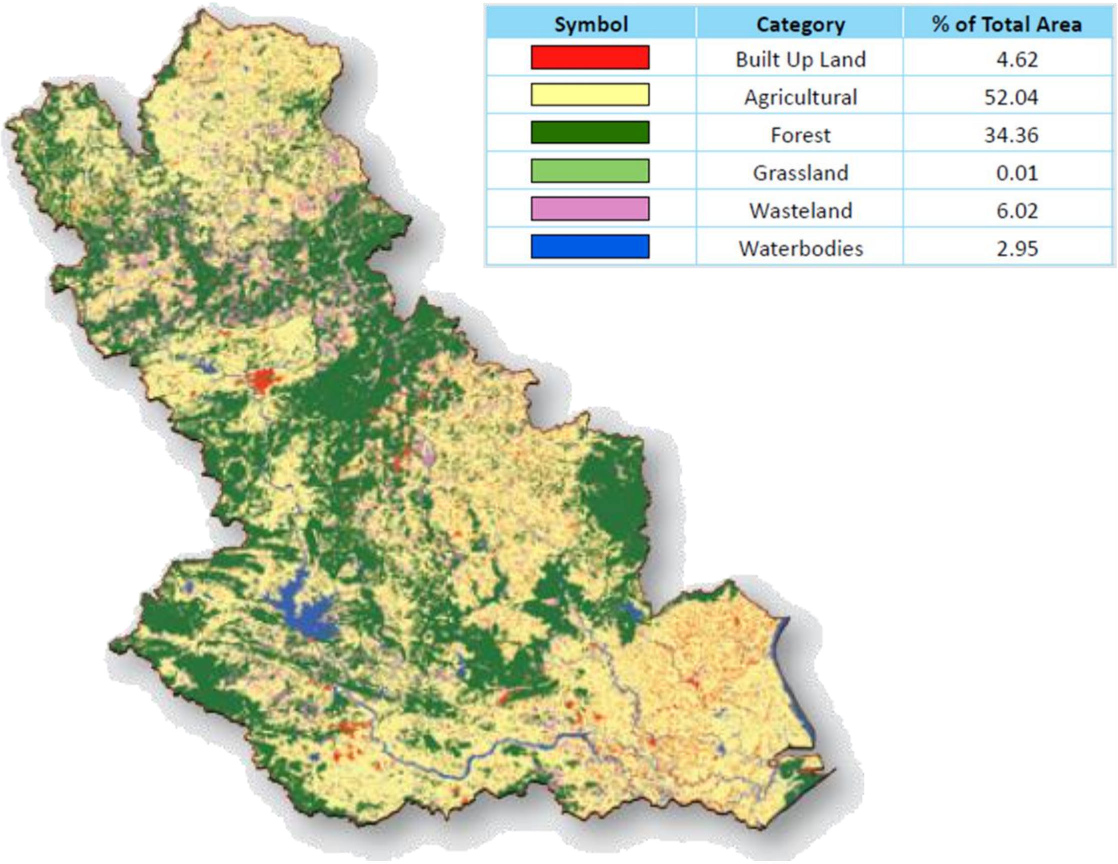


Figure 3.2: Digital Elevation Model



Symbol	Category	% of Total Area
🟥	Built Up Land	4.62
🟨	Agricultural	52.04
🟩	Forest	34.36
🟩	Grassland	0.01
🟪	Wasteland	6.02
🟦	Waterbodies	2.95

Figure 3.3: Land use land cover map

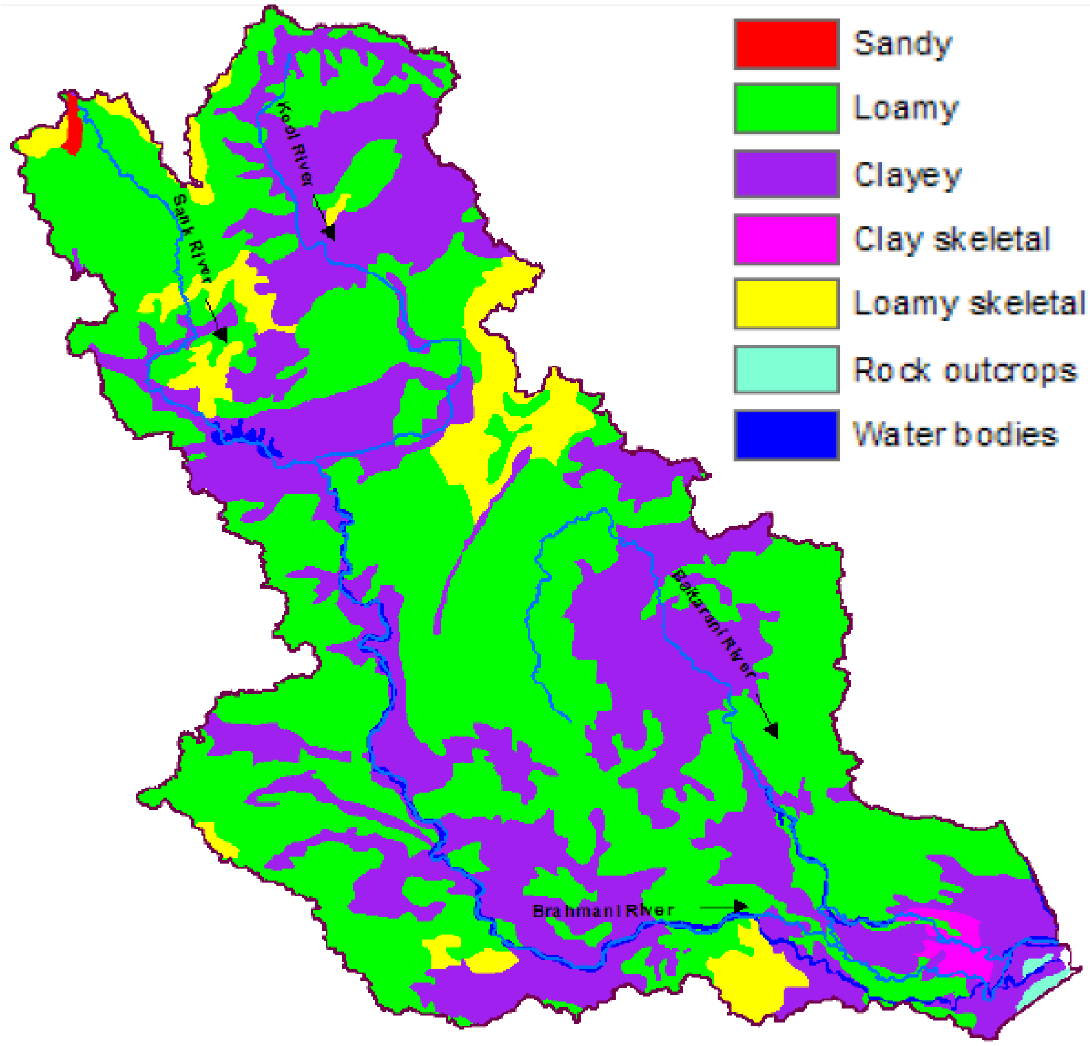


Figure 3.4: Soil map

3.2.2 Gauge discharge data

The daily data of discharge and water level at these locations were collected from CWC and state Govt. The details of gauge discharge (GD) data collected for the study are summarised in Table 3.1.

Figure 3.5: Location of gauging sites

Table 3.1 GD data availability

Site Name	River	Period
Tilga	Sankh	1979-12
Jaraikela	Koel	1972-12
Panposh	Brahmani	1996-12
Gomlai	Brahmani	1979-12
Talcher	Brahmani	1985-96
Altuma	Brahmani	1990-12
Jenapur	Brahmani	1979-12
Champua	Baitrani	1990-12
Anandpur	Baitrani	1979-12
Akhuapada	Baitrani	1973-12
Indupur	Brahmani	2003-12
Keonjhar	Baitrani	1994-12
Rengali	Brahmani	1977-12
Swampatna	Baitrani	1971-12
Talcher	Brahmani	*1995-12*

3.2.3 Rainfall data

The daily and monthly rainfall data were collected from IMD and State Govt. organisations. Figure 3.6 shows location of raingauge stations. Daily rainfall data from IMD are available for 19 stations. In addition to the point rainfall data the gridded data of 0.25 x 0.25 deg for 1901 to 2013 are also obtained from IMD.

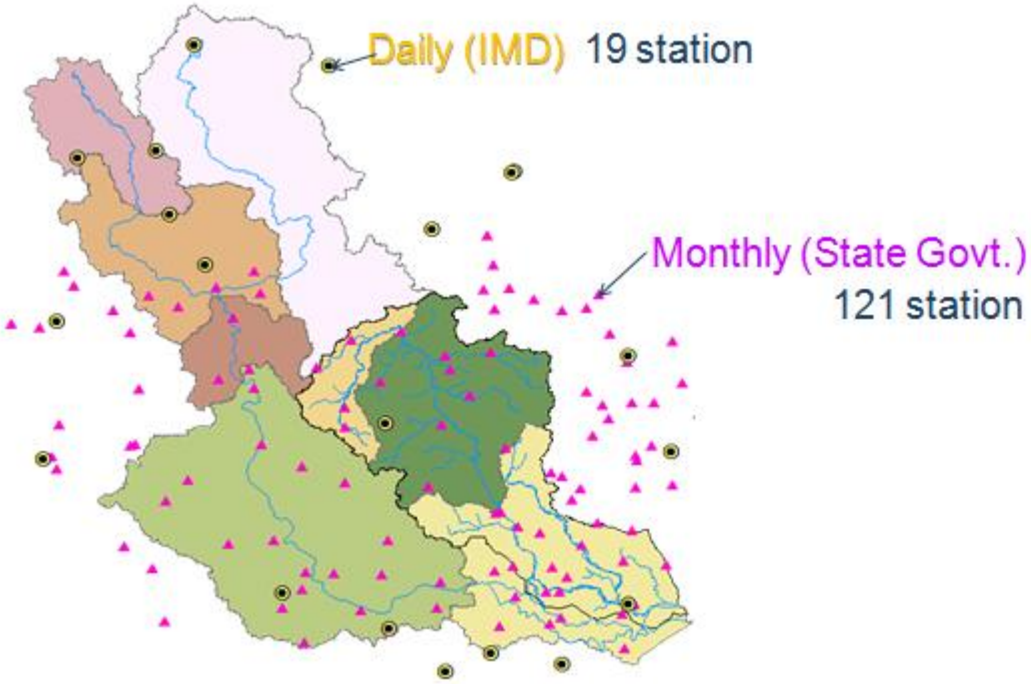


Figure 3.6: Location of raingauge stations

4 METHODOLOGY

4.1 Statistical Trend Analysis

Hydrologic variables usually vary in space as well as in time. The measurements collected in hydrology are in the form of a time series. Time series is a sequence of value arranged in order of their occurrence in time or space. They are represented by either continuous or discrete series. A series is called discrete if the observations are recorded at a distinct time instant or at different point in space. If the observations are recorded continuously in time or space, it was called continuous. Usually, in hydrology practices, a time series is discrete time. Time series analysis detects and describes quantitatively each of the generating process underlying a given sequence of observation. Time series analysis can be describe briefly as shown in Figure 4.1.

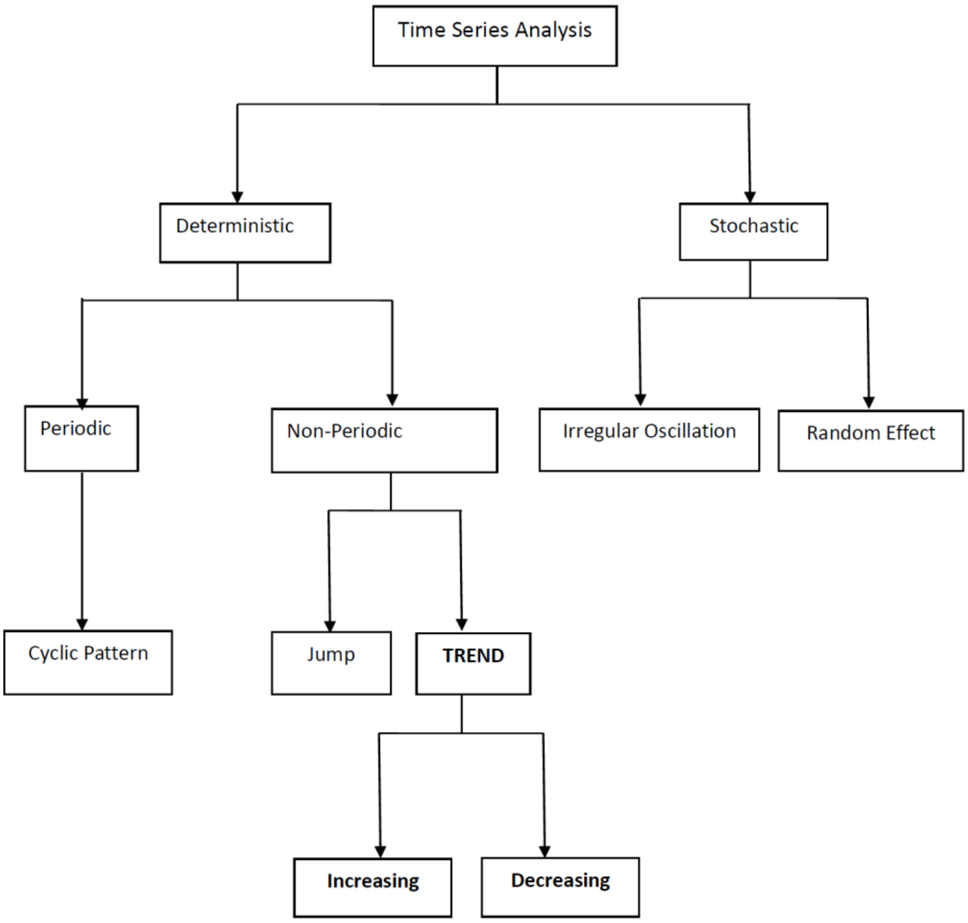


Figure 4.1: Time Series Analysis

The TREND software package of eWater is used to analyze the hydrologic data statistically to obtain the decreasing or increasing trend of rainfall and stream flow series. TREND sofware was developed by Cooperative Research Centre for Catchment Hydrology, Australia in year 2006. It was designed to facilitate statistical testing for trend, change and randomness in hydrological and other time series data. TREND has 12 statistical tests that can be used to test for trend, change and randomness in hydrological and other time series data. Statistical analysis included in TREND is:

1. Mann-Kendall (non-parametric test for trend)
2. Spearman's Rho (non-parametric test for trend)
3. Linear Regression (parametric test for trend)
4. Distribution-Free CUSUM (non-parametric test for step jump in mean)
5. Cumulative Deviation (parametric test for step jump in mean)
6. Worsley Likelihood Ratio (parametric test for step jump in mean)
7. Rank-Sum (non-parametric test for difference in median from two data periods)
8. Student's t (parametric test for difference in mean from two data periods)
9. Median Crossing (non-parametric test for randomness)
10. Turning Points (non-parametric test for randomness
11. Rank Difference (non-parametric test for randomness)
12. Autocorrelation (parametric test for randomness).

