

**RAINFALL-RUNOFF SIMULATION MODEL
BASED ON WATER BALANCE CONCEPT FOR
BASINWIDE WATER RESOURCE ASSESSMENT - A CASE
STUDY IN UPPER AND LOWER CATCHMENTS OF
DEDURU OYA BASIN, SRI LANKA**

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Degree of Master of Science in Water Resources Engineering and
Management

Department of Civil Engineering

University of Moratuwa

Sri Lanka

October 2015

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Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of
Master of Science in Water Resources Engineering and Management

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October 2015

DECLARATION

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ABSTRACT

A rainfall-runoff simulation model based on water balance concept was developed and applied for the water resources assessment in upper and lower catchments of Deduru Oya basin. The model was selected due to its capacity to analyze the spatial variation of runoff generation characteristics, simplicity and limited input data requirement. The model was developed for the entire basin where the model parameters were calibrated, validated and optimized appropriately using monthly hydrological datasets. The calibration run results obtained were found to be acceptable with value of 0.17 for Mean Ratio of Absolute Error (MRAE) and 0.91 for Nash–Sutcliffe Coefficient (NSC) which were used as error estimates. At the same time, the basin was divided into two sub-catchments and modeled separately using refined constant parameter values which have been used for entire basin to check the performance of the model. In this case, incorporation of sub-catchments separately has shown better performance of the model enhancing model accuracy by 2% according to MRAE and same value for NSC. The river gauging station in the downstream of the reservoir is not functioning since the commissioning of the reservoir in 2014. To overcome the issues in decision making due to the lack of continuous observed streamflow data up to date and to study reservoir effect on stream flow, the calibrated and validated model was extended by carrying out a model scenario analysis with the incorporation of the recently commissioned Deduru Oya Reservoir and associated basin conditions as of August, 2015 in an attempt to perform a basin wide water assessment with the objective to overcome the data inadequacies pertaining to required spatial and temporal resolutions in historical precipitation and streamflow time series data. The construction of the reservoir was found to have a significant impact in reducing peak floods in the downstream due to mid-level extreme events by dampening and reducing the peak flood. It was found that due to a similar event in May 2015, the reservoir retention and detention was effective in reducing the associated peak flood by 66.04%. However, the impact on extreme events were found to be reduced due to possible opening of the gates. The results of the extended model were not validated due to unavailability of observed data. However, these results will provide reference and scope for the future research in the same field. The study concluded that the rainfall-runoff modelling is an essential tool for comprehensive assessment and management of water resources and the model can be applied in the same basin with future conditions or in basins with similar characteristics elsewhere.

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1 INTRODUCTION

A rainfall-runoff model is a mathematical model which describes the relation of rainfall-runoff in a catchment or it can be expressed as a simplified representation of a complex catchment system. As a response to a rainfall hyetograph given as input, it precisely produces the surface runoff hydrograph or in other words, a model calculates the transformation of rainfall into runoff quantity in the particular catchment. The linear reservoir model is a well-known runoff model, but in practice its applicability is limited due to inherent non-linearity in most natural systems. A runoff model with a non-linear reservoir is more universally applicable, but it holds only for catchments whose surface area is limited by the condition that the rainfall can be considered more or less uniformly distributed over the entire catchment. When the catchment area is too large for this application based on a single catchment, it can be divided into sub-catchments where the various runoff hydrographs can be combined together using flood routing techniques for enhancement of accuracy of result.

The estimation of runoff or discharge flow characteristics of a catchment can be carried out by rainfall-runoff modeling. For the modeling and analyzing, it requires historical records of rainfall and streamflow data over a sufficient length of period to accurately estimate the long-/short term and high-/low-flow variations of runoff in the catchment adequately representing the catchment response characteristics .

When the rain falls over the catchment, a certain quantity of it infiltrates into the ground whereas the remaining quantity flows over the surface of the catchment and finally joins into rivers and streams. A portion of the rainwater which has been infiltrated into the ground will also join the streamflow in the form of subsurface runoff, namely rapid and delayed groundwater flows, under favorable geological conditions. The runoff which is transformed from the rainfall undergoes losses due to many factors such as absorption, evaporation, evapotranspiration, further infiltration, interception and seepage. These losses depend on the geological and physical conditions of the ground and atmosphere of the catchment location.

An accurate simulation of a rainfall-runoff model can play a significant role in urban and environmental planning, land use, flood and water resources management of a watershed as well as mitigation of drought impacts on water resources systems (Saeidifarzad, Vahid,

Aalami, & Chau, 2014). The water resources availability assessment requires detailed insights into hydrological processes. Studying the complexity of hydrological processes, needed for sustainable catchment management, is basically based on understanding rainfall characteristics and catchment properties, for which rainfall–runoff modeling studies are useful. Rainfall–runoff models have been widely used in hydrology over the last century for number of applications and they play an important role in optimal planning and management of water resources in catchments.

Water Resources Assessment (WRA) is defined as the “determination of the sources, extent, dependability and quality of water resources for their utilization and control, and water resources are the water available, or capable of being made available, for use in sufficient quantity and quality at a location and over a period of time appropriate for an identifiable demand” (World Meteorological Organization, 2012).

Water resources are essentially renewable resources that are the basis for the mere existence and development in a society. The water resources are used for agriculture, aquatic environments, drinking, industry, recreation, sanitation, transport and many other functions. Effective and proper utilization of these resources require assessment and management in terms of quantity and quality both spatially and temporally of the catchment (Moreda,1999).

The major river basins are the most convenient unit for any planning, assessment or appraisal of water resources (Miloradov & Marjanovic, 1998). According to Water Resources Assessment (1997), the main activities required and involved for basic assessment of water resources are data collection, modeling, analyzing and dissemination. In a particular basin, the water resources component comprises of detailed hydrological and water resources assessment models which are used to simulate the spatial and temporal water availability in different parts of the basin in terms of inflow variability and potential change, water use withdrawals, return flows, and system constraints imposed by different management policies (Kimaite, 2011).

Reliable estimates of streamflow generated from catchments based on actual or predicted rainfall are required as part of the information sets that help policy makers for making decisions on water resources planning and management. The characteristics of the streamflow time series that influence water resources system modeling and planning can include the sequencing of flows on daily and longer time steps, spatial and temporal variability of flows, seasonal distribution and characteristics of high and low flows.

To overcome the water related problems, extensive care should be given to the operation and management of reservoirs and watersheds (Choudhari, Panigrahi, & Paul, 2014). The reservoirs are managed to reduce the effect of floods in downstream of the dams through the provision of storage and controlled discharge of flood inflows. In other cases, floods contribute decisively to the refilling of reservoirs. The influence of reservoirs on river regimes and floods depends on the purpose of the reservoir, the seasonality of high and low discharges and the state of the reservoir when a flood occurs (Moreno, Begueria, & Ruiz, 2002). Enlargement of reservoir capacity implies further changes in the flow pattern and subsequent changes in erosion, deposition and sediment transport in the downstream (Moreno, Begueria, & Ruiz, 2002).

In real time operation, adaptive flood control and measurement becomes crucial, since spatial and temporal dynamic rainfall/flood patterns may change between different rain events or even within one event, in particular if there will be more severe conditions induced by the climate change. Usually, flood control computations consist of reservoir and river flow routing simulation and inundation prediction (Shengyang, 2013). Decision making process in flood control and management vary from one another in terms of style and content. Three stages are distinguished in the decision making: (i) pre-flood preparation, (ii) operational flood management and (iii) post-flood assessment (Dahm, 2006) quoted by Shengyang (2013).