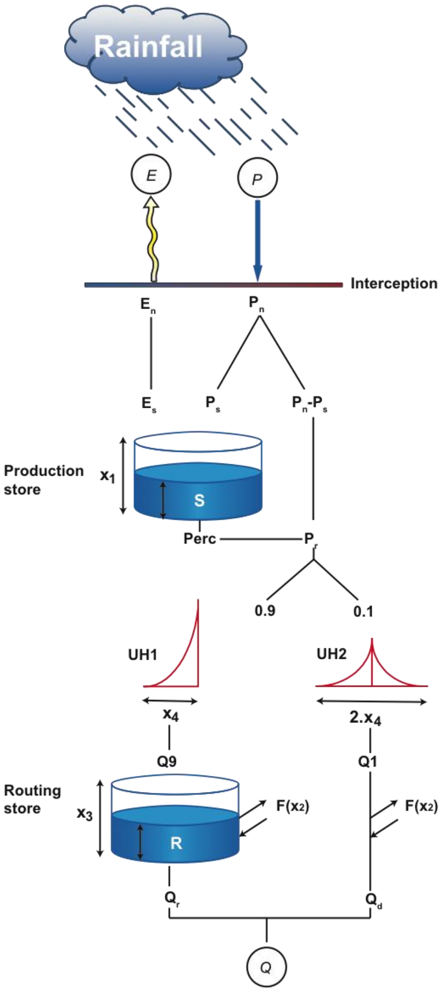
TREND allows easy statistical testing using different tests and it supports various time series data input formats. TREND also provides simple statement of test result and displays test statistic and critical values for various statistical significance levels. It can also perform resampling analysis to determine critical test statistic values and allows easy retrieval of test results. TREND performs the statistical tests only on annual time series data. The statistical tests in TREND are only valid if the time series data is not serially correlated. Most time-series data with time steps shorter than the annual time step are serially correlated.

4.2 Model Description

4.2.1 GR4J model

The GR4J model is a catchment water balance model that relates runoff to rainfall and evapotranspiration using daily data. The model contains two stores and has four parameters.

The development of the GR4J model was initiated by Claude Michel at the beginning of the 1980s at Cemagref, France. The first version of the model only had a single parameter. Further development of the GR4J model was undertaken using a modelling approach where large numbers of catchments were used to evaluate and improve the model. The 4-parameter version proposed by Perrin (2000) and detailed by Perrin (2002) and Perrin et al. (2003). Figure 4.2 shows a schematic diagram of the model.



Parameter	**Definition**
E	Potential areal evapotranspiration
E_n	Net evapotranspiration capacity
E_s	Actual evaporation rate
$F(x_2)$	Groundwater exchange term
P	Areal catchment rainfall
Perc	Percolation leakage
P_n	Net rainfall
P_r	Total quantity of water to reach routir functions
P_n-P_s	Amount of net rainfall that goes directly the routing functions
P_s	Amount of net rainfall that goes directly the production store
Q	Total stream flow
$Q1$	Output of UH2
$Q9$	Output of UH1
Q_d	Direct flow component
Q_r	Routed flow component
R	Water content in the routing store
S	Water content in the production store
UH1, UH2	Unit hydrographs
x_1	Capacity of the production soil (SMA) sto (mm)
x_2	Water exchange coefficient (mm)
x_3	Capacity of the routing store (mm)
x_4	Time parameter (days) for unit hydrographs

Figure 4.2 : Schematic diagram of GR4J model with description of parameters.

P is rainfall depth and E is potential evapotranspiration estimate that are inputs to the model. P is an estimate of the areal catchment rainfall, computed by any interpolation method from available rain gauges. E is generally based on long-term average monthly or daily values, which means the same potential evapotranspiration series could be repeated every year, although a recorded time series of E would be expected to give a better result. All water quantities (input, output, internal variables) are expressed in mm, by dividing water volumes by catchment area, when necessary.

Determination of net rainfall and PE

The first operation is the subtraction of *E* from *P* to determine either a net rainfall P_n or a net evapotranspiration capacity E_n. In GR4J, this operation is computed as if there were an interception storage of zero capacity. P_n and E_n are computed with the following equations:

$$if\ (P \geq E)\ then\ (P_n = P - E)\ and\ (E_n = 0) \tag{1}$$

Otherwise: $(P_n = 0)$ and $(E_n = E - P)$ (2)

Production store

This store can be considered as a soil moisture accounting (SMA) store. In case P_n is not zero, a part P_s of P_n fills the production store. It is determined as a function of the level *S* in the store by equation 3.

$$P_s = \frac{x_1 \bullet \left(1 - \left(\frac{S}{x_1}\right)^2\right) \bullet \tanh\left(\frac{P_n}{x_1}\right)}{1 + \frac{S}{x_1} \bullet \tanh\left(\frac{P_n}{x_1}\right)} \tag{3}$$

In the other case, when E_n is not zero, an actual evaporation rate is determined as a function of the level in the production store to calculate the quantity E_s of water that will evaporate from the store. It is obtained by:

$$Es = \frac{S.(2 - \frac{S}{x_1}).\tanh(\frac{En}{x_1})}{1 + (1 - \frac{S}{x_1}).\tanh(\frac{En}{x_1})} \tag{4}$$

The water content in the production store is then updated with:

$$S = S - E_s + P_s \tag{5}$$

Note that *S* can never exceed x_1. A representation of the rating curves obtained with Equation 3 and Equation 4 is shown in Figure 4.3.

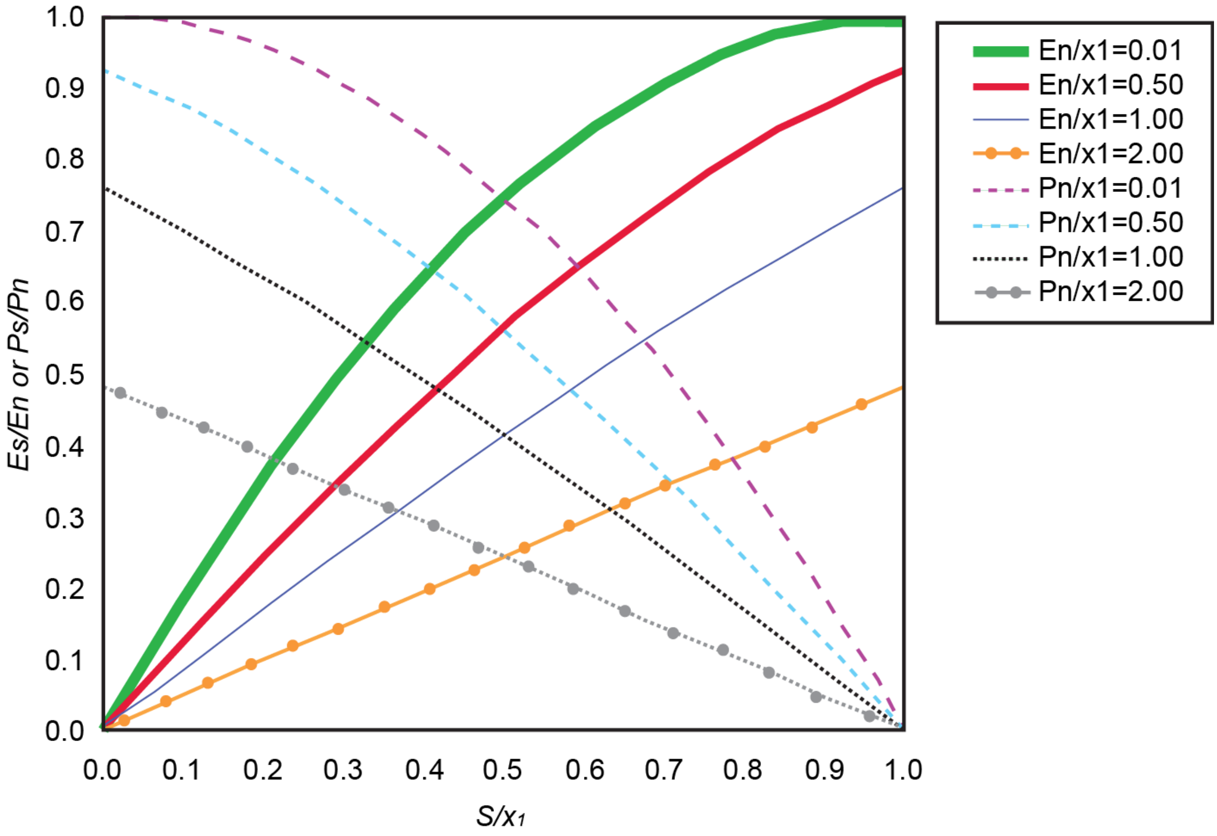


Figure 4.3: Behaviour of the production functions (E_s/E_n: solid line; P_s/P_n: dashed line) as a function of storage rate S/x_1 for different values of E_n/x_1 or P_n/x_1

A percolation leakage Perc from the production store is then calculated as a power function of the reservoir content:

$$Perc = S\left\{1-\left[1+\left(\frac{4}{9}\frac{S}{x_1}\right)^4\right]^{-1/4}\right\} \tag{6}$$

Perc is always lower than *S*. The reservoir content becomes:

$$S = S - Perc \tag{7}$$

The percolation function in Equation 6 occurs as if it originated from a store with a maximum capacity of $9 \div 4 \cdot x_1$. Given the power law of the mathematical formulation, this means that the percolation does not contribute much to the stream flow and is interesting mainly for low flow simulation.

Linear routing with unit hygrographs

The total quantity P_r of water that reaches the routing functions is given by:

$$\mathrm{P_r} = Perc + (P_n - P_s) \tag{8}$$

P_r is divided into two flow components according to a fixed split: 90 % of P_r is routed by a unit hydrograph ***UH1*** and then a non linear routing store, and the remaining 10% of P_r is routed by a single unit hydrograph ***UH2***. With ***UH1*** and ***UH2***, one can simulate the time lag between the rainfall event and the resulting stream flow peak. Their ordinates are used in the model to spread effective rainfall over several successive time-steps. Both unit hydrographs depend on the same time parameter x_4 expressed in days. However, ***UH1*** has a time base of x_4 days whereas ***UH2*** has a time base of $2 \cdot x_4$ days. x_4 can take real values and is greater than 0.5 days.

In their discrete form, unit hydrographs ***UH1*** and ***UH2*** have n and m ordinates respectively, where n and m are the smallest integers exceeding x_4 and $2 \cdot x_4$respectively. This means that the water is staggered into n unit hydrograph inputs for ***UH1*** and m inputs for ***UH2***. The ordinates of both unit hydrographs are derived from the corresponding S-curves (cumulative proportion of the input with time) denoted by ***SH1*** and ***SH2*** respectively. ***SH1*** is defined along time t by:

$$For\ t \leq 0,\ SH1(t) = 0 \tag{9}$$

$$For\ 0 < t < x_4,\ SH1(t) = \left(\tfrac{t}{x_4}\right)^{\frac{5}{2}} \tag{10}$$

$$For\ t \geq x_4,\ SH1(t) = 1 \tag{11}$$

SH2 is similarly defined by:

$$For\ t \leq 0,\ SH2(t) = 0 \tag{12}$$

$$For\ 0 < t \leq x_4,\ SH2(t) = \frac{1}{2}\left(\frac{t}{x_4}\right)^{\frac{5}{2}} \tag{13}$$

$$For\ x_4 < t < 2 \cdot x_4, SH2(t) = 1 - \frac{1}{2}(2 - \frac{t}{x_4})^{\frac{5}{2}} \tag{14}$$

$$For\ t \geq 2 \bullet x_4,\ SH2(t) = 1 \tag{15}$$

UH1 and ***UH2*** ordinates are then calculated by:

$$UH1(j) = SH1(j) - SH1(j-1) \tag{16}$$

$$UH2(j) = SH2(j) - SH2(j-1) \tag{17}$$

where:

j is an integer. t each time-step, the outputs ***Q9*** and ***Q1*** of the two unit hydrographs correspond to the discrete convolution products and are given by:

$$Q9(k) = 0.9 \sum_{j=1}^{1} UH1(j) \bullet Pr(k-j+1) \tag{18}$$

$$Q1(k) = 0.1 \sum_{j=1}^{m} UH2(j) \bullet Pr(k-j+1) \tag{19}$$

where:

$$\begin{aligned} l &= \text{int}(x_4) + 1; \\ m &= \text{int}(2 \bullet x_4) + 1 \end{aligned} \tag{20}$$

Inter catchment groundwater exchange

A groundwater exchange term F that acts on both flow components, is then calculated as:

$$F = x_2 \left(\frac{R}{x_3} \right)^{\frac{7}{2}} \tag{21}$$

Where **R** is the level in the routing store, **x_3** its "reference" capacity and **x_2** the water exchange coefficient. **x_2** can be either positive in case of water imports, negative for water exports or zero when there is no water exchange. The higher the level in the routing store, the larger the exchange. In absolute value, **F**cannot be greater than **x_2: x_2** represents the maximum quantity of water that can be added (or released) to (from) each model flow component when the routing store level equals **x_3**. Note that Le Moine (2008) proposed an improved formulation of this function, with an additional parameter.

Non linear routing store

The level in the routing store is updated by adding the output **$Q9$** of **$UH1$** and **F** as follows:

$$R = max(0; R + Q9 + F) \tag{22}$$

The outflow **Q_r** of the reservoir is then calculated as:

$$Qr = R.\left\{1 - \left[1 + \left(\frac{R}{x_3}\right)^4\right]^{-\frac{1}{4}}\right\} \tag{23}$$

Q_r is always lower than **R**, as shown in Figure 4. The formulation of the output of the store is the same as the percolation from the SMA store. The level in the reservoir becomes:

$$R = R - Q_r \tag{24}$$

Note that, although the reservoir can receive a water input greater than the saturation deficit **x_3-R** at the beginning of a time-step, the level in the reservoir can never exceed the capacity **x_3** at the end of a time-step. Therefore, the capacity **x_3** could be called the "one day ahead maximum capacity". This routing store is able to simulate long stream flow recessions, when necessary.

If $0.5 \leq x_4 \leq 1$, **$UH1$** has a single ordinate equal to one and **$UH2$** has only two ordinates.

Total stream flow

Like the content of the routing store, the output **$Q1$** of **$UH2$** is subject to the same water exchange **F** to give the flow component **Q_d** as follows:

$$Qd = \max(0; Q1 + F) \tag{25}$$

Total stream flow ***Q*** is finally obtained by:

$$Q = Qr + Qd \tag{26}$$

The Source implementation of GR4J includes a baseflow filter than can be used to estimate a baseflow amount from the overall runoff flux, ***Q***. GR4J uses the same baseflow filter as is used in the observed catchment runoff depth model

4.2.1.1 Parameters or settings

Information on parameters is provided in Table 4.1. All four parameters are real numbers. x_1 and x_3 are positive, x_4 is greater than 0.5 and x_2 can be either positive zero or negative.

Table 4.1: Parameters in GR4J and their default values

Parameter	Description	Units	Default	Range
x_1	Capacity of the production soil (SMA) store	mm	350	1-1500
x_2	Water exchange coefficient	mm	0	-10.0-5.0
x_3	Capacity of the routing store	mm	40	1-500
x_4	Time parameter for unit hydrographs	days	0.5	0.5-4.0
k	Filter parameter given by the recession constant (as in observed catchment runoff depth model) Note: not the same ***k*** as used in equations 18 and 19, above.	none	n.a.	0-1
C	Shape parameter (as in observed catchment runoff depth model)	none	n.a.	0-1

Note that some coefficients in the model equations above appear as fixed values, eg. a power 4 in Equation 6 and Equation 20, a fixed split 10% - 90% of effective rainfall, a 2.5 exponent in the computation of the unit hydrographs, a 2.25 coefficient related to the percolation function in Equation 6. These values were chosen as those yielding the best model results in many different test conditions. They were fixed because leaving them free did not significantly improve (or even degraded) the model results while adding unhelpful complexity to the model structure.

Most optimisation algorithms used to calibrate the model parameter values require knowledge of an initial parameter set. This initial set may consist of median values obtained on a large variety of catchments. Approximate 80 % confidence intervals for the four parameters are also provided in Table 4.2. They were derived from the 0.1 and 0.9 percentiles of the distributions of model parameter values obtained over a large sample of catchments. Given the small number of model parameters, simple optimisation algorithms are generally capable of identifying parameter values yielding satisfactory results. The choice of an objective function depends on the objectives of model user. Note that care should be taken to set appropriate initial conditions of the internal state variables in the model to avoid discrepancies at the beginning of the simulation periods. One year can be used for model warm-up at the beginning of each simulation.

Table 4.2: Values of median model parameters and approximate 80% confidence intervals

Parameter	Median Value	80% Confidence Interval
x_1	350	100-1200
x_2	0	-5 to 3
x_3	90	20-300
x_4	1.7	1.1-2.9

Leaving both the k and C parameters at 0 has the effect of disabling the baseflow filter, and all runoff are reported as quickflow.

4.2.2 Sacramento Model

The Sacramento Model is a continuous rainfall-runoff model used to generate daily stream flow from daily rainfall and potential evapotranspiration data. It uses soil moisture accounting to simulate the water balance within the catchment (i.e. functional unit). The conceptual layout of the model is shown in Figure 4.4. At each model time step the sequence of calculations is:

- Soil moisture depletion by evapotranspiration and soil moisture redistribution.
- Soil moisture replenishment by rainfall and percolation, and streamflow generation.

The internal Sacramento Model calculations represent water quantities using units of depth (in millimetres). The model outputs are converted to volumes by multiplying by the catchment area.

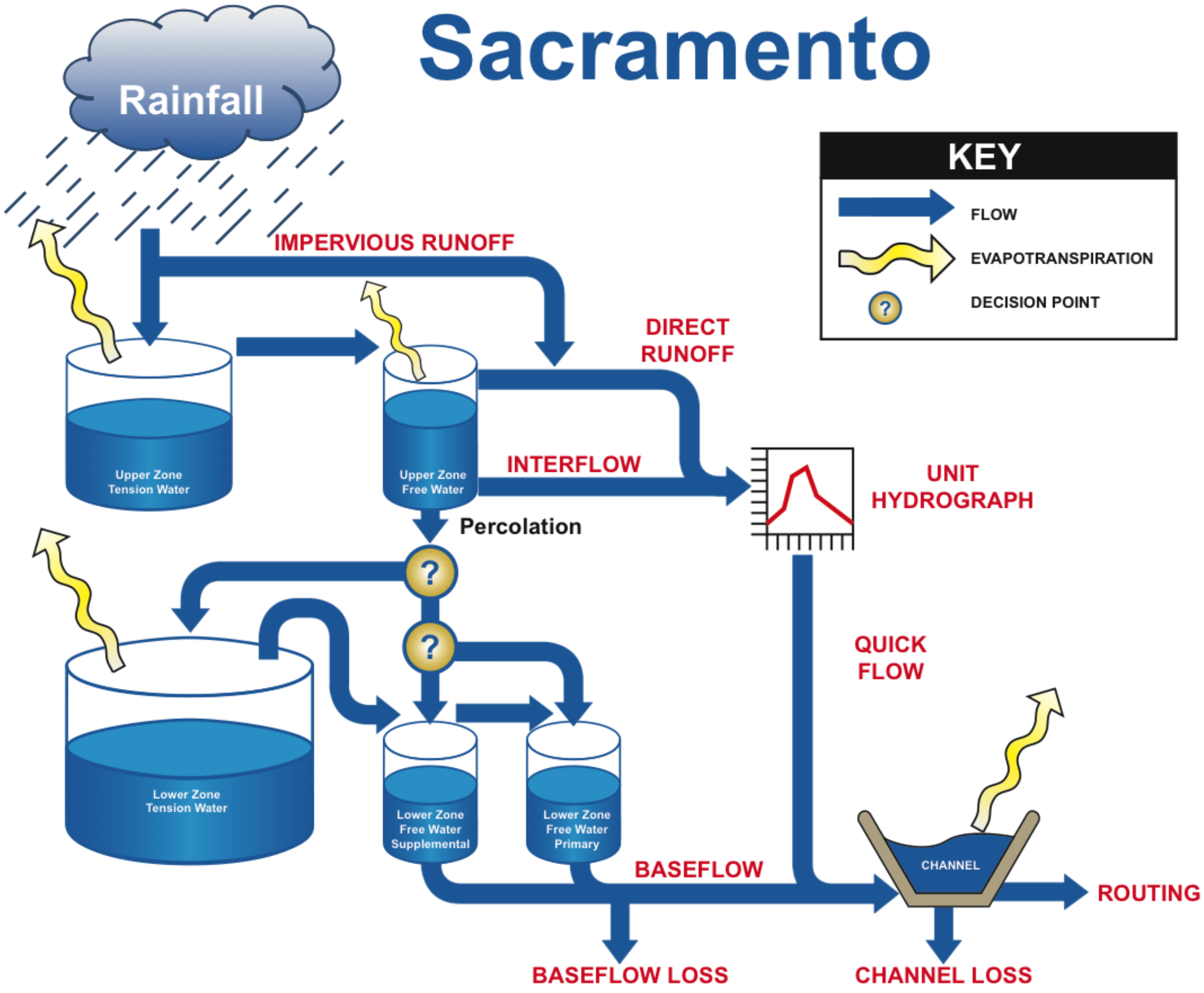


Figure 4.4: Sacramento Model

There are five stores in the Sacramento Model:

a) Upper zone tension water (***UZTW***);
b) Upper zone free water (***UZFW***);
c) Lower zone tension water (***LZTW***);
d) Lower zone primary free water (***LZFWP***); and
e) Lower zone supplementary free water (***LZFWS***).

The tension water stores represent the volume of water that is held in the soil matrix by surface tension. Water can only be removed from the tension water stores by evapotranspiration. In the case of the free water stores, water can move through the soil vertically and laterally to other stores, and be discharged as interflow (upper zone) or baseflow (lower zone).

The Sacramento Model divides the catchment into impervious and pervious areas. The impervious area is the portion of the catchment that is covered by lakes, rivers, pavement and other impervious surfaces that are directly connected to the stream network. The impervious area produces runoff from any rainfall while the pervious area only produces runoff when rainfall is sufficiently heavy. The Sacramento model also allows the user to specify a variable impervious area, which is a portion of the catchment that can become impervious when the catchment is quite saturated.

Streamflow generated by the Sacramento Model is made up of four main forms:

1) impervious runoff from permanent impervious areas and direct runoff from variable impervious areas,
2) surface runoff, which occurs when Upper Zone Free Water storage is full and the precipitation intensity exceeds the rate of percolation and interflow
3) interflow resulting from the lateral drainage of the Upper Zone Free Water storage
4) baseflow, which is composed of primary and supplemental baseflow

Impervious runoff, direct runoff and surface runoff have no time delay in the Sacramento model, occurring in the same time interval as the rain that generated the runoff component. Interflow generally has a time delay in terms of days, supplemental baseflow a delay of weeks or months and primary baseflow a delay of months or years. The generation of surface runoff, interflow and baseflow depends on the amount of water in each soil moisture store relative to that store's capacity, and the rate at which water moves into and out of the stores.

4.2.2.1 Parameters or settings

The Sacramento model uses a total of sixteen parameters to simulate the water balance. Of these:

- five define the size of soil moisture stores (UZTWM, UZFWM, LZTWM, LZFSM, LZFPM);
- three calculate the rate of lateral outflows (LZPK, LZSK, UZK);
- three calculate the percolation of water from the upper to the lower soil moisture stores (PFREE, REXP, ZPERC);
- two calculate impervious runoff (PCTIM, ADIMP);
- three calculate losses in the system (SIDE, SSOUT, SARVA);
- five allow time delays to be applied to instantaneous runoff (UH1…UH5); and
- the final parameter, RSERV, has very low sensitivity and optimization of this term is generally not warranted (Burnash ***et al***, 1973).

Table 4.3: Parameters of Sacramento model

Parameter	**Description**	**Units**	**Default**	**Min**	**Max**
LZPK	The ratio of water in ***LZFPM***, which drains as base flow each day.	fraction	0.01	0.001	0.015
LZSK	The ratio of water in ***LZFSM*** which drains as base flow each day.	fraction	0.05	0.03	0.2
UZK	The fraction of water in ***UZFWM***, which drains as interflow each day.	fraction	0.3	0.2	0.5
UZTWM	Upper Zone Tension Water Maximum. The maximum volume of water held by the upper zone between field capacity and the wilting point which can be lost by direct evaporation and evapotranspiration from soil surface. This storage is filled before any water in the upper zone is transferred to other storages.	mm	50	25	125
UZFWM	Upper Zone Free Water Maximum, this storage is the source of water for interflow and the driving force for transferring water to deeper depths.	mm	40	10	75
LZTWM	Lower Zone Tension Water Maximum, the maximum capacity	mm	130	75	300

	of lower zone tension water. Water from this store can only be removed through evapotranspiration.				
LZFSM	Lower Zone Free Water Supplemental Maximum, the maximum volume from which supplemental base flow can be drawn.	mm	25	15	300
LZFPM	Lower Zone Free Water Primary Maximum, the maximum capacity from which primary base flow can be drawn.	mm	60	40	600
PFREE	The minimum proportion of percolation from the upper zone to the lower zone directly available for recharging the lower zone free water stores.	percent/100	0.06	0.0	0.5
REXP	An exponent determining the rate of change of the percolation rate with changing lower zone water storage.	none	1.0	0.0	3.0
ZPERC	The proportional increase in Pbase that defines the maximum percolation rate.	none	40	0.0	80
SIDE	The ratio of non-channel baseflow (deep recharge) to channel (visible) baseflow.	ratio	0.0	0.0	0.8
SSOUT	The volume of the flow which can be conveyed by porous material in the bed of stream.	mm	0.0	0.0	0.1
PCTIM	The permanently impervious fraction of the basin contiguous with stream channels, which contributes to direct runoff.	percent/100	0.01	0.0	0.05
ADIMP	The additional fraction of the catchment which develops impervious characteristics under soil saturation conditions.	percent/100	0.0	0.0	0.2
SARVA	A decimal fraction representing that portion of the basin normally covered by streams, lakes and vegetation that can deplete stream	percent/100	0.0	0.0	0.1

	flow by evapotranspiration.				
RSERV	Fraction of lower zone free water unavailable for transpiration	percent/100	0.3	0.0	0.4
UH1	The first component of the unit hydrograph, i.e. the proportion of instantaneous runoff not lagged	percent/100	1.0	0	1
UH2	The second component of the unit hydrograph, i.e. the proportion of instantaneous runoff runoff lagged by one time-step	percent/100	0.0	0	1
UH3	The third component of the unit hydrograph, i.e. the proportion of instantaneous runoff runoff lagged by two time-steps	percent/100	0.0	0	1
UH4	The fourth component of the unit hydrograph, i.e. the proportion of instantaneous runoff runoff lagged by three time-steps	percent/100	0.0	0	1
UH5	The fifth component of the unit hydrograph, i.e. the proportion of instantaneous runoff runoff lagged by four time-steps	percent/100	0.0	0	1

In Source, up to five unit hydrograph terms (***UH1...UH5***) can be set to lag the runoff over time. When using RRL v1.0.5 the unit hydrograph term is fixed at 1 for the first time increment, and 0 for the subsequent time increments, and therefore no unit hydrograph routing is applied in RRL. Equivalent behaviour would be achieved with the Sacramento Model in Source by setting ***UH1*** = 1 and ***UH2*** through ***UH5*** to 0. The Sacramento Model in Source is configured with a set of default values for each model parameter. There are also upper and lower bounds for each parameter.