In Sri Lanka, in most of the recent years and particularly on 17th December, 2012 there were continuous and heavy rainfall in upstream (Kurunegala/Kegalle) and downstream (Chilaw) of Deduru Oya Basin and as a result more than 300,000 people of Kurunegala and Puttalam districts were displaced and among the most affected. Ministry of Disaster Management has stated that the recent flooding in December 2014 has caused damage to numerous structures situated within the floodplain, including buildings, roads, utilities, machineries and electronics, industry and communication equipment, food stocks, cultural artifacts, fields and lives of people.

Sustainable water resources management interventions are essential in Deduru Oya basin to increase or sustain water resources, especially for the agriculture and livestock sectors. However, water resources assessment on the catchment scale is therefore one of the key activities to provide insight into water available for agricultural purposes.

This research was carried out with the objective of developing a reliable rainfall-runoff model for water resource assessment in the upstream and downstream of Deduru Oya Basin considering the historical data at five rain gauge stations with monthly rainfall, one station with monthly average evaporation and a station with monthly streamflow over a twenty four year period. The specific need of modeling is recognized due to the ever increasing demand for water in the basin where it dictates the necessity for the development of hydrological modeling to assess the water resources for planning and management. This ultimate goal will help to manage the water resources in an integrated way and at the lowest possible basin level. Not only will the findings of this study contribute to enhancing our knowledge base, but they will also contribute to inform and enlighten the decision makers in water resources development planning in Deduru Oya Basin to achieve better results.

1.1 Problem Statement

Expansion of population leads to increase in demands on water resources, whereas the water resources are finite. The rising demand on water resources is the cause of conflict among the water consumers in water resources management. The human activities are becoming increasingly intensive and diverse with an ever growing trend and causing more impacts on natural water resources through depletion and pollution. At the same time due to the effect of climate change, the precipitation occurs unevenly over the regions. During the peak rainfall, the runoff flowing into the river channel is drastically increasing and as a result the downstream floodplains get inundated, submerging the nearby infrastructures and blocking the traffic routes. In most of the recent years due to continuous and heavy rainfall in upstream of Deduru Oya basin, many people and infrastructure in Kurunegala and Puttalam districts were affected as there were no storage measures in the upstream.

1.2 Objectives of the Study

The objectives of this research were classified into two sections as follows:

1.2.1 Main objective

Main objective of this study is to develop a rainfall-runoff simulation model based on water balance concept and appraise its performance in water resources assessment in Deduru Oya

Basin targeting the downstream flood control and reservoir storage effect in the upstream and downstream of the basin.

1.2.2 Specific objectives

The specific objectives for the study are:

- i. To study the rainfall and watershed characteristics of Deduru Oya basin based on long term monthly rainfall and river discharge data.
- ii. To identify the sub-catchments, and develop, calibrate and verify a three parameter rainfall-runoff model for each sub-catchment under stationarity condition at different temporal and spatial scales to compare the simulated streamflow with observed discharge.
- iii. To determine the water availability in terms of discharge in upstream and downstream catchments.
- iv. To recommend on the results of model and scenario analysis for the water resources assessment, development and management in the basin.

2 LITERATURE REVIEW

2.1 Introduction to Rainfall-Runoff Models

As the term "rainfall-runoff model" suggests, the major input into the model is an estimate of rainfall, and the output is an estimate of runoff (Knapp, Durgunoglu, & Ortel, 1991). The first monthly water balance models were developed by Thornthwaite (1948). An accurate prediction requires an appropriate model structure and methods to estimate model parameters (Dijk, 2010).

The rainfall-runoff modeling is considered as standard tool routinely used for the investigation and developing application in catchment hydrology (Quan, 2006). The simplified water balance model is applied to calculate excess rainfall where runoff can be calculated as $RO = F \times EP$ (Karamouz, Szidarovszky, & Zahraie, 2003), where RO is the calculated runoff from excess rainfall in month, F is the lag coefficient for converting excess rainfall to runoff and EP is excess rainfall in month (Sharifi, 1996).

Model with rainfall and evaporation as input are usually found to be more realistic, especially in reproducing seasonal flows and intermediate water balance variables (Moreda, 1999). Regression and correlation techniques essentially determine the functional relationship between rainfall and runoff (Sharifi, 1996).

2.2 Classification of Rainfall-Runoff Models

Rainfall-runoff models are normally characterized or classified to help describe and discuss their capabilities, strengths, and limitations. There is no universal method to characterize rainfall-runoff models, and models have been classified in several ways depending on the criteria of interest. According to Knapp et al. (1991), the rainfall-runoff models are classified as follows:

2.2.1 Event based and continuous simulation model

Rainfall-runoff models are either event based models or continuous simulation (CS) models. Event models estimate the runoff from an individual storm event, i.e., describing a relatively short period within the hydrologic record. Event models ordinarily evaluate a partial set of the hydrologic processes that affect the watershed: infiltration, overland and

channel flow, and possibly interception and detention storage. Most event models use a constant time interval, whose value may typically range from minutes to several hours.

Continuous simulation models operate for a sustained period that includes both rainfall events and interstorm conditions. To legitimately evaluate the streamflow during interstorm periods, CS models should include additional hydrologic properties such as evapotranspiration, shallow subsurface flow, and groundwater flow. Also crucial to these models is an accounting of the soil moisture and how it relates to changes in infiltration. The CS time interval can be daily, hourly, sub-hourly, or even variable.

2.2.2 Conceptual and hydrodynamic model

This categorization describes the types of equations used in the model to describe the hydrologic processes. These categories of models are identified as: 1) "black-box" or transfer functions, 2) conceptual models, and 3) hydrodynamic models. Black-box models rely upon a statistical correspondence between the model input (rainfall) and model output (runoff) without relation to any underlying physical processes.

2.2.3 Lumped and distributed parameter model

The hydrologic parameters used in the rainfall-runoff models can be represented in either a lumped or distributed manner. The lumping method averages the total rainfall, its distribution over space, soil characteristics, overland flow conditions, etc. for the entire watershed, ignoring all flow-routing mechanisms that exist within it. Distributed parameters both describe the geographical variation of parameters across the watershed and discriminate between changes in the hydrologic processes that occur throughout the watershed during the entire runoff generation period.

2.2.4 Models with fitted, physically determined, or empirically derived parameters

Parameters for rainfall-runoff models can be, 1) fitted through calibration, 2) determined from field measurements, or 3) empirically fixed. Fitted parameters, set in the calibration process, typically have no little or no physical interpretation. Physically determined parameters are derived from measurable watershed characteristics such as slope, channel width, hydraulic conductivity of soils, etc. Measured values may not always produce the best results when used directly in a model. Thus, some physically determined parameters

may be adjusted during the calibration process and are not necessarily equal to the measured values in the field.

2.3 Strength and Weakness of Rainfall-Runoff Models

In principle, the monthly water balance models can take a simpler form and use a smaller number of parameters than the corresponding daily hydrological models. Models are helpful in computing forecasts and in generating arbitrarily long runoff series (Xu & Vandewiele, 1994).

Munyanneza et al. (2014) have stated that the models have been widely used in hydrology over the last century for number of applications and play an important role for generating design return period peak flood and for optimal planning and management of water resources in catchments.

Xu and Singh (2004) have stated that model is relatively straightforward to apply to accurately simulate the historical basin discharges. The model could be an empowering tool for water resource managers to prepare for and mitigate the effects of regional climate change on their local hydrologic resources.

On the other hand the models often have problems with the parameter estimation which constitutes the largest obstacle to the successful application of water resources assessment models (Xu & Singh, 2004). Munyanneza et al. (2014) reported that the main challenge associated with successfully applying rainfall–runoff models lies in the lack of monitored data, mainly rainfall spatial distribution over the catchment area, since rainfall is the primary input in any hydrological model.