As with any modelling, the accuracy and reliability of the results from the Sacramento Model are determined by how representative the model is of the catchment (particularly as the Sacramento Model is lumped) and also by the quality of the rainfall, evaporation and stream flow data used. The accuracy and reliability of the model can be assessed using the results of comparisons with observed data. As a rule, the calibrated parameter values of a specific catchment should not be transposed to other catchments, unless the reliability of this transposition can be assessed. The parameter set is unique to the climate, topography, size, geology, soil and vegetation type of the catchment on which it was calibrated. There is no proven methodology to adjust these parameters to other catchments, including subcatchments, of the calibrated catchment.

4.2.3 SIMHYD

SIMHYD is a conceptual rainfall-runoff model that estimates daily stream flow from daily rainfall and areal potential evapotranspiration data. The model contains three stores for interception loss, soil moisture and groundwater. The model has seven parameters. SIMHYD operates at a functional unit scale and daily time-step. Cooperative Research Centre for Catchment Hydrology. SIMHYD is a simplified version of the daily conceptual rainfall-runoff model, HYDROLOG, that was developed in 1972 (Porter 1972; Porter and McMahon 1975) and the more recent MODHYDROLOG (Chiew & McMahon 1991). The SIMHYD model has seven parameters as compared to the 17 parameters required for HYDROLOG and the 19 for MODHYDROLOG.

SIMHYD has been widely applied to a large number of Australian catchments by several hydrologists (Peel et al., 2000; Chiew et al., 2008). The extent of its use outside of Australia is unknown but the conceptual structure is not particularly limited to Australian catchments and with appropriate calibration and testing it is likely that it could be successfully applied in other countries.

The structure of the simple lumped conceptual daily rainfall-runoff model, SIMHYD, is shown in Figure 4.5. In SIMHYD, daily rainfall first fills the interception store, which is emptied each day by evaporation. The excess rainfall is then subjected to an infiltration function that determines the infiltration capacity. The excess rainfall that exceeds the infiltration capacity becomes infiltration excess runoff.

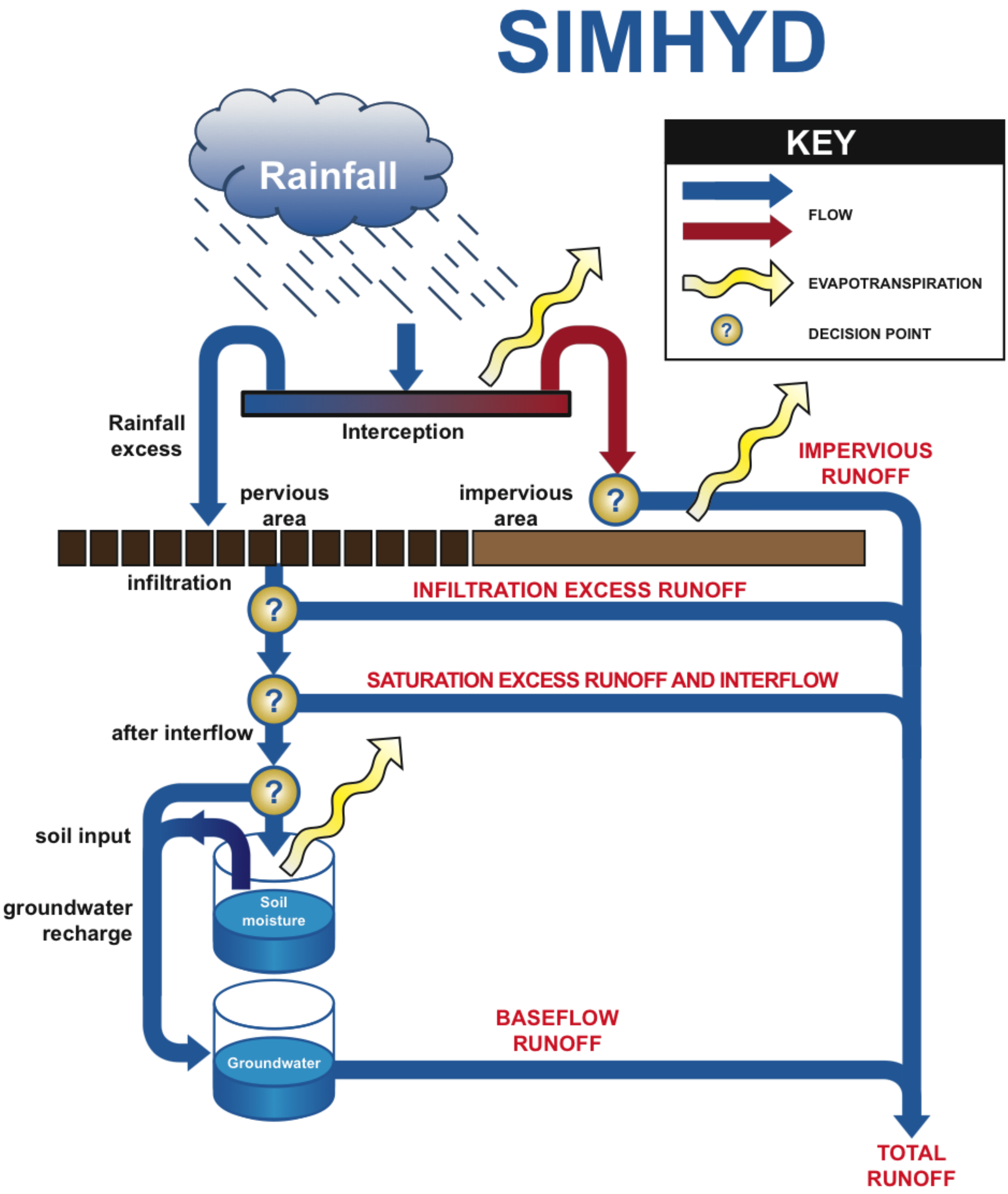


Figure 4.5: Structure of the SIMHYD rainfall-runoff model

Moisture that infiltrates is subjected to a soil moisture function that diverts the water to the stream (interflow), groundwater store (recharge) and soil moisture store. Interflow is first estimated as a linear function of the soil wetness (soil moisture level divided by soil moisture capacity). The equation used to simulate interflow therefore attempts to mimic both the interflow and saturation excess runoff processes (with the soil wetness used to reflect parts of the catchment that are saturated from which saturation excess runoff can occur). Groundwater recharge is then estimated, also as a linear function of the soil wetness. The remaining moisture flows into the soil moisture store. Evapotranspiration from the soil moisture store is estimated as a linear function of the soil wetness, but cannot exceed the atmospherically-controlled rate of areal potential evapotranspiration. The soil moisture store has a finite capacity and overflows into the groundwater store. Base flow from the groundwater store is simulated as a linear recession from the store. The model therefore estimates runoff generation from three sources - infiltration excess runoff, interflow (and saturation excess runoff) and base flow.

The model requires daily rainfall and potential evapotranspiration data. The rainfall and evaporation data sets need to be continuous (no gaps) and overlapping. Catchment area in km^2 is required to provide flow output volumes. Daily flow data in ML/day, m^3/s or mm/day may be required to calibrate the model.

4.2.3.1 Parameters or settings

Model parameters are summarised in Table 1.

Table 4.4: SIMHYD Model Parameters

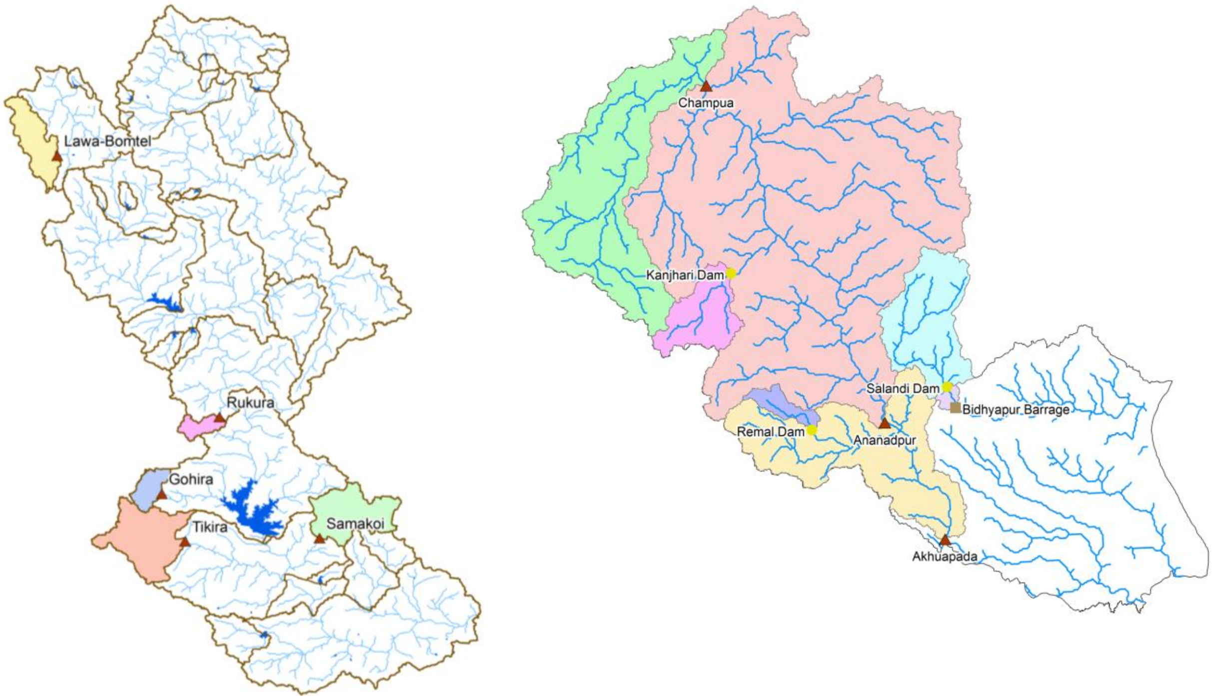
Parameter	Description	Units	Default	Min	Max
Baseflow coeff.	Base flow Coefficient		n.a.	0.0	1.0
Impervious Threshold	Impervious Threshold	mm	n.a.	0.0	5.0
Infiltration Coeff.	Infiltration Coefficient		n.a.	0.0	400
Infiltration shape	Infiltration Shape		n.a.	0.0	10.0
Interflow Coeff.	Interflow Coefficient		n.a.	0.0	1.0
Perv. Fraction	Pervious Fraction		n.a.	0.0	1.0
RISC	Rainfall Interception Store Capacity	mm	n.a.	0.0	5.0
Recharge	Recharge Coefficient		n.a.	0.0	1.0

Parameter	Description	Units	Default	Min	Max
coefficient					
SMSC	Soil Moisture Store Capacity	mm	n.a.	1.0	500

The relative sensitivity of parameters will vary between catchments but generally the model is most sensitive to the soil moisture store capacity, pervious fraction and base flow index.

4.3 Catchment Delineation

The DEM developed above is used to delineate the catchment and drainage network.. The DEM is filled to remove any local sink and then used to derive the flow direction and flow accumulation grids which are further used for defining and segmenting the streams and the catchment grid. Once drainage point is defined, the drainage network and catchment boundary is masked as a separate project. The drainage point is selected on the stream grid near to the point of interest. This catchment and drainage network as shown in Figure 4.6 is used henceforth for further computation.



(a) Brahmani river basin

(b) Baitarani River Basin

Figure 4.6: Catchment and drainage network derived from DEM

4.4 Description of optimizers

4.4.1 Uniform random search

This is a very simple optimization method where by the parameter space for each parameter is divided up into a specified number of intervals between the minimum and maximum bound. The optimization proceeds by randomly selecting from the available options for each parameter then running the model and assessing the objective function. This repeat for a specified number of times and the option with the best objective function value is taken as the optimum solution. This method is rarely used in practice but may be used as a reference to compare the performance of optimization methods for a given problem.

4.4.2 Pattern search

The pattern search is the simplest of all the search methods and has the advantage that it is quick but can suffer from finding local optimums rather than global optimums. This is particularly the case when models are strongly non-linear. The problems of reaching local optimums can be overcome by using a multi-start on the search.

4.4.3 Multi start pattern search

The initial sampling of the parameter space provides the potential for locating the global optimum without being biased by pre-specified starting points. This method works by dividing the parameter values into a specified number of increments between the specified bounds. For each of these possible starting points a pattern search is carried out. The best optimum of the pattern searches is taken as the global optimum.

4.4.4 Rosenbrock method

The Rosenbrock method is a local search method having some similarities with the Pattern Search method described as above. It was originally designed in order to optimize an industrial process in chemical engineering, and to handle response curves with peculiar features such as functions with narrow curved valleys (e.g. Rosenbrock’s banana function detailed in this section). A stage is the search in the parameter space following successive directions along an orthonormalised set of vectors (base) of the same dimension as the parameter space. To illustratethe idea behind the algorithm, we will step through the first few iterations of a Rosenbrock search on the aforementioned “banana function”, rather than a set of equations. This two-parameter function is defined as:

$$z = (1 - x)2 + 100(y - x2)2 \quad (1)$$

The global minimum is found at $x = y = 1$, and is in a long and narrow valley.