Another potential problem is having no reliable flow data that can lead to the reliable calibration and validation of catchment parameters. One of the biggest limitations of the rainfall-runoff models that are widely used in practice is their lack of representation of areal variability within the catchment (Boughton, 2004).

2.4 Input Data for Modelling

The primary inputs to the model are the monthly streamflow (m^3/s), the monthly catchment rainfall (mm), and monthly actual evapotranspiration (mm); the latter two are to derive the residual rainfall, which is the main independent variable in the multiple regression

formulation (Nawaz & Adeloye, 1999). The models that use rainfall and evaporation as input are usually found to be more realistic, especially in reproducing seasonal flows and intermediate water balance variables (Moreda, 1999).

Perera and Wijesekera (2011) have stated that Abulohom et al. (2001) have developed a rainfall runoff model based on water balance equations where inputs to the model includes precipitation and potential evapotranspiration on monthly basis which in turn gives simulated runoff at watershed outlet.

The evaporation of water is an emission of water vapor by a free surface or in other words, the transformation from the liquid to the gaseous state of aggregation at a temperature below the boiling point (Liebe, 2002). The two main factors influencing evaporation from an open water surface are the supply of energy to provide latent heat of vaporization and the ability to transport the vapor away from the evaporative surface: solar radiation and wind (Moreda, 1999).

The key element in the long term water balance of a catchment is the value of the actual long term evapotranspiration as the variation of evapotranspiration throughout the year results in variations in the soil moisture content (Xu & Singh, 2004). Evaporation is profoundly important in the quantification of water resources assessment modeling as it can account up to 90 percent of precipitation in drier area (World Meteorological Organization, 2012).

In conceptual rainfall runoff modeling, one of the two terms, pan evaporation and potential evapotranspiration are equally used as input, which exerts energy to extract water from open surface or soil moisture storage (Moreda, 1999). The correlations developed between pan evaporation (EP) and potential evaporation (PET) is $PET = f_p \times EP$ where f_p is a coefficient that varies usually from 0.7 to 0.8. In Sri Lanka, Irrigation Department recommended pan coefficient of 0.8 for water demand modeling (Wijesekera, 2011).

Wijesekera, (2001) has carried out a water balance modeling to ascertain the required modification in evaporation from a reservoir to achieve a improved model results. Computation has revealed that changes so desired are highly unrealistic reaching extremely high percentage. This has indicated that evaporation values were not a major cause of the model result.

On the other hand, the runoff is continuously lost through seepage or deep percolation and it depends upon the permeability of soil. In Sri Lanka, the monthly seepage loss is assumed to be 0.5% of the volume of water (Ponrajah, 1984). Wijesekera (2001) have stated that the seepage coefficient assumption of 0.5% of volume of water in the reservoir is the quantity lost by seepage does not appear to be realistic and the seepage amounts to much more. Therefore, the seepage coefficient was changed to 2%.

2.5 Parameters for Modelling

The problem with the parameter estimation still constitutes the largest obstacle to the successful application of water rainfall-runoff models (Xu, 2000). The parameters of conceptual hydrological models can be inferred by either subjective trial and error fitting or by using automatic optimization routines. Xu (2000) has stated that James (1972) argued that only rigid adherence to a standard optimization procedure would enable compilation of a sufficiently comprehensive database for use in regression studies relating model parameters to catchment characteristics.

2.5.1 Runoff coefficient

Runoff coefficient (C) is a dimensionless coefficient relating the amount of runoff to the amount of precipitation received. It is a larger value for areas with low infiltration and high runoff and lower for permeable land. It is important for flood control, channel construction and for possible flood zone hazard delineation. A high runoff coefficient (C) value may indicate flash flooding areas during storms as water moves fast overland on its way to a river channel or a valley flow. For model calibration, the runoff coefficient as a parameter was adjusted where it is necessary (Wijesekera & Rajapakse, 2013).

Runoff is governed by many factors in addition to rainfall. It is long known that land use, soil type and slope are the primary catchment characteristics that govern runoff and hence runoff coefficient (De Smedt et al, 2000) quoted by Perera and Wijesekera (2011).

Determining runoff coefficient and its variation with the major parameters is important for water resources assessments giving due consideration to the soil, slope and land use variations (Perera & Wijesekera, 2011). In their study, the runoff coefficients were optimized using Mean Ratio of Absolute Error (MRAE) to indicate the degree of matching of observed and simulated streamflow hydrographs. Model evaluations for mathematical

model of flood mitigation were done using the Mean Relative Absolute Error (MRAE) and the Nash Sutcliffe model efficiency coefficient, and coefficient of correlation (Wijesekera & Rajapakse, 2013).

2.5.2 Baseflow contribution to streamflow

In many hydrograph analyses, a relationship between the surface flow hydrograph and the effective rainfall (rainfall minus losses) is sought to be established. The surface flow hydrograph is obtained from the total storm hydrograph by separating the quick response flow from the slow response runoff (Subramanya, 2014). It is usual to consider the interflow as a part of the surface flow in view of its quick response. Thus, only the base flow is to be deducted from the total storm hydrograph to obtain the surface flow hydrograph. Detailed knowledge of groundwater contribution to streams, i.e., base flow, is important in water resources assessment areas (Szilagyi, 2004).

Modeling at finer time scale (monthly and daily) requires the inclusion of soil moisture dynamics to accurately estimate the water balance (Tekleab et al., 2011).

The baseflow recession constant is a non-dimensional parameter which describes the rate at which streamflow decreases when the stream channel is recharged by groundwater. The precision of estimates of hydrograph recession constants depend heavily upon assumptions regarding the structure of the model errors (Kroll & Vogel, 1996). Baseflow recession constants are used routinely for modeling surface runoff (Bates and Davies, 1988) and for constructing unit hydrographs by separating the baseflow component of streamflow from the total streamflow to obtain direct runoff.

Tallaksen (1995) reviews the application of base flow recession constants for forecasting low flows. Estimates of hydrograph recession constants are required for the calibration of rainfall-runoff models (Kelman, 1980). Demuth and Hagemann (1994) stated that the models which relate low flow statistics to basin characteristics can be significantly improved by using the baseflow recession constant as one of the independent basin parameters in modelling catchment response.

In another study, the event rainfall and runoff were estimated from the observations through a combination of baseflow separation and storm flow recession analysis, producing a storm flow recession coefficient (Dijk, 2010).

Longobardi et al. (2010) have stated that the slow contribution to stream flow is mainly represented by baseflow and deep subsurface flow, whereas the fast contribution is mainly represented by shallow subsurface flow and surface flow. In very humid areas, the coefficient of variation of base flow is low and in arid areas the base flow coefficient of variation is very high and the goodness of fit is poor because of many events that occur with dry antecedent conditions, possibly generated by the infiltration excess mechanism.

2.6 Data Length for Modelling

A data length of 10 years is necessary and sufficient for a reliable calibration of monthly water balance models of humid basins (Xu & Vandewiele, 1994).

Munyanneza et al. (2014) have developed a catchment hydrological model for 257.4 km² catchment by using semi-distributed hydrological model with its soil moisture accounting, unit hydrograph, linear reservoir (for baseflow) and Muskingum–Cunge (river routing) methods. In their study, rainfall data from 12 stations and streamflow data from 5 stations were collected over a period of 2 years (May 2009 to June 2011). The catchment was divided into five sub-catchments and the model parameters were calibrated separately using the observed streamflow data. Calibration results were acceptable at four stations with a Nash–Sutcliffe model efficiency index of 0.65 on daily runoff at the catchment outlet as simulated.

Sampath et al. (2014) have simulated the inflows to Deduru Oya reservoir by using thirty years daily rainfall data from 6 rain gauge stations in the basin and runoff data from 1984 to 1989 together with monthly evaporation.

Tekleab et al. (2011) have calibrated twenty large catchments of the Blue Nile at Kessie Bridge station and the Ethiopian - Sudanese border using data from 1995 - 2000, and validated with data sets from 2000 - 2004 and the model has produced reasonable good performance with a Nash and Sutcliffe efficiency of (ENS) 0.70 and a root mean squared error of 177 mm/yr.

A decade model would also be good enough to study the water availability of a river flow for irrigation diversion and to study the soil water evolution in a soil, to manage crop water requirements (Moreda, 1999).

Vandewiele and Elias (1994) have calibrated the monthly water balance of ungauged catchment obtained by geographical regionalization using ten years rainfall data and found that 10 years data to be a minimum for a reliable calibration.

Knapp et al. (1991) have stated that according to McPherson and Zuidema (1977), the hydrological data record period should be at least ten years to support the flood frequency analysis.

2.7 Objective Functions for Parameter Optimization

The objective function is defined as an equation that is used to compute a numerical measure of the deviation between the model calculated output and the observed catchment output (Moreda, 1999).

Rainfall-runoff models generally have a large number of parameters which are not directly measurable and must, therefore, be estimated through model calibration, i.e. by fitting the simulated outputs of the model to the observed outputs of the catchment. Abdulla and Badranih (2009) stated that optimization methods are used to calibrate the conceptual rainfall-runoff models by finding the values for the model parameters that minimize or maximize the appropriate specific calibration criterion.

2.7.1 Nash-Sutcliffe Coefficient (NSC)

Munyanneza et al. (2014) have stated that NSC is used to assess the agreement between observations and simulations. Nash-Sutcliffe Coefficient indicates how well the plot of observed versus simulated data fits the 1:1 line. The NSE ranges between $-\infty$ and 1.0 (inclusive of 1), with NSE = 1.0 being the optimal value. Closer the value of NSC to unity, the better the model explains the variance (Moreda, 1999).

Values between 0.0 and 1.0 are generally viewed as acceptable levels of performance, whereas values <0.0 indicates that the mean observed value is a better predictor than the simulated value, which indicates unacceptable performance (Nash and Sutcliffe, 1970) quoted by (Moriassi et al., 2007).

Perrin et al. (2006) have stated that when NSC is equal to zero means that the model is not better than basic one parameter and negative value indicates that the model is worse than

the basic parameter. The NSC is computed by using Equation (1), where Q_{obs} = observed discharge, Q_{sim} = simulated discharge and Q_{mean} = mean of simulated discharge.

$$NSC = 1 - \frac{\sum(Q_{obs} - Q_{sim})^2}{\sum(Q_{obs} - Q_{mean})^2}$$

.....Equation (1)

Moriasi et al. (2007) have stated that NSE was recommended for two major reasons: (1) it is recommended for use by ASCE (1993) and Legates and McCabe (1999), and (2) it is very commonly used, which provides extensive information on reported values. Sevat and Dezetter (1991) also found NSE to be the best objective function for reflecting the overall fit of a hydrograph (Moriasi et al., 2007).

2.7.2 Root Mean Square Error (RMSE)

The Root Mean Square Error (RMSE) is one of the commonly used error index statistics (Chu and Shirmohammadi, 2004; Singh et al., 2004; Vasquez-Amábile and Engel, 2005) quoted by Moriasi et al. (2007). It is commonly accepted that the lower the RMSE the better the model performance.

2.7.3 Mean Ratio of Absolute Error (MRAE)

The Mean Ratio of Absolute Error (MRAE) is computed using Equation (2).

$$MRAE = \frac{\sum \frac{ABS(Q_{obs} - Q_{sim})}{Q_{obs}} \times 100}{n}$$

..... Equation (2)

Where O_{bs} = observed discharge, Q_{sim} = simulated discharge and n = number of observations. The MRAE indicates the degree of matching of calculated and observed streamflow hydrographs. Wijesekera (2000) has used this MRAE as an objective function for the parameter optimization for monthly water balance modeling of Gin Ganga watershed. The objective function MRAE was also used by Perera and Wijesekera (2011) to compare calculated and observed streamflow of three wet zone basins of Sri Lanka.

2.8 Model Calibration and Validation

Knapp et al. (1991) have stated that Dendrou (1982) has identified calibration, validation, and verification as the three crucial steps for the proper application of a model. Calibration is the process of optimizing or systematically adjusting parameter values to get a set of parameters which provides the best estimate of the observed streamflow.

Tekleab et al. (2011) have stated that main objective of calibration (and validation) is finding the optimal parameter set that maximizes or minimizes the objective function for the intended purposes.

The successful application of the hydrologic watershed model depends upon how well the model is calibrated which in turn depends on the technical capability of the hydrological model as well as the quality of the input data (Choudhari et al., 2014).

According to Refsgaard (1997), model validation is the process of demonstrating that a given site-specific model is capable of making “sufficiently accurate” simulations, although “sufficiently accurate” can vary based on project goals. Model verification investigates the range of conditions over which the model will produce acceptable results.

An accurate simulation of the rainfall-runoff process can play a significant role in urban and environmental planning, land use, flood and water resources management of a watershed as well as mitigation of drought impacts on water resources systems (Saeidifarzad et al., 2014). Most of the rainfall-runoff models still rely on calibration to achieve an accurate representation of the hydrology model (Urbonas & Wre, 2007).

2.9 Error in a Model

Differences between observations and simulated model response are basically caused by four different error sources (Refsgaard and Storm, 1996) quoted by (Madsen, 2000). The four types of error in model is due to; (1) errors in meteorological input data, (2) errors in recorded observations, (3) errors and simplifications inherent in the model structure and (4) errors due to the use of non-optimal parameter values.

2.10 Statistical Tests for Model Performance Evaluation

Each of the objective functions can serve as a measure of performance of any given model as the single objective function is inadequate to serve as a universal tool for the optimization of hydrologic model (Diskin & Simon, 1977).

Moriasi et al. (2007) have stated that there is no comprehensive guidance available to facilitate model evaluation in terms of the accuracy of simulated data compared to measured flow and constituent values. It is a necessary process to identify key parameters and parameter precision required for calibration (Ma et al., 2000) quoted by Moriasi et al. (2007). According to the U.S. EPA (2002), the process used to accept, reject, or qualify model results should be established and documented before beginning model evaluation.

Coefficient of determination (R^2) describes the degree of co-linearity between simulated and measured data. It describes the proportion of the variance in measured data explained by the model. The R^2 ranges from 0 to 1, with higher values indicating less error variance, and typically values greater than 0.5 are considered acceptable (Santhi et al., 2001, Van Liew et al., 2003) quoted by Moriasi et al. (2007).

The mean absolute error (MAE), mean square error (MSE), and root mean square error (RMSE) indices are valuable because they indicate error in the units of the constituent of interest, which aids in analysis of the results. The RMSE, MAE, and MSE values of 0 indicate a perfect fit. RMSE and MAE values less than half the standard deviation of the measured data may be considered low and that either is appropriate for model evaluation (Singh et al., 2004) quoted by Moriasi et al. (2007).

A feature of errors from a conceptual rainfall-runoff model is that there is a tendency for errors to persist so that sequences of positive errors (underestimation) or negative errors (overestimation) are common (Nawaz & Adedoye, 1999).

The percent exceedance probability curve illustrates how well the model reproduces the frequency of measured flows throughout the calibration and validation periods (Van Liew et al., 2007) quoted by Moriasi et al. (2007).