4.4.5 Multi start Rosenbrock search

The initial sampling of the parameter space provides the potential for locating the global optimum without being biased by pre-specified starting points. This method works by dividing the parameter values into a specified number of increments between the specified bounds. For each of these possible starting points a Rosenbrock search is carried out. The best optimum of the Rosenbrock searches is taken as the global optimum.

4.4.6 Genetic algorithm

The genetic algorithm is a search procedure based on the mechanics of natural selection and natural genetics, which combines an artificial survival of the fittest with genetic operators abstracted from nature [Holland, 1975]. The genetic algorithm searches among a population of points and works with a coding of the parameter set rather than the parameter values themselves. It uses probabilistic transition rules. Populations of m (100) points are chosen initially at random in the search space. The objective function values are calculated at all points and compared. From these points two points are selected at random. The selected points are subsequently used to generate a new point in a certain random manner with occasionally added random disturbance.

4.4.7 Shuffled complex evolution

The SCE-UA method is a general purpose global optimization program. It was originally developed by Dr. Qingyun Duan .The SCE method is based on a synthesis of four concepts that have proved successful for global optimization: (a) combination of probabilistic and deterministic approaches; (b) clustering; (c) systematic evolution of a complex of points spanning the space, in the direction of global improvement; and (d) competitive evolution.

Optimization algorithm like Shuffled Complex Evolution (SCE), Uniform Random Sampling (URS), Rosenbrock, SCE then Rosenbrock etc are evaluated for their performance.

4.5 Objective functions

4.5.1 Nash-Sutcliffe criterion (Coefficient of efficiency)

It is used to explore the predictive power of hydrological models, can range from $-\infty$ to **1**. An efficiency of **1** (E = **1**) corresponds to a perfect match of modeled discharge to the observed data and $E = 0$ indicates that the model predictions are as accurate as the mean of the observed data, whereas an efficiency less than zero ($E < 0$) occurs when the observed mean is a better predictor than the model or, in other words, when the residual variance (described by the numerator in the expression below), is larger than the data variance (described by the denominator). Nash–Sutcliffe efficiency can be used to quantitatively describe the accuracy of model outputs other than discharge.

$$E = 1 - \frac{\sum_{t=1}^{T} (Q_m^t - Q_o^t)^2}{\sum_{t=1}^{T} \left(Q_o^t - \overline{Q_o}\right)^2}$$

Where, Q_0 is the mean of observed discharges, and Q_m is modeled discharge. Q_o^t is observed discharge at time t.

4.5.2 Sum of square errors

The residual sum of squares (RSS), also known as the sum of squared residuals (SSR) or the sum of squared errors of prediction (SSE), is the sum of the squares of residuals (deviations predicted from actual empirical values of data). A small RSS indicates a tight fit of the model to the data.

$$RSS = \sum_{i=1}^{n} (y_i - f(x_i))^2$$

Where, yi is the i th value of the variable to be predicted, xi is the i th value of the explanatory variable, and is the predicted value of yi.

4.5.3 Root mean square error (RMSE)

The root-mean-square deviation (RMSD) or root-mean-square error (RMSE) (or sometimes root-mean-squared error) is a frequently used measure of the differences between values (sample and population values) predicted by a model or an estimator and the values actually observed. The RMSD of an estimator with respect to an estimated parameter is defined as the square root of the mean square error:

$$\mathrm{RMSD}(\hat{\theta}) = \sqrt{\mathrm{MSE}(\hat{\theta})} = \sqrt{\mathrm{E}((\hat{\theta} - \theta)^2)}$$

RMSE is a way of measuring how good our predictive model is over the actual data, the smaller RMSE the better way of the model behaving, that is if we tested that on a new data set (not on our training set) but then again having an RMSE of 0.37 over a range of 0 to 1, accounts for a lot of errors versus having an RMSE of 0.01 as a better model. BIAS is for overestimating or underestimation.

4.5.4 Absolute value of bias

The **bias** function is the difference between estimator's **value** and the true **value** of the parameter. An estimator or decision rule with zero **bias** is called unbiased.

4.6 Selection of the objective function

The selection of the objective function will give the calibration a bias toward the range of flows that the objective function determines as most significant. The intended use of the model should be taken into consideration when selecting the objective function. The selected object should give a bias towards the flow characteristics that are of greatest importance such as overall volume, monthly volume, surface runoff and base flow. The following objective functions are compared for evaluation of model performance in this study.

- NSE Daily
- NSE Monthly
- NSE Monthly & Bias Penalty
- NSE Daily & Flow Duration
- NSE Daily & log Flow Duration
- Minimise Absolute Bias
- NSE Daily & Bias Penalty

5 ANALYSIS AND RESULTS

5.1 Statistical Analysis

The box plots of mean annual flow rate are shown in Figure 5.1. The flow variation at Champua and Anandpur are shown in Figure 5.2. It may be observed that the during flood season major quantity is discharged. The linear trend analysis of discharge at Champua is shown in Figure 5.3. It is observed that there is slightly decreasing trend of annual discharge at Champua. This is mainly due to decrease trend of winter season flow, as there is no trend of flow in flood season and summer seasons. However, at Anandpur site located in downstream of Champua, there is increase trend of discharge in winter season (Figure 5.4).

The various other statistical tests for trend, step change in mean/median, difference in mean/median in two different data periods and randomness for annual and seasonal flow at Anandpur are shown in Figure 5.5 and Figure 5.6 with limits of various significance levels.