2.11 Uses of Rainfall-Runoff Model

The monthly water balance models have been widely employed for the conversion of rainfall into runoff. Generally, the monthly water balance models are mainly applied in three

fields; (1) reconstruction of the hydrology of catchments, (2) assessment of climate change impacts, and evaluation of seasonal geographical patterns of water supply and irrigation demand (Xu and Singh, 1998) quoted by Perrin et al. (2006).

Rainfall-runoff modeling can be used for a variety of purposes. A common use is for design purposes when complete hydrographs are needed and peak discharge values alone are insufficient. The use of relatively simple rainfall-runoff models has become common over the years for designing detention storage or for design projects in medium to large watersheds where channel and floodplain storage are important factors in evaluating the flood hydrograph (Pilgrim, 1986) quoted by Knapp et al. (1991).

Conceptual runoff models are frequently used as tools for a wide range of tasks to compensate the lack of measurements as the conceptual runoff models are practical tools, especially if the reliability in their predictions can be assessed (Seibert, 1999).

2.12 Effect of Upstream Reservoir on Downstream Basin

The reservoirs can be used to supply drinking water, generate hydroelectric power, increase the water supply for irrigation, provide recreational opportunities, control the downstream floods and improve certain aspects of the environment. Wijesekera, (2001) has stated that water balance of a reservoir can easily identify the fluctuations of reservoir storage through the fluctuations of inflow to the reservoir, seepage from the reservoir, evaporation and water extractions for purposes such as cultivation.

The Yesa reservoir with 74 m high dam, with original capacity of 450 hm³, maximum capacity for a flood of 2240 m³/s and basin of 2,181 km² in Spain is filled from October to May-June and then releases large quantities of water in the summer via canal, and as a result the frequency of floods downstream of the dam is decreased. The reduction mainly depends on two factors: i) the water storage level, and ii) the season of the year. According to Moreno et al., (2002) the floods are very well controlled when the reservoir level is lower than 50% and when it is between 50% and 70%, only the highest floods are controlled.

To overcome the water related problems, extensive care should be given to the operation and management of reservoirs and watersheds (Choudhari et al., 2014). The poor land use planning and land management practices during rapid development have adversely impacted the surface runoff quantities and quality through the reduction of land cover,

deterioration of river water quality and an increase of impervious surface area. A major challenge still remaining is the accurate prediction of catchment runoff responses to rainfall events (McCull and Aggett, 2006) quoted by Choudhari et al. (2014). Enlargement of reservoir capacity implies further changes in the flow pattern and subsequent changes in erosion, deposition and sediment transport to the downstream (Moreno et al., 2002).

According to Moreno et al. (2002), the effects of the reservoir on floods can be studied: i) by comparing the daily measurements before and after the construction of the reservoir, or (ii) by comparing the daily data between the inflow and outflow series (since the construction of the reservoir). The first option does not avoid the problem of medium term climatic trends, while the second can be used to compare the information upstream and downstream of the reservoir using the same time series in consideration.

To assess the effects of the reservoir in controlling floods, the return periods of floods have been calculated by adjusting the Partial Duration Series over the 97 percentile to a General Pareto Distribution (Madsen et al., 1997) quoted by Moreno et al. (2002). Upstream rainfall variability and flow abstraction for irrigation are key parameters in understanding low flows in rivers (Smakhtin, 2001; Smakhtin *et al.*, 2006) quoted by Vanoel et al. (2008).

Wijsekera (2001) has developed a monthly water balance model for Lunugamvehera reservoir (with a drainage area of 749 km²) using data period from 1990-1994 for streamflow, pan evaporation (average of 4.5 mm/day) and water release from the reservoir. In this case, reservoir water release fluctuations have not shown uniformity in the pattern except a vague presentation of peak and lean water release periods. The water release during Maha (October-March) and Yala (April-September) season were 90,750 and 65,000 ac.ft., respectively. The model has provided a near perfect match for the months of 1992 November, 1993 October and 1993 December showing a discrepancy.

2.13 Seasonal Rainfall in Deduru Oya Catchment

Dantanarayana et al. (2013) have noted that Deduru Oya basin in Sri Lanka receives about 50% of the annual rainfall during inter monsoon months (March, April, October and November), about 35% during Southwest monsoon months (May to September), while remaining 15% during Northwest monsoon months (December to February).

Sampath, Weerakoon and Herath (2015) have studied that the rainfall is the only source of water and there are no trans-basin diversions into or out of the Deduru Oya Basin at present.

The rainfall in the basin has a significant temporal and spatial variation. Annual rainfall ranges from 2600 mm in the upper basin to 1100 mm in the lower basin. The Deduru Oya carries flash floods during rainy season and very low flow during dry season. Presently nearly 1000 MCM of water flows to sea annually from the basin.

2.14 Flood Control Measures

From flood forecasting point of view, the decision makers need rainfall-runoff models and a flood forecasting software system (Shengyang, 2013). Climate change could be in future lead to more severe and extreme flood events (Trenberth K., 2005) quoted by Shengyang, (2013). According to the 2007 report of the United Nations Intergovernmental Panel on Climate Change (IPCC), “the frequency of heavy precipitation events has increased over most land areas”. It is likely that up to 20% of the world population will live in areas where river flood potential would increase significantly by the 2080 (IPCC, 2007).

In multi-reservoir operation, the reservoir routing for just one single reservoir flow regulation is done by calculating the mass balance of all the reservoirs in-pool water storage. Generally, for the real-time flood control and management, it is required to follow the strategy and plans, the annual strategy, which have been made before flood season comes according to design and historical floods.

2.15 Flood Issues in Deduru Oya Basin

By 17th December, 2012, due to flood and landslides caused by continuous heavy rainfall in upstream and downstream of Deduru Oya, more than 300,000 were affected. In the north-western province, Deduru Oya River overflowed, severely affecting the Kurunegala and Puttalam districts. The town of Chilaw was under water for several days and at least three people died in the area. The most affected villages were Wattakakaliya, Savarana, Nariyagama, Thisogama, Manuwangama, and Jayabima.

According to records in Ministry of Disaster Management, Sri Lanka, the flood had caused damage to numerous structures situated within the floodplain, including buildings, roads, utilities, machineries and electronics, including industry and communication equipment, food stocks, cultural artifacts, fields and lives of people. An overflowing Deduru Oya in November 2012 has displaced 2,811 families; 13,840 men, women and children in the Chilaw, Mahawewa, Arachchikattuwa and Pallama areas.

3 METHODOLOGY

The methodology developed, following the problem identification and literature review, to carry out the study is schematically shown in the Figure 3.1.