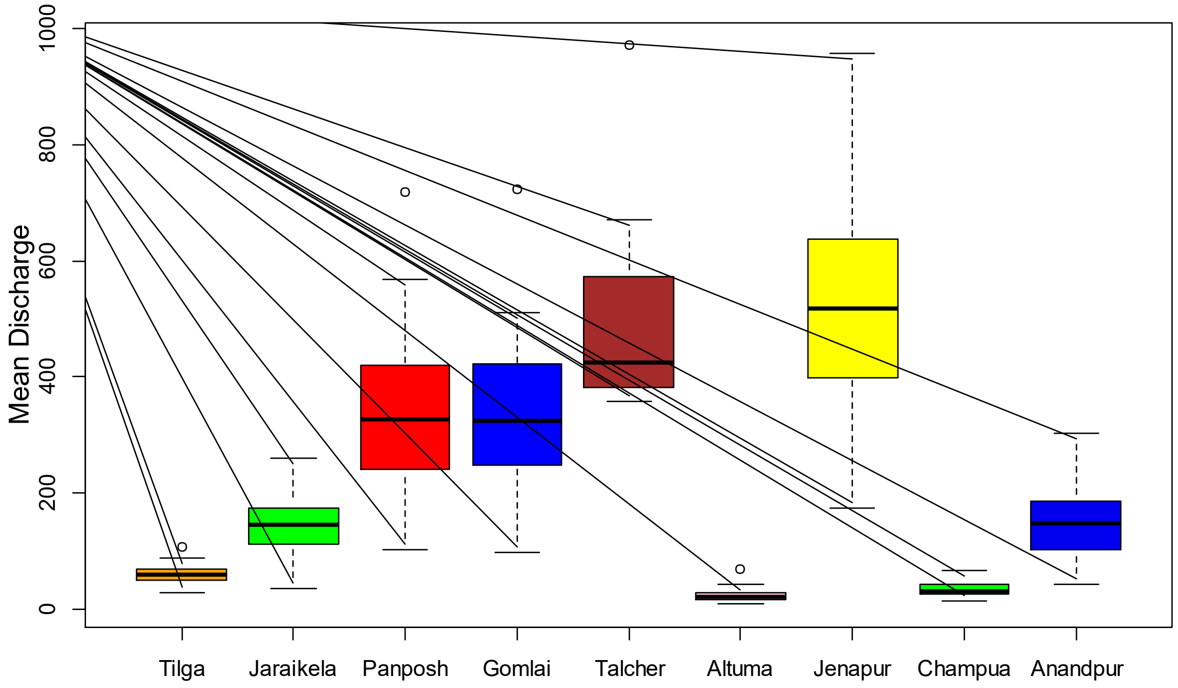


Figure 5.1: Mean annual flow rate

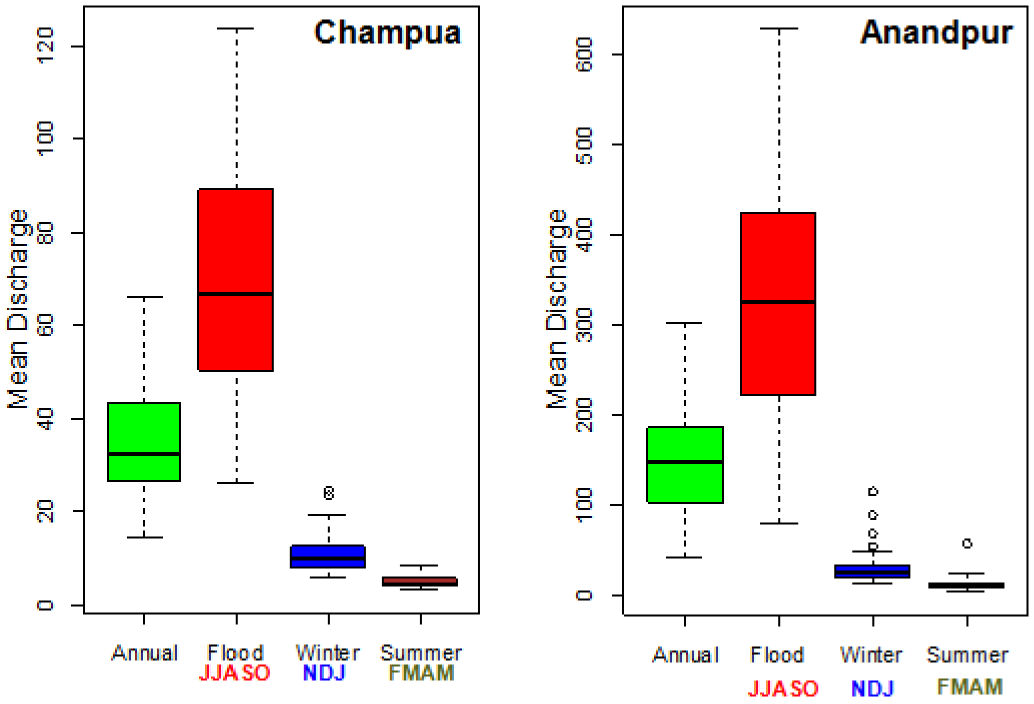


Figure 5.2: Annual and seasonal flow variation

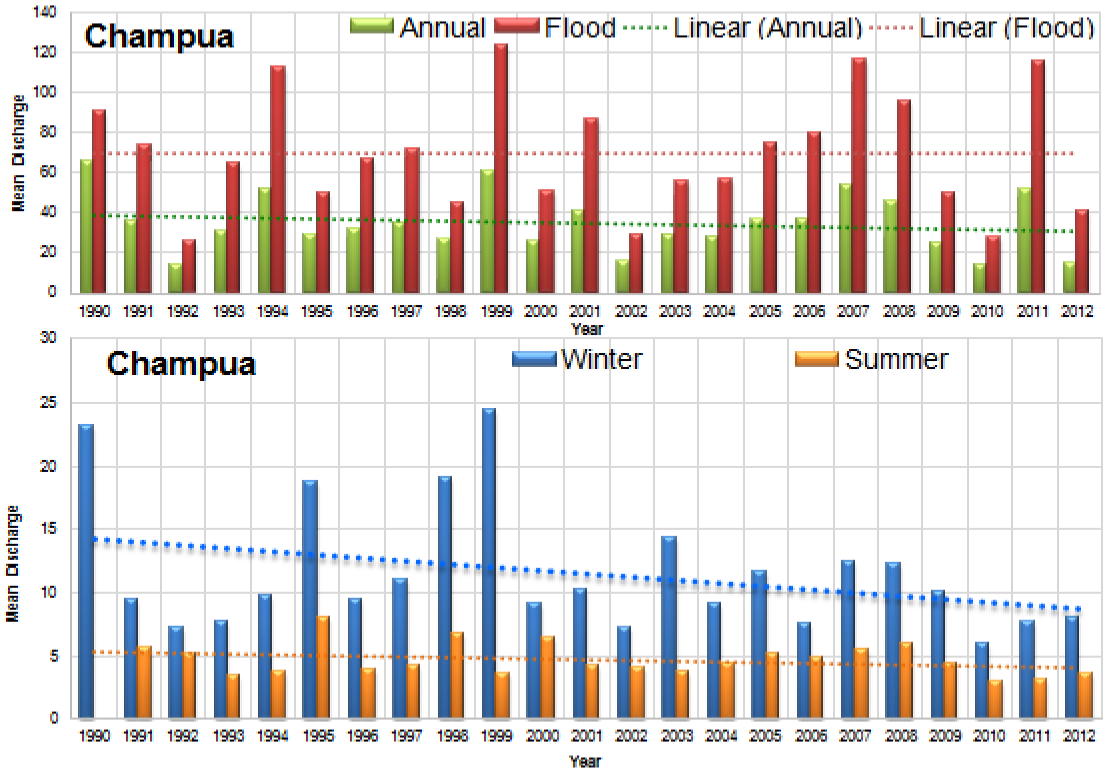


Figure 5.3: Linear trend of discharge at Champua

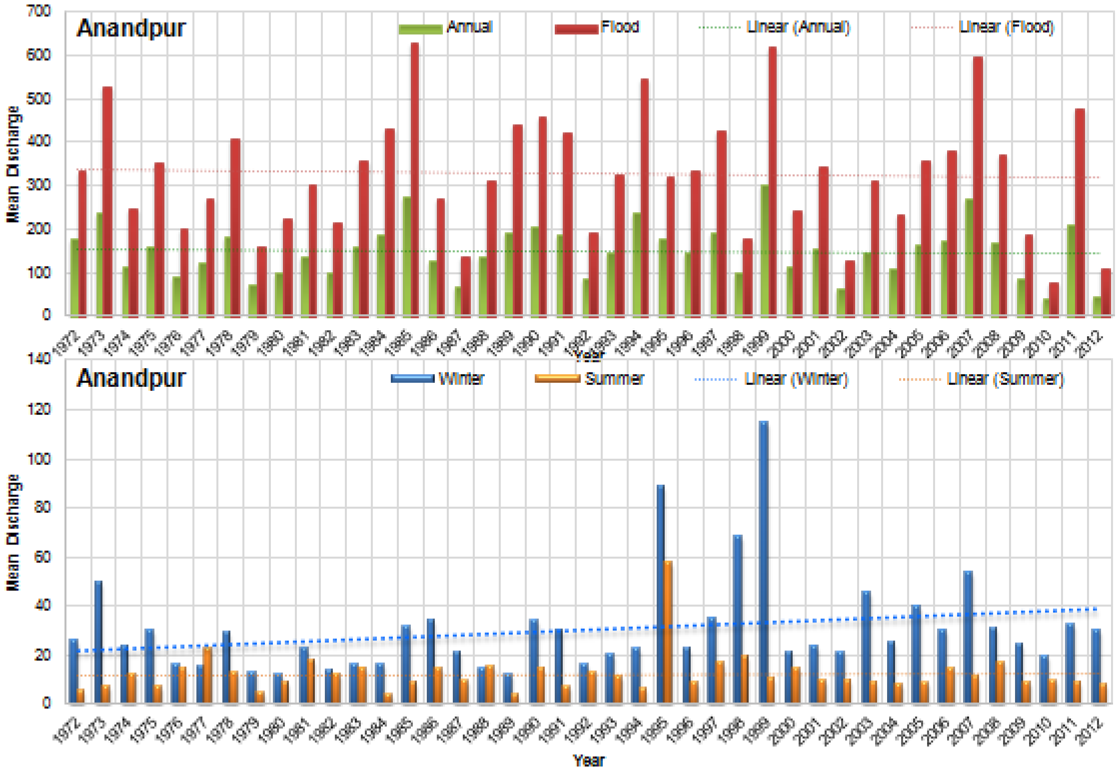


Figure 5.4: Linear trend of discharge at Anandpur

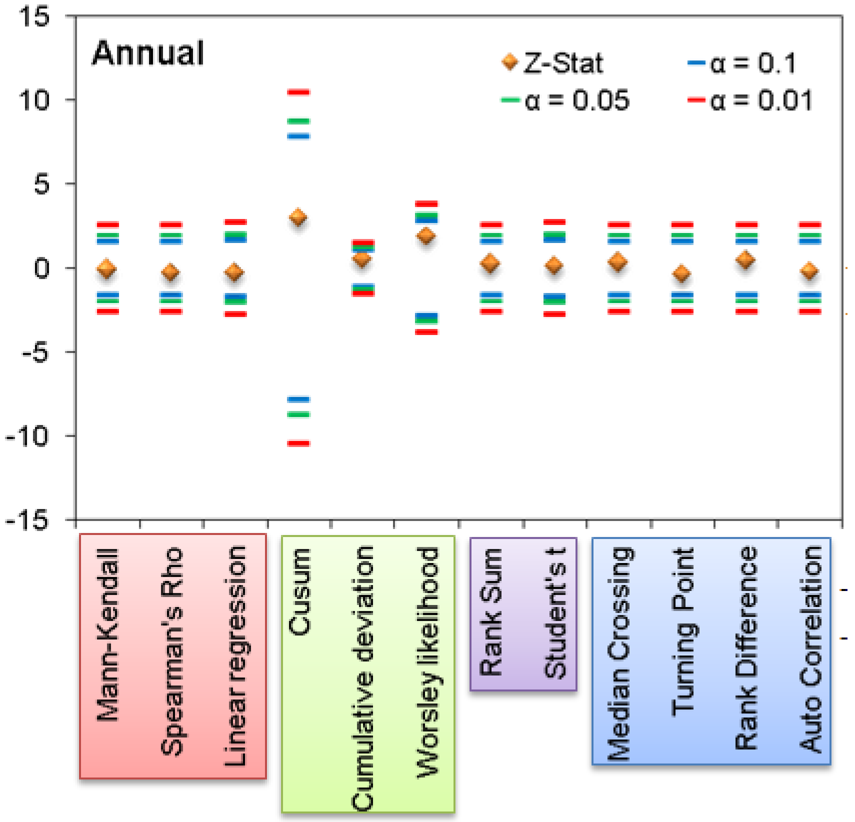


Figure 5.5: Annual trend of discharge at Anandpur

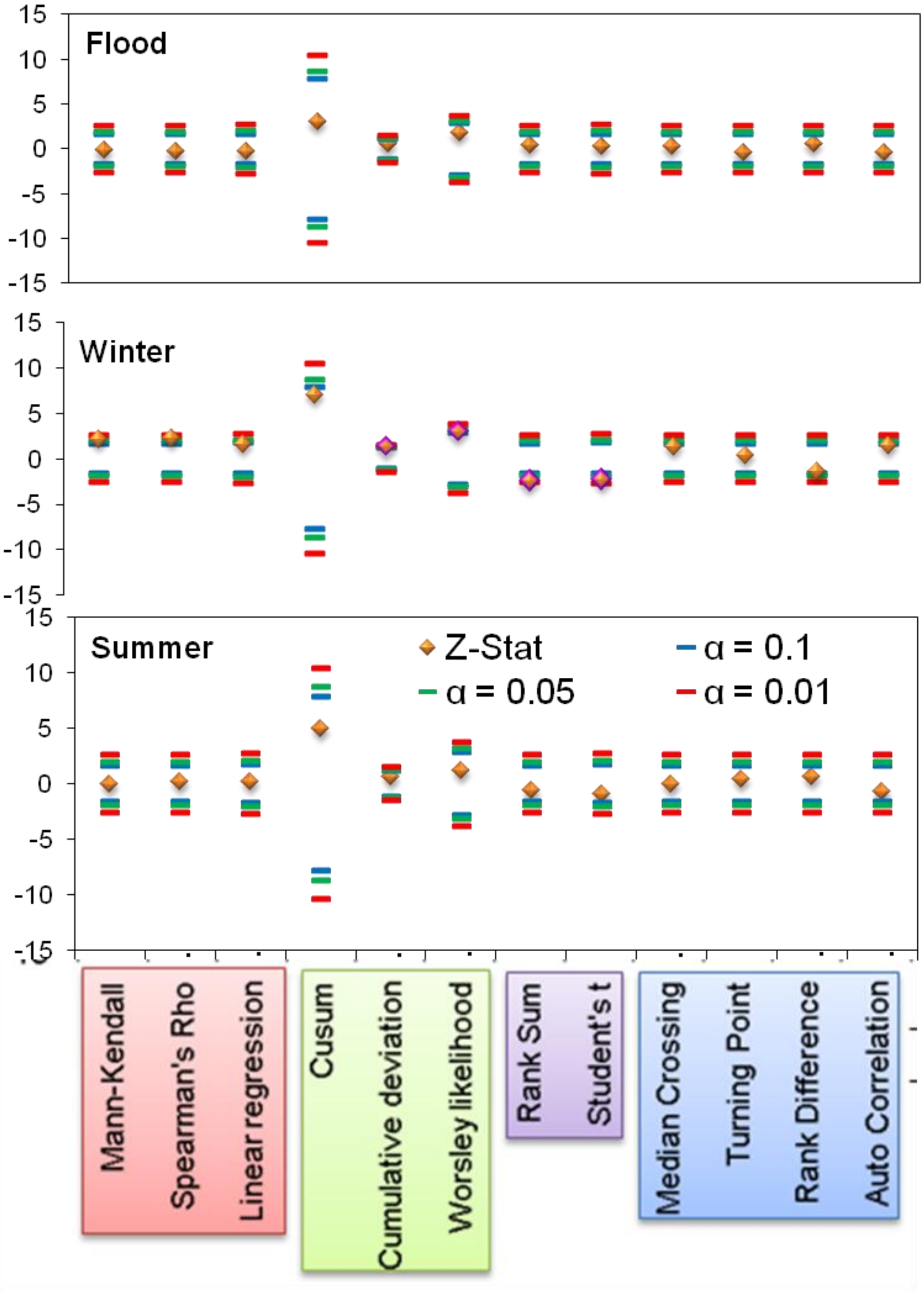


Figure 5.6: Seasonal trend of discharge at Anandpur

5.2 Catchment modelling in Source

The drainage pattern of Baitarani River Basin along with location of gauging sites and dams are shown in Figure 5.7 (a). Based on these locations the basin is divided in to seven sub basins. The schematic of catchment model in source along with their connection is shown in Figure 5.7 (b). Similarly the schematic of catchment model for Brahmani basin is shown in Figure 5.8. The Brahmani basin is divided into 39 sub catchments. However, the detail analysis is carried out for only the Baitarani basin, as the modelling for Brahmani basin is mainly carried out by the Australian team.

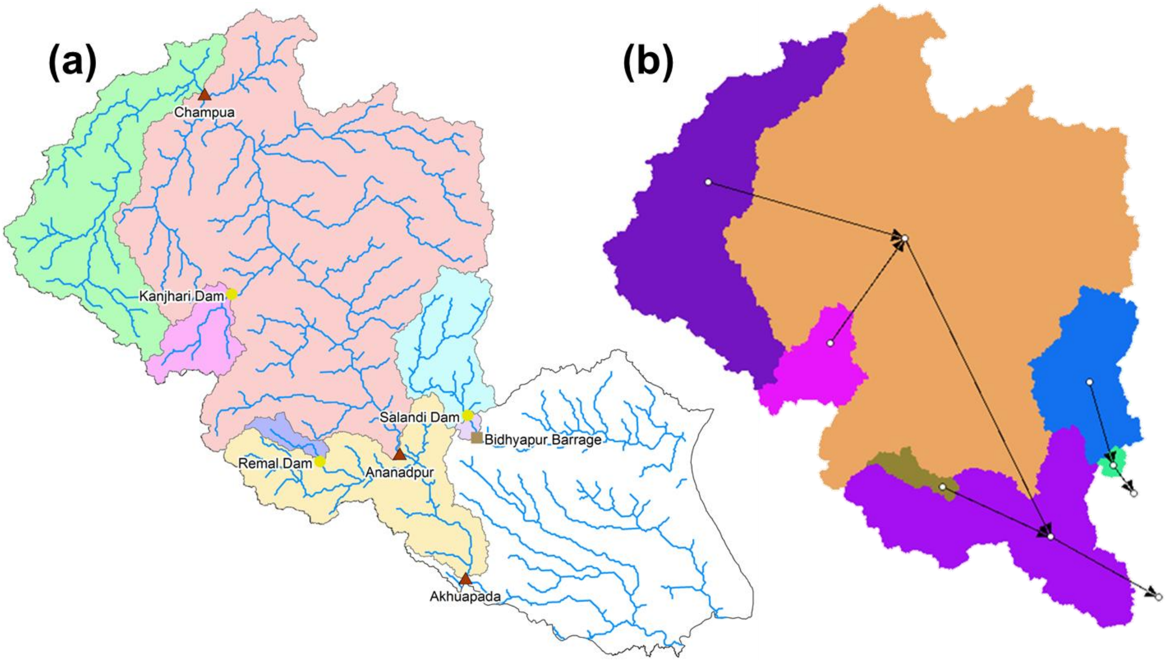


Figure 5.7: Baitarani River Basin (a) drainage system (b) catchment model schematic

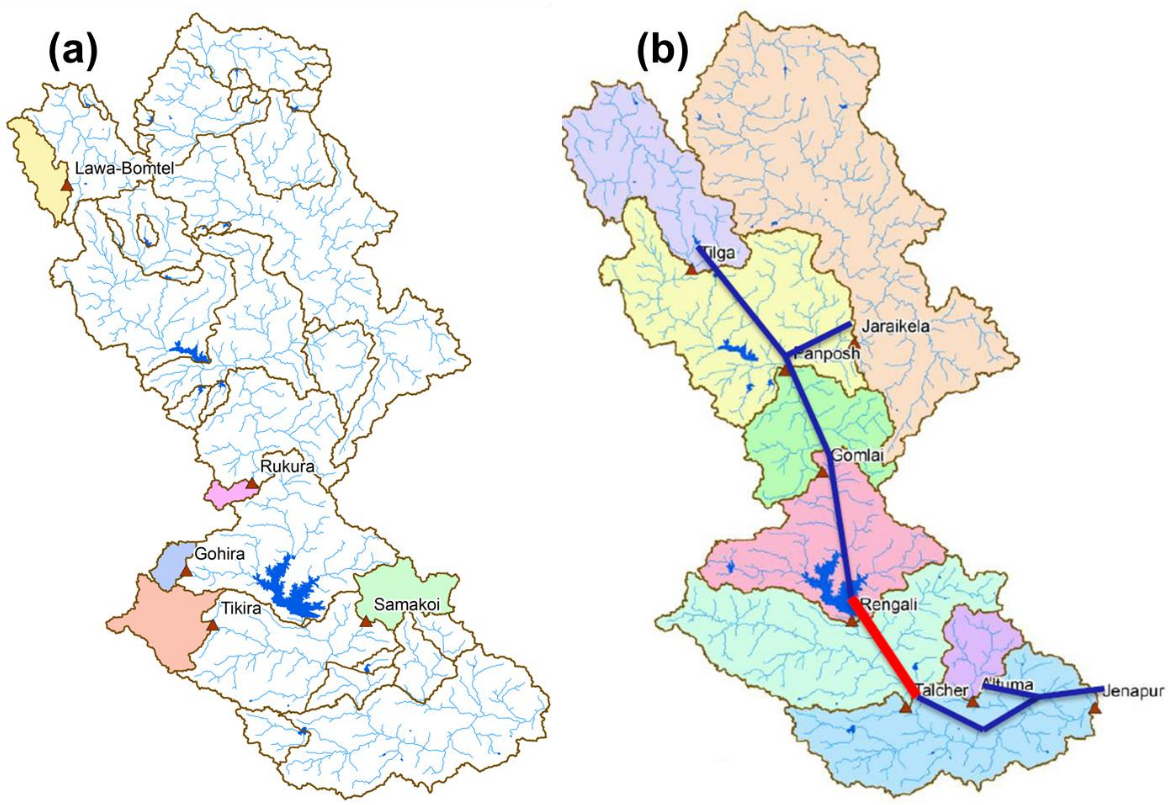


Figure 5.8: Brahmani River Basin (a) drainage system (b) catchment model schematic

5.2.1 Optimisation algorithms

Four Optimization algorithm Viz. Shuffled Complex Evolution (SCE), Uniform Random Sampling (URS), Rosenbrock, SCE then Rosenbrock are evaluated for their performance. The period from June 1990 to May 1995 are used for warm up and simulation results (runoff) during the period June 1995 to May 2008 are compared with that of observed discharge for evaluation. The NSE daily is selected as the objective function for comparing performance of optimisation algorithms. Repetitive runs/simulations are performed to check consistency of the algorithms. The performance of various Optimisation algorithms are shown in Figure 5.9. It may be noted that SCE then Rosenbrock algorithm provided best results. It is also observed that using this method the NSE value of different runs are also consistent. Hence, for further analysis the SCE then Rosenbrock algorithm is selected.