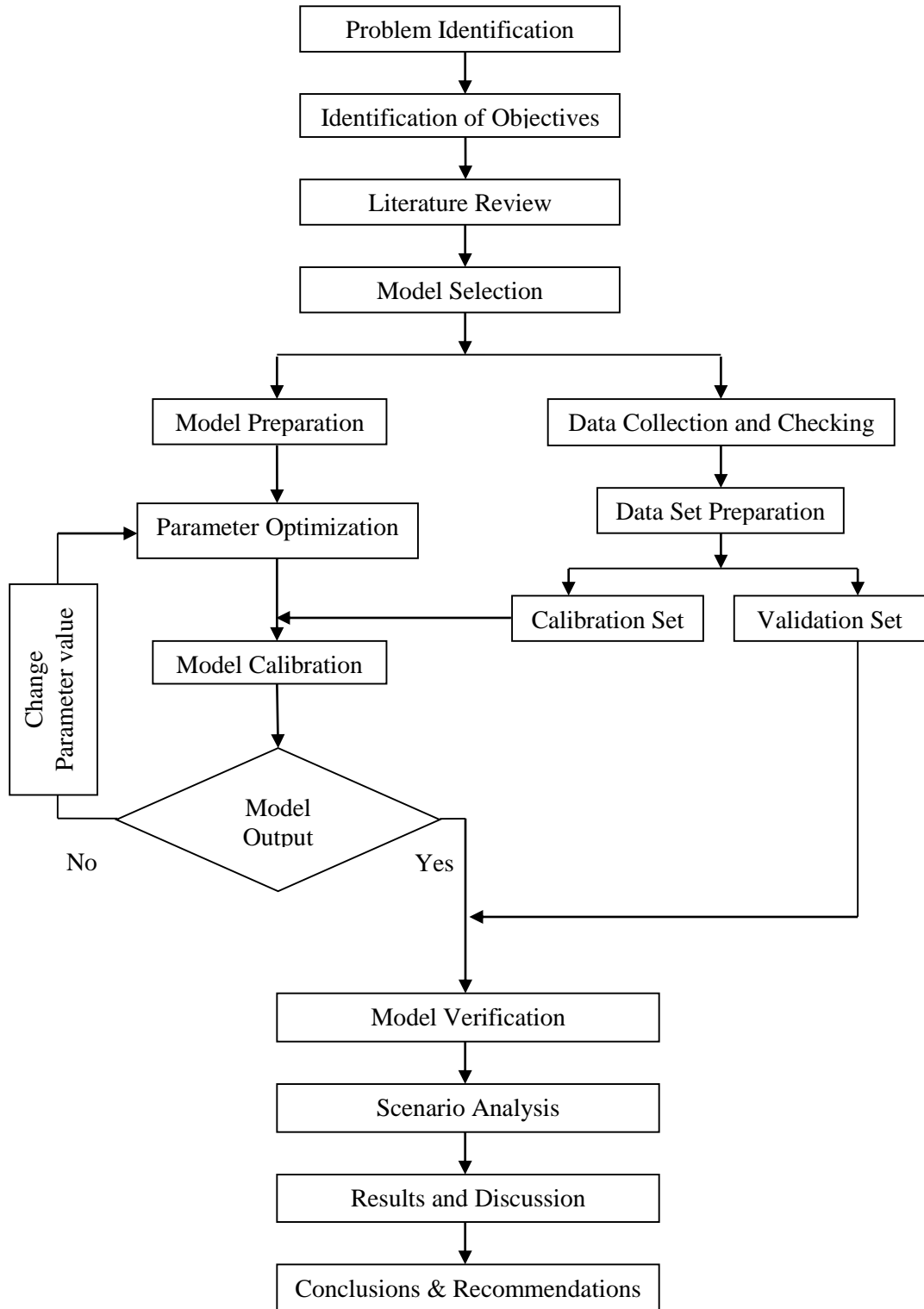


Figure 3.1: Methodology flowchart for the study

3.1 General

The problem and objectives of the study were identified and the literature review was carried out to select the type of hydrological model and related literature supports to perform the required computations and analyses to achieve the objectives of the study. The hydrological data collected were the monthly rainfall and streamflow whose gauging stations were located within the catchment boundary. The missing data were identified and rectified and the data sets were compiled for calibration and validation purpose. All the three parameters used in the model were optimized based on trial and error method using Mean Ratio of Absolute Error (MRAE) and Nash-Sutcliffe Coefficient (NSC) as error estimates. According to the value of optimized parameters, calibration and validation was carried out and the model was used for subsequent analyses.

Simultaneously, the model output was examined and cross checked to ensure whether it is satisfactory or not. In case the model output was not satisfactory, the parameter values were changed until the results were satisfactory and then the verification was done using the pre-processed validation data set. Based on model results, the scenario analyses were carried out and conclusions and recommendations for the model were derived based on these results and the results of the scenario analyses accordingly.

3.2 Model Concept

Based on water balance concept, a rainfall-runoff model was framed where the inflows into an imaginary reservoir are the baseflow (slow and quick flow), direct rainfall and catchment runoff. At the same time, the outflows (losses) from the reservoir are evaporation, evapotranspiration, seepage and discharge through sluices and spillway.

The final discharge was simulated at the outlet of reservoir by taking into the account of cumulative discharges from the sluices and spillway, and it was compared with the observed discharges by optimizing the three parameters; runoff coefficient, initial discharge (slow baseflow) and baseflow contribution coefficient for quick baseflow. The Mean Ratio of Absolute Error and Nash-Sutcliffe Coefficient were used as objective functions to compute the model error. The model calibration was carried out for the dataset from 1990 to 2001, and then verified the model using same optimized parameter values for the dataset from 2002 to 2013.

3.3 Spreadsheet Model for Model Computation

A spreadsheet model was framed for the rainfall-runoff model computation. This spreadsheet computes calculation in three major steps as follows;

- i. Inflow computation
- ii. Outflow computation
- iii. Final discharge simulation

The simulated discharge was applied to both calibration and validation with observed streamflow dataset to check an agreement with observed discharge by using three parameters; runoff coefficient, baseflow contribution coefficient for rapid baseflow and an initial discharge (slow baseflow).

3.4 Catchment Geometric Parameters

The catchment parameters required for the model computations are; (i) area of the whole catchment and sub-catchment(s), (ii) location of an imaginary reservoir (iii) stream gauging station, (iv) pan evaporation station and (v) rainfall stations. These parameters were computed using Geographic Information System (GIS) and shape files.

3.5 Schematic of Reservoir Water Balance Components

The Figure 3.2 shows the schematic diagram of the reservoir water balance approach which consist of direct rainfall, runoff from the catchment and baseflow contribution as inflows to the reservoir. The outflows from the reservoir are evaporation, evapotranspiration, seepage, spill discharge and the water issue for various uses such as irrigation, industry purposes, domestic usage, etc.

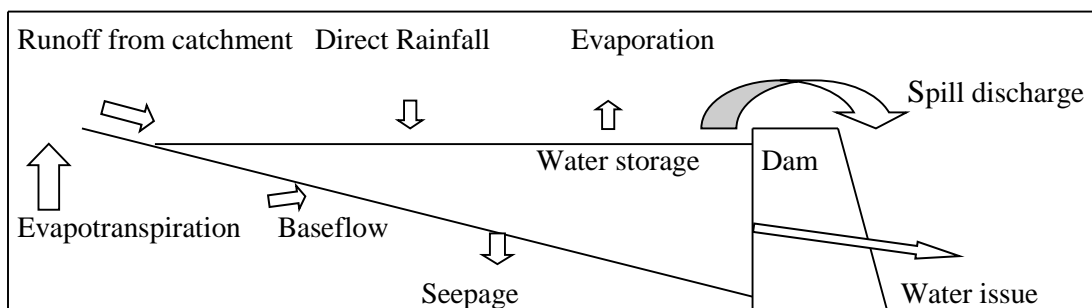


Figure 3.2: Schematic of reservoir water balance components

The water balance equation used for the reservoir water balance operation is represented as shown in the Equation (3)

$$I - O = \Delta S \dots \dots \dots \text{Equation (3)}$$

Where I is inflow to the reservoir (catchment) and it consists of:

- i. Runoff from the catchment
- ii. Direct rainfall to reservoir
- iii. Baseflow contribution

O is an outflow from the reservoir and it consists of:

- i. Evaporation from water surface
- ii. Seepage through reservoir bed
- iii. Evapotranspiration from plants and trees
- iv. Spill discharge over the dam
- v. Water issue for various uses

ΔS is the change in water storage in the reservoir when there is a difference in inflows and outflows of the reservoir.

3.6 Model Structure

The structure of the rainfall-runoff modeling using three parameters was discussed separately as mentioned below:

3.6.1 Hypothetical water reservoir

In order to simulate the water discharge at the outlet of a basin, an imaginary reservoir cumulatively representing all depression and other minor storages in the basin was assumed at the outlet of the catchment with 120 m dam spill length, 3 m dam spill height, 1 m sluice sill level with 2 numbers of sluices with 2 m depth and 1.5 m width. Accordingly, the depth-area-capacity values were adopted as shown in the Table 3.1 and then an area capacity diagram was developed as depicted in the Figure 3.3 for the reservoir water balance system.