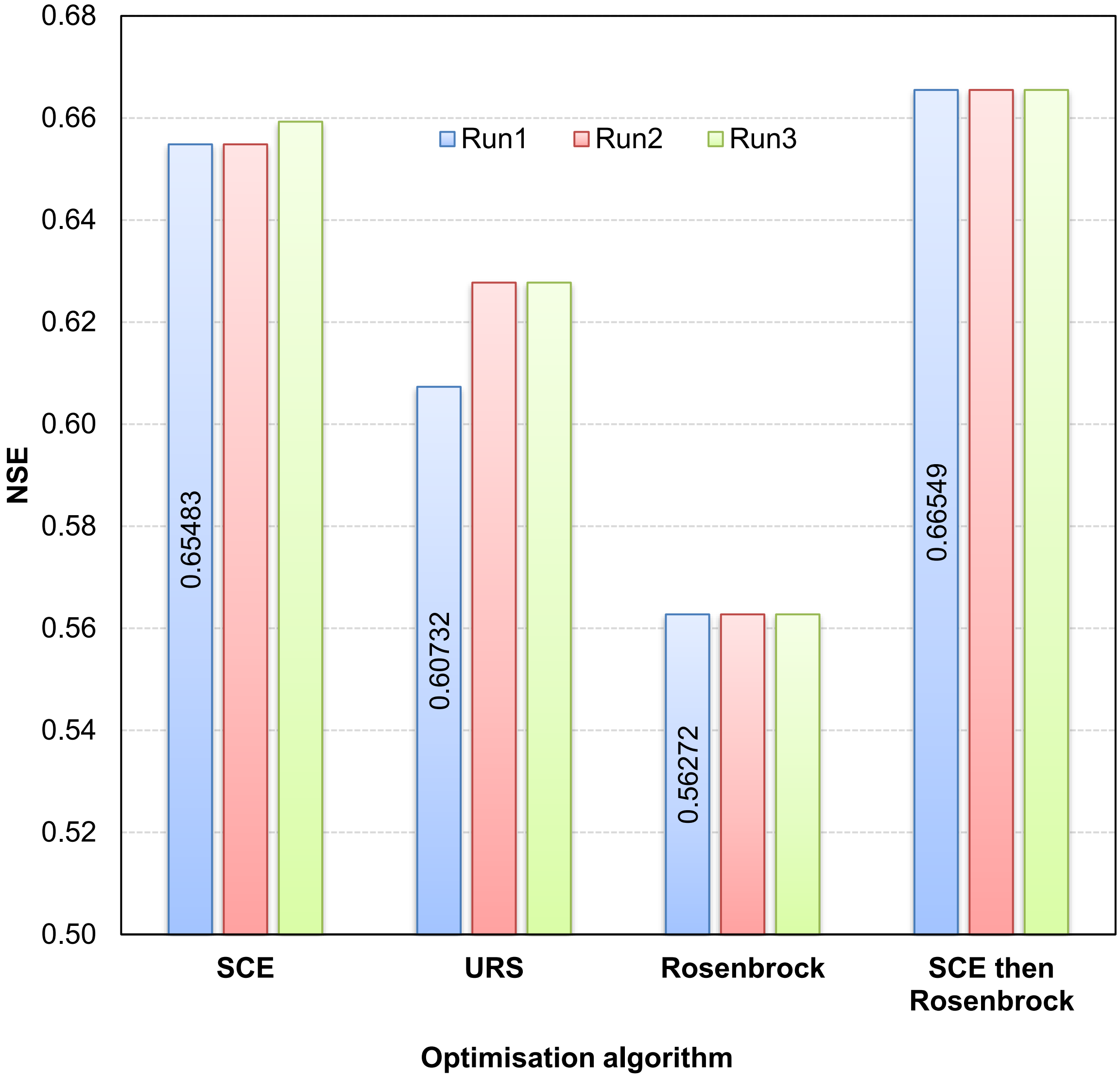


Figure 5.9: Comparison optimisation algorithms

5.2.2 Objective function

Along with NSE Daily, various other objective functions viz. NSE Monthly, NSE Monthly & Bias Penalty, NSE Daily & Flow Duration, NSE Daily & log Flow Duration, Minimise Absolute Bias, NSE Daily & Bias Penalty etc. are also compared. Comparison of observed and simulated discharge using various objective functions is shown in Figure 5.10. Further, comparison of flow duration curve (FDC) is shown in Figure 5.11. The FDC is considered as an important criteria as the model the source plat form is being used for development water resources management planning. It is observed that the objective function of NSE Monthly & Bias Penalty is identified to be most appropriate.

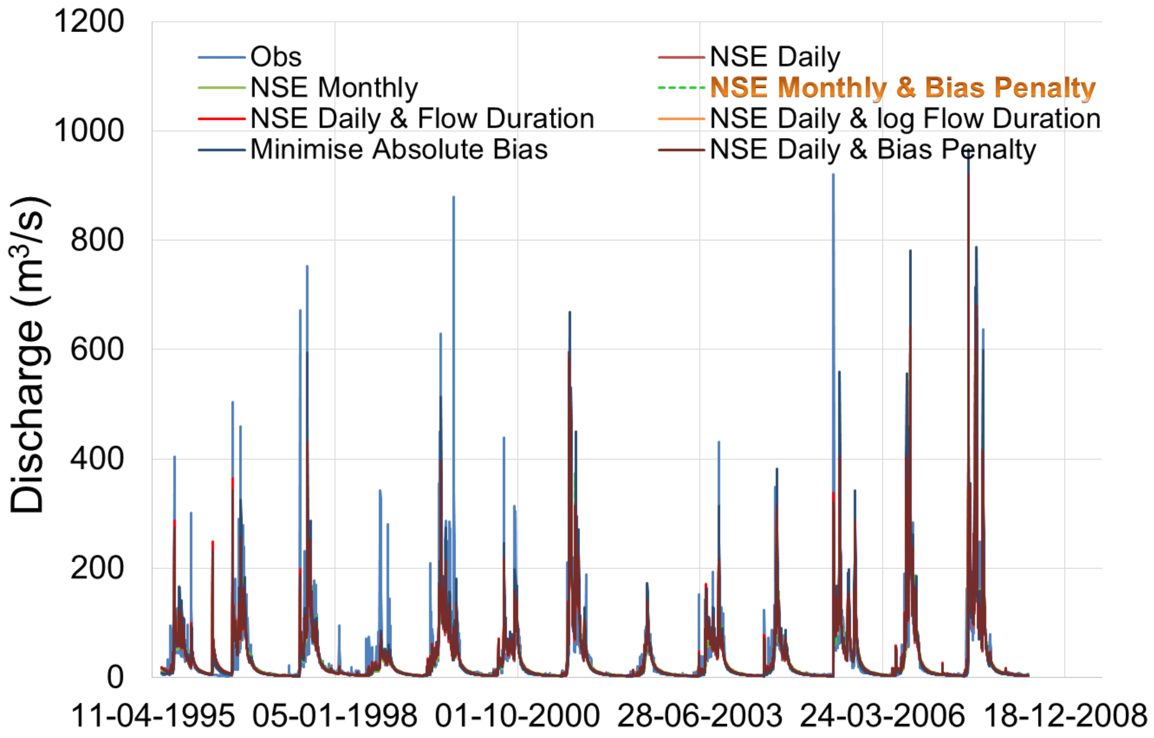
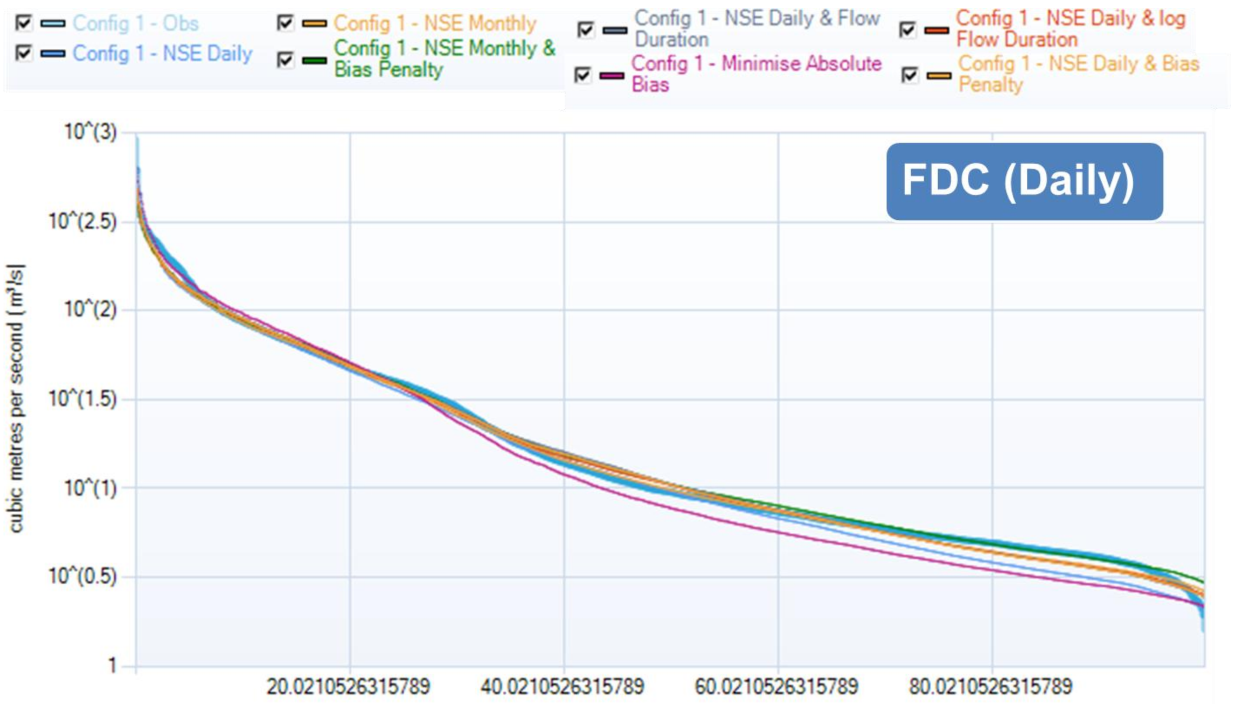


Figure 5.10: Comparison of discharge hydrograph



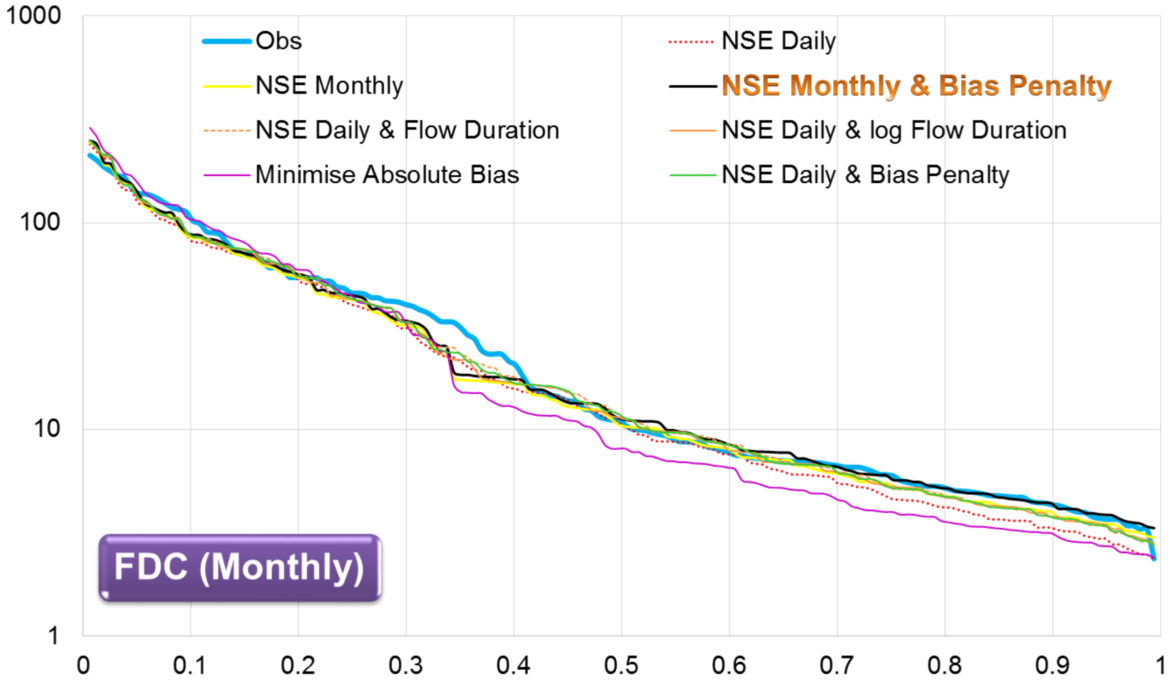


Figure 5.11: Comparison of flow duration curve

5.3 Inter Model Comparison

The simulation results for three rainfall run off models viz. GR4J, Sacramento and SimHyd are compared. The NSE Monthly with Bias Penalty for GR4J, Sacramento and SimHyd model are estimated to be 0.83818, 0.755164 and 0.859462 respectively. It may be noted that the NSE value of both GR4J and SimHyd are very close. Comparison of observed and simulated discharge are shown in Figure 5.12. Further, comparison of flow duration curve (FDC) is shown in Figure 5.13. The FDC is considered as an important criteria as the model the source plat form is being used for development water resources management planning. It is observed that the by comparing FDC the GR4J model is identified to be most appropriate in this case.

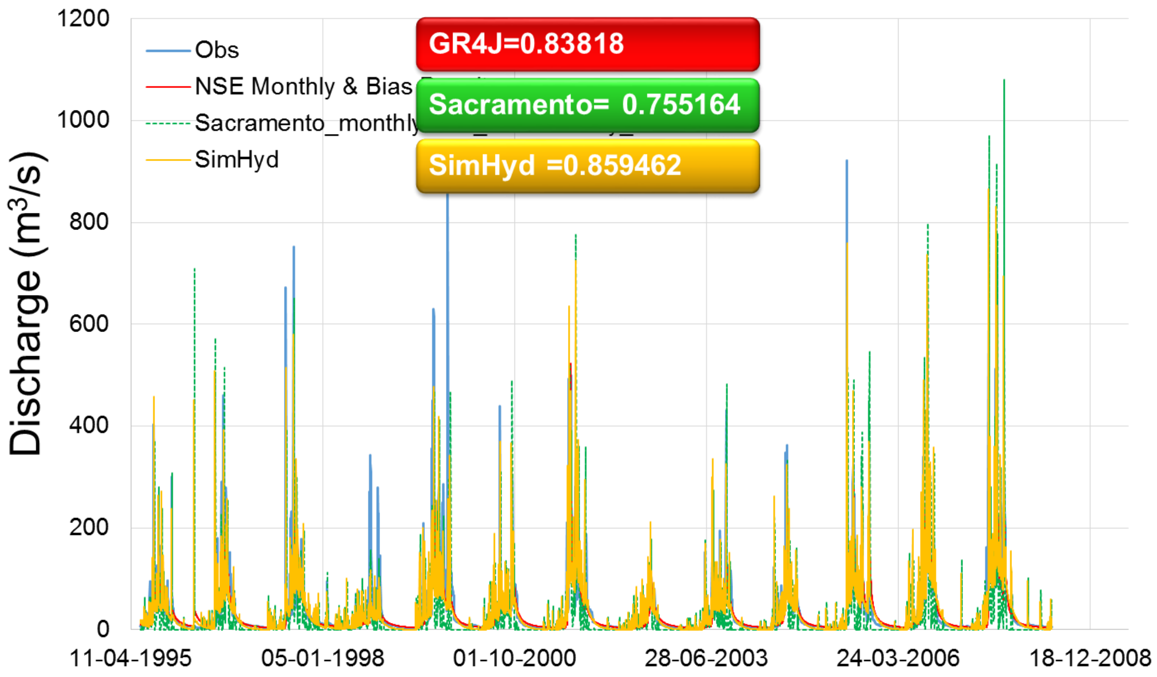


Figure 5.12: Model Comparison with discharge hydrograph

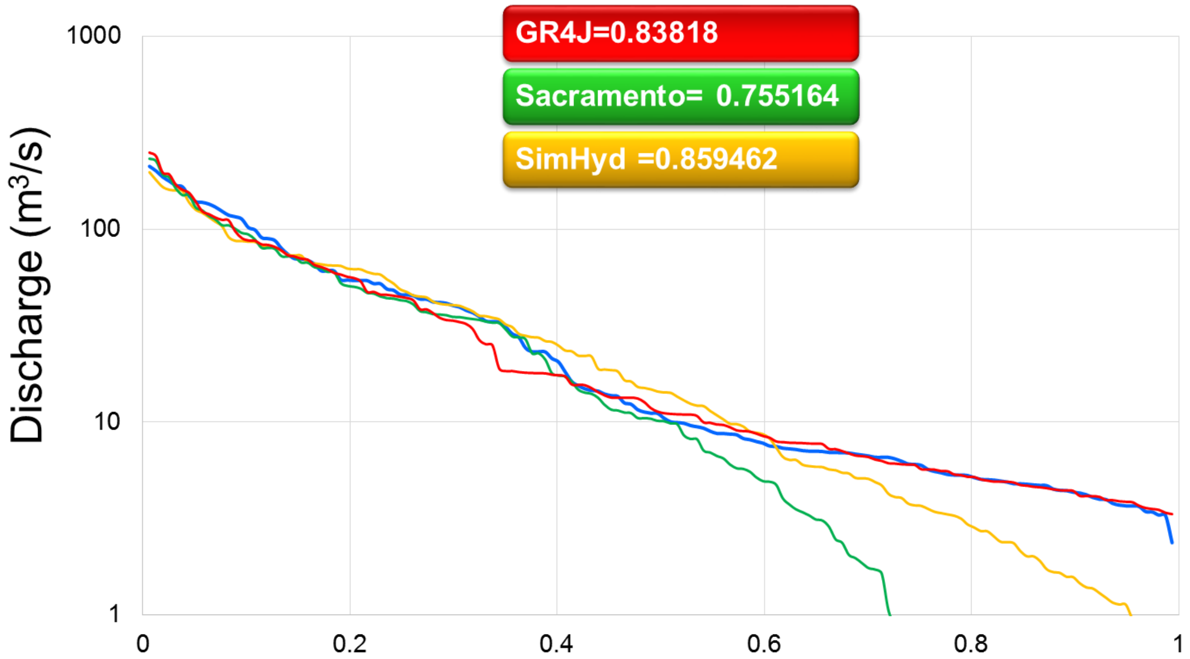


Figure 5.13 Model Comparison with flow duration curve

6 CONCLUSIONS

In the India-Australia Water Science and Technology Partnership programme, Australia is collaborating with the Ministry of Water Resources to pilot the source river basin modelling platform in India. The MoWR, GOI is planning to develop an Integrated Water Resources Management (IWRM) plan for Brahmani Baitarani basin using the eWater source river basin modelling platform. The eWater source is Australia's first national river basin scale water modelling system. The source modelling platform has been developed to take a holistic approach to water management including human and ecological impacts. This includes integrating policy, addressing water savings and sharing for a whole river and connected groundwater systems including cities, agricultural and environmental demands. This study is carried out to develop a rainfall runoff model for Brahmani Baitarani river basin in source platform and test its applicability in this basin.

The rainfall runoff models presently available in Source are: Sacramento (sixteen parameters), SIMHYD (7 parameter), SMARG, GR4J (modèle du Génie Rural à 4 paramètres Journalier) (four parameters), IHACRES (six parameters), AWBM (3 parameter), SURM. The GR4J model along with Sacramento and Simhyd are selected for model comparison. The rainfall runoff model is being setup with daily rainfall data of .25°×.25° obtained from IMD and ET data from Terrestrial Hydrology Group, Princeton University. Various objective functions viz. NSE Daily, NSE Monthly, NSE Monthly & Bias Penalty, NSE Daily & Flow Duration, NSE Daily & log Flow Duration, Minimise Absolute Bias, NSE Daily & Bias Penalty etc. are used to for calibration model. Further optimization algorithm like Shuffled Complex Evolution (SCE), Uniform Random Sampling (URS), Rosenbrock, SCE then Rosenbrock etc are evaluated for their performance.

The various other statistical tests for trend, step change in mean/median, difference in mean/median in two different data periods and randomness for annual and seasonal flow at Champua gauging site shows that the period from 1990 to 2012 are stationary and free from any trend. Hence, this period is selected for modelling in eWater Source. The performance of various Optimisation algorithms are compared and it is observed that SCE then Rosenbrock algorithm provided best results. It is also observed that in case of SCE then Rosenbrock, the variability is minimum among different simulation runs. Along with NSE Daily, various other objective functions viz. NSE Monthly, NSE Monthly & Bias Penalty, NSE Daily & Flow Duration, NSE Daily & log Flow Duration, Minimise Absolute Bias, NSE Daily & Bias Penalty etc. are also compared. Comparison of observed and simulated discharge along with flow duration curve (FDC) the objective function of NSE Monthly & Bias Penalty is identified to be most appropriate. The FDC is considered as an important criteria as the model the source plat form is being used for development water resources management planning.

Statistical evaluation of these three models found that in Baitarani basin, all three models had monthly Nash Sutcliffe Coefficient (NSE) greater than 0.8 with the exception of Sacramento being 0.75. Overall, the SimHyd model achieved the highest NSE value of 0.86. Though the NSE of GR4J model is of 0.84, the flow duration curve is best represented by his model. It is observed that the GR4J model has performed better in comparison to other model for this basin. Moreover, it has only four parameters to calibrate, which also reduces uncertainty.

7 References

Abghari H., Hossein T., P. Hosseinzadeh (2012) “River Flow Trend In West Of Iran During The Past 40 Years : Impact Of Precipitation Variables’ , Global and Planetary Change

Beven, K.J., 1989. Changing ideas in hydrology: the case of physically based models. J. Hydrol., 105, 157-172.

Bhunya, P K, Panda, S.N, Goel M.K. (2011). Synthetic Unit Hydrograph Methods: A Critical Review. The Open Hydrology Journal. 5. 10.2174/1874378101105010001.

Burnash, RJC, Ferral, RL & McGuire, RA 1973, A generalized streamflow simulation system: conceptual modeling for digital computers, Technical Report, Joint Federal and State River Forecast Center, US National Weather Service and California Department of Water Resources, Sacramento, CA.

Chiew FHS, Vaze J, Viney NR, Jordan PW, Perraud J-M, Zhang L, Teng J, Young WJ, Penaarancibia J, Morden RA, Freebairn A, Austin J, Hill PI, Wiesenfeld CR and Murphy R (2008) Rainfall-runoff modelling across the Murray-Darling Basin. A report to the Australian Government from the CSIRO Murray-Darling Basin Sustainable Yields Project. CSIRO, Australia. 62pp

Chiew, F.H.S. (2010). Lumped conceptual rainfall-runoff models and simple water balance methods: overview and applications in ungauged and data limited regions. Geography Compass,

Chiew, FHS & McMahon, TA 1991, ‘Improved modelling of the groundwater processes in HYDROLOG’, Proceedings of the 20th Hydrology and Water Resources Symposium, Perth, October 1991, Institute of Engineers Australia, pp. 492-497.

Chow, V. T., D. R. Maidment and L. W. Mays, (1988),. Applied Hydrology, McGraw Hill

Davie, T. (2008) Fundamentals of Hydrology. 2nd Edition, Routledge, New York.

Erchan K., Serdar K. (2003) ‘Trend Analysis of Streamflow In Turkey’, Journal of Hydrology 289 P 128-144

Kundzewicz W. Z, Cecilia S. and Thomas M. (2004) ‘Trends In Flood nd Low Flow Series’,Global Runoff Data Centre (GRDC), Germany

Kundzewicz W. Z, Darius G., Thomas ., Iwona P., Maciej R., Cecelia S.n and Malgorzata S. (2005) 'Trend Detection In River Flow Series : 1. Annual Maximum Flow' , Hydological Sciences Journal

Marius - Victor Birsan, Liliana Zaharia, Viorel Chendes, Emilia Branescu (2012)"Recent Trends In Streamflow In Romania (1976-2005)' , Romanian Reports in Physics, Vol. 64, No.1, P. 275-280.

Nune R., B.A. George, P. Teluguntla and A. W. Western (2012) 'Relating Trend In Streamflow To Anthropogenic Influences : A Case Study Of Hmayat Sagar Cathchment, India', Department of Infrastructure Engineering, The University of Melbourne, Australia

Ogunlela AO and Kasali. MY(2002). Evaluation of four methods of storm hydrograph development for an ungaged watershed. Published in Nigerian Journal of Technological development. Faculty of engineering and Technology, University of Ilorin, Ilorin, Nigeria. 2002 (2); 25 – 34

Peel, M. C., F. H. S. Chiew, A. W. Western and T. A. McMahon (2000). Extension of Unimpaired Monthly Streamflow Data and Regionalisation of Parameter Values to Estimate Streamflow in Ungauged Catchments. Canberra, National Land and Water Resources Audit.

Perrin, C. (2000), Vers une amélioration d'un modèle global pluie-débit au travers d'une approche comparative, Thèse de Doctorat thesis, 530 pp, INPG (Grenoble) / Cemagref (Antony).

Perrin, C. (2002), Vers une amélioration d'un modèle global pluie-débit au travers d'une approche comparative, La Houille Blanche, 84-91.

Porter, JW & McMahon, TA 1975, 'Application of a catchment model in southeastern Australia', Journal of Hydrology, vol. 24, pp. 121-134.

Porter, JW 1972, The synthesis of continuous streamflow Department of Civil Engineering, Monash University, Melbourne, p. 222.

Reshma, T., Kumar, P., Babu M. and Kumar K., (2010) "Simula-tion of Runoff in Watersheds Using SCS-CN and Musk-ingum-Cunge Methods Using Remote Sensing and Geo-graphical Information Systems," International Journal of Advanced Science and Technology, Vol. 25, , pp. 31-42

Roy D. and Banerjee, D. (2010) "Performance Analysis of the Proposed Reservoir Project in the State of West Bengal," Hydrology and Earth System Sciences Discussions, Vol. 7, No. 1, , pp. 1373-1405. doi:10.5194/hessd-7-1373-2010

Salami A W (2009) Evaluation of Methods of Storm Hydrograph Development for lower Niger River basin. Journal of American Science 2009:5 (4):23-32

Sherman, 1932 L.K. Sherman Stream flow from rainfall by unit-graph method. Eng. News Rec., 108 (1932), pp. 501-505

Viney N, Vaze J, Chiew F, Perraud, J, Post D and Teng J. (2009). Comparison of multimodel and multi-donor ensembles for regionalisation of runoff generation using five lumped rainfall-runoff models in: 18th World IMACS Congress and MODSIM09 International Congress on Modelling and Simulation, July 2009, Cairns: Modelling and Simulation Society of Australian and New Zealand and International Association for Mathematics and Computers in Simulation: 3428-3434.