An understanding of the magnitude of the dynamics of reservoir water balance is important to compare the observed discharge with simulated discharge.

Table 3.1: Depth - area - capacity of the reservoir

Index	Depth (m)	Area (m ²)	Volume (m ³)	Capacity (m ³)
1	0.0	0	0	0
2	0.5	12000	3000	3000
3	1.0	30000	10500	13500
4	1.5	84000	28500	42000
5	2.0	150000	58500	100500
6	2.5	204000	88500	189000
7	3.0	288000	123000	312000
8	3.5	384000	168000	480000
9	4.0	504000	222000	702000
10	4.5	660000	291000	993000
11	5.0	900000	390000	1383000
12	5.5	1500000	600000	1983000

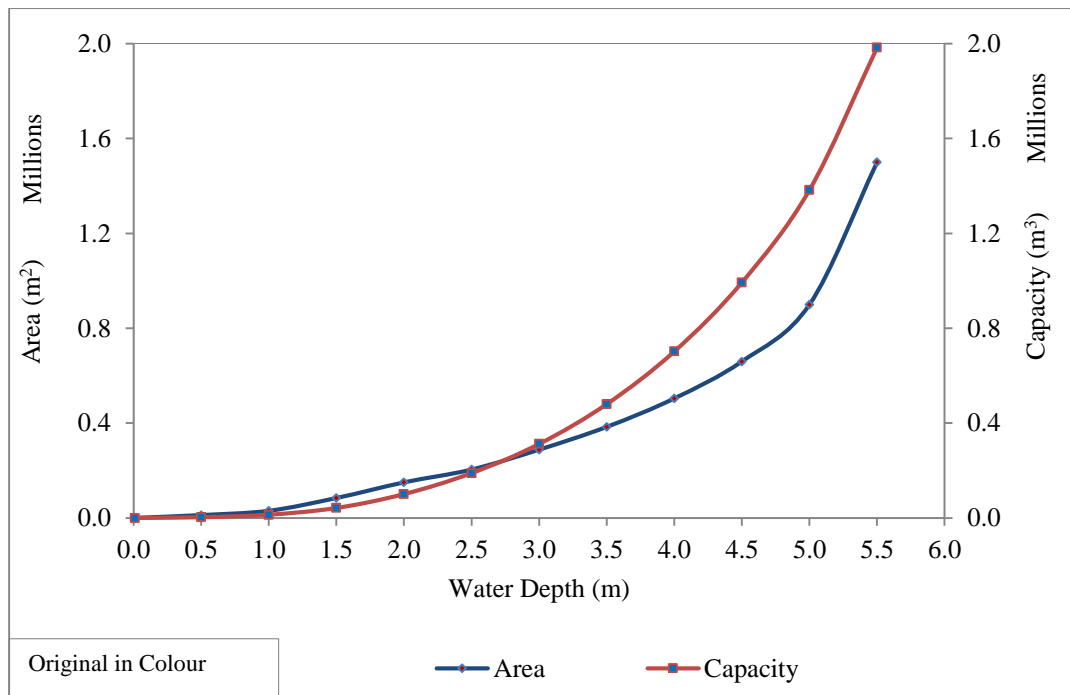


Figure 3.3: Area capacity diagram of reservoir

3.6.2 Inflows to the reservoir

i. Runoff calculation in the reservoir

According to the equation developed to calculate the runoff volume, Equation (4) was used for calculating the volume of runoff that adds to the reservoir.

$$\text{Volume of runoff} = \text{Area of catchment} \times \text{Runoff Coefficient} \times \text{Rainfall Depth} \dots\dots\dots \text{Equation (4)}$$

ii. Baseflow contribution to streamflow

The hydrograph recession constants are required for forecasting low flows, hydrograph analysis, low flow frequency analysis and for the calibration of rainfall-runoff models (Kroll & Vogel, 1996). Riggs (1961), Bingham (1986), Vogel and Kroll (1992), Demuth and Hagemann (1994) have stated that the rainfall-runoff models which relate low flow statistics to basin characteristics can be significantly improved by using the baseflow recession constant as one of the independent basin parameter. In case of subsurface runoff, it has included the groundwater contribution to the channel system as rapid groundwater flow in the upper part of initially unsaturated subsurface and as delayed groundwater flow in the lower part of the saturated subsurface. The water that percolates to the groundwater moves at much slower velocities and reaches the stream over longer periods of time such as weeks and month (Beven, 2000). Total streamflow to the channel includes the baseflow existing in the basin prior to the storm and the runoff due to the given storm precipitation. Therefore, the cumulative streamflow consists of both surface runoff and subsurface runoff in the catchment.

For the model, delayed groundwater was used as one of the three parameters called Initial Discharge. This parameter can be optimized with other two parameters simultaneously based on trial and error method targeting to get same pattern of simulated and observed discharge. The value of Initial Discharge was cross checked with field visit knowledge (Fig. 3.4) by using the Equation (5) and this value can be taken as constant throughout the model.

$$Q = A \times V \dots\dots\dots \text{Equation (5)}$$

Where;

Q is Initial discharge (m^3/month).

A is average cross sectional area perpendicular to the streamflow (m^2).

V is and average velocity of stream flow (m/s).

On the other hand, the rapid groundwater contributing to streamflow can be calculated by adding the surface runoff of previous and present month where sum of these two runoff can be multiplied by a parameter called Baseflow Contribution Coefficient. Equation (6) is to be used to calculate the rapid groundwater flow.

$$\text{Rapid groundwater flow} = \text{BCC} * (\text{Previous} + \text{Present month runoff})$$

.....Equation (6)

Where BCC is Baseflow Contribution Coefficient.

Therefore, total volume of baseflow contributing to streamflow can be obtained by adding the rapid and delayed groundwater flow.

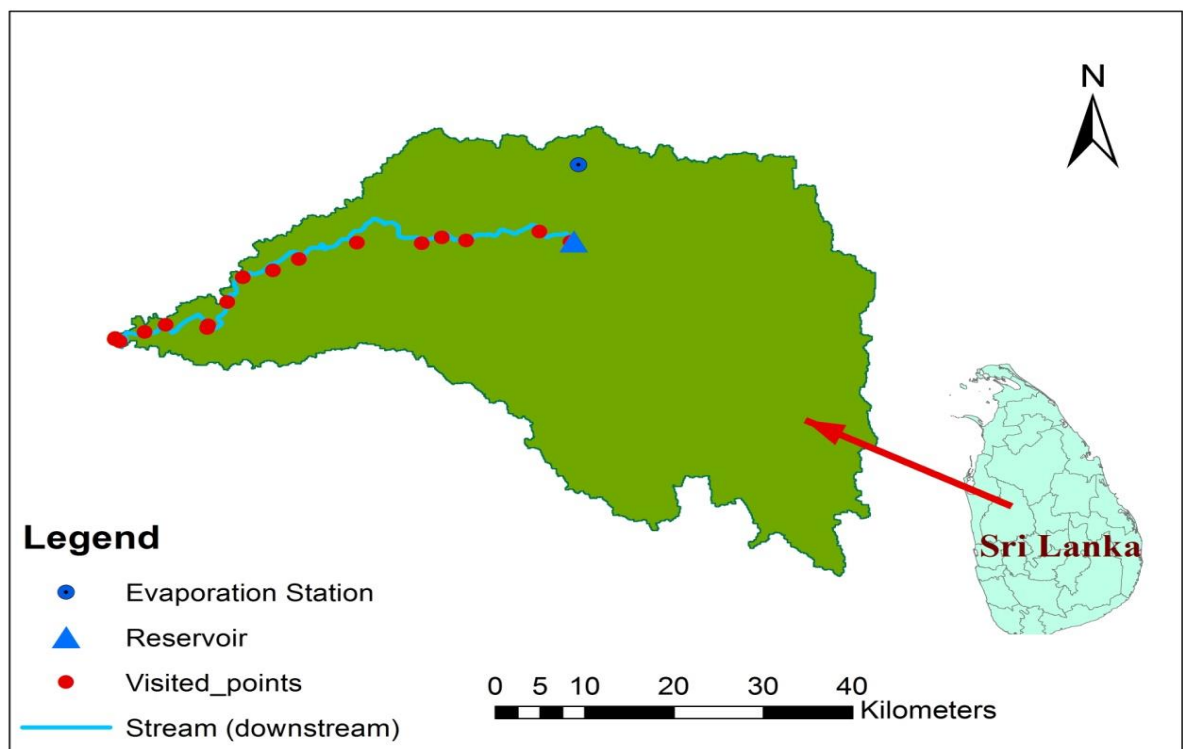


Figure 3.4: Visited points in downstream of Deduru Oya basin

3.6.3 Outflows from the reservoir

i. Evaporation

Evaporation loss can be calculated based on the reservoir area by interpolating the depth-area-capacity curve of reservoir. The reduction of reservoir water due to evaporation can be computed using Equation (7) according to Jayatilaka et al. (2001).

$$EV = PE \times RA \text{.....Equation (7)}$$

Where;

EV is evaporation (m³/month).

EP is measured pan evaporation (m/month).

RA is reservoir water surface area (m²).

ii. Seepage through reservoir bed

The seepage of water through the reservoir bed represents a significant component of the reservoir water reduction. The seepage has been assumed as a percentage of the water stored in the reservoir (Jayatilaka et al., 2001). The monthly seepage from the reservoir has been taken as 0.5 percent of the reservoir water volume according to the manual on the design of irrigation headworks for small catchments in Sri Lanka (Ponrajah, 1984).

iii. Evapotranspiration

Evaporation (EP) corresponds to the combination of evaporation and transpiration of moisture from the land phase to the atmospheric phase. They are the most important losses in the hydrological cycle and therefore, it is considered as a significant factor in rainfall-runoff modeling. Correlations have been developed between pan evaporation and evapotranspiration (Penman, 1948) as shown by the Equation (8).

$$ET = f_p \times EP \dots \dots \dots \text{Equation (8)}$$

Where f_p is a coefficient taken as 0.8 according to Ponrajah (1984).

3.6.4 Water storage in reservoir

Monthly water storage in the reservoir can be computed using Equation (9).

$$\text{Inflow (Initial storage + Runoff + Initial discharge of stream + Baseflow) - Outflow (Evaporation + Evapotranspiration + Seepage) = Change in Storage} \dots \dots \dots \text{Equation (9)}$$

The initial storage for commencing the model runs can be taken equal to minimum operation level of the reservoir.

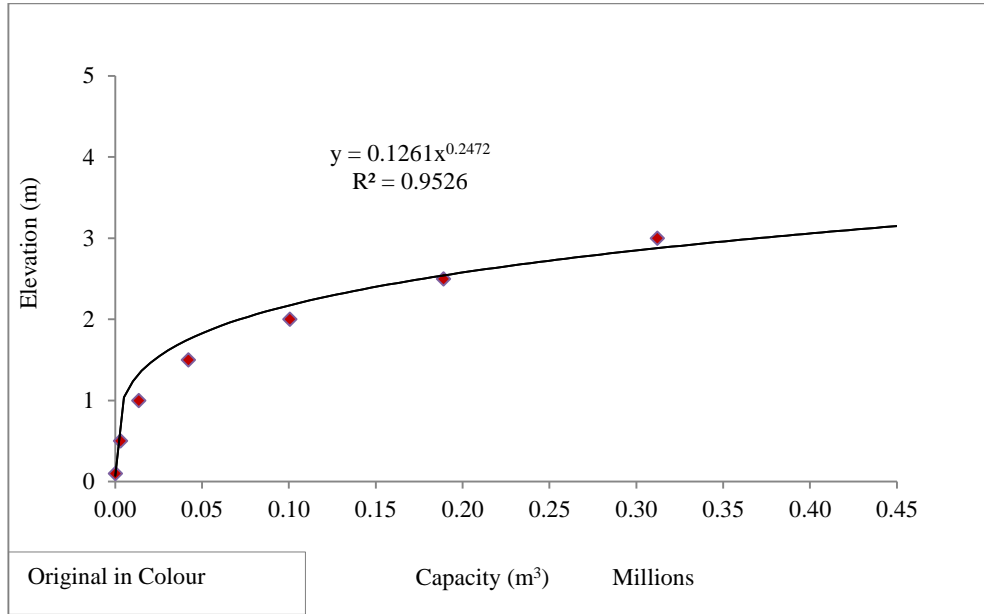


Figure 3.5: Water elevation and reservoir capacity

The overall depth of water (inclusive of water height in the reservoir and spillage) can be calculated using Equation (10), which was obtained from the water elevation corresponding to its capacity curve as shown in the Figure 3.5.

$$Y = 0.1261X^{0.2472} \dots\dots\dots\text{Equation (10)}$$

Where;

Y is the depth of water (m).

X is the operational storage in the reservoir (m³).

3.6.5 Discharge through reservoir sluices

The water is discharged (m³/month) through two numbers of sluices and its quantity can be calculated using Equation (11).

$$Q = C_d \times A\sqrt{(2gh)}\dots\dots\dots\text{Equation (11)}$$

Where;

Q is discharge through sluice (m³/month).

C_d is coefficient of discharge; the value of C_d was taken as 0.6 according to recommendation by Jayakody, Mowjood, & Gunawardena (2004) and Ponrajah (1984).

A is area of opening of sluice (3 m²).

g is acceleration due to gravity (9.81 m/s²).

h is head loss across sluice (m).

3.6.6 Discharge through reservoir spillway

Monthly spillway discharge (m³/month) can be calculated using Equation (12) according to Ponrajah (1984).

$$Q = C_d \times L \times H^{3/2} \dots\dots\dots \text{Equation (12)}$$

Where;

Q is spillway discharge (m³/month).

C_d is coefficient of discharge, the value of C_d was taken as 2.8 for broad crested weir.

L is length of the spill (120 m).

H is spill afflux height (3 m).

3.6.7 Simulated discharge from the reservoir outlet

The total simulated discharge will be taken as the sum of discharge through sluices and spillway when entire basin is considered and for an upstream sub-catchment, it is the sum of spillage and 20% of total water issued through upstream sluices which is accounted as a return flow to the downstream according to Ponrajah (1984). These monthly simulated discharges will be based on optimized value of three parameters and then it is use for comparing with the observed discharges.

4 DATA COLLECTION AND DATA CHECKING

4.1 Study Area

Deduru Oya basin has area of 2597.76 km², out of which 93.34% lies in Kurunegala, and 2.52%, 2.36%, 1.74%, 0.04% and 0.01% in Kandy, Puttalam, Matale, Kegalle and Anuradhapura districts, respectively (Fig. 4.1). The basin topography varies from the coastal flat plains on the western boundary to the hilly regions on its eastern boundary (elevation 980 m MSL). The length of main river channel is approximately 115 km. Annual discharge of river is more than 1000 MCM. About 90% of the catchment area comes under intermediate zone and rest of the areas in mountainous region which falls under mid country wet zone.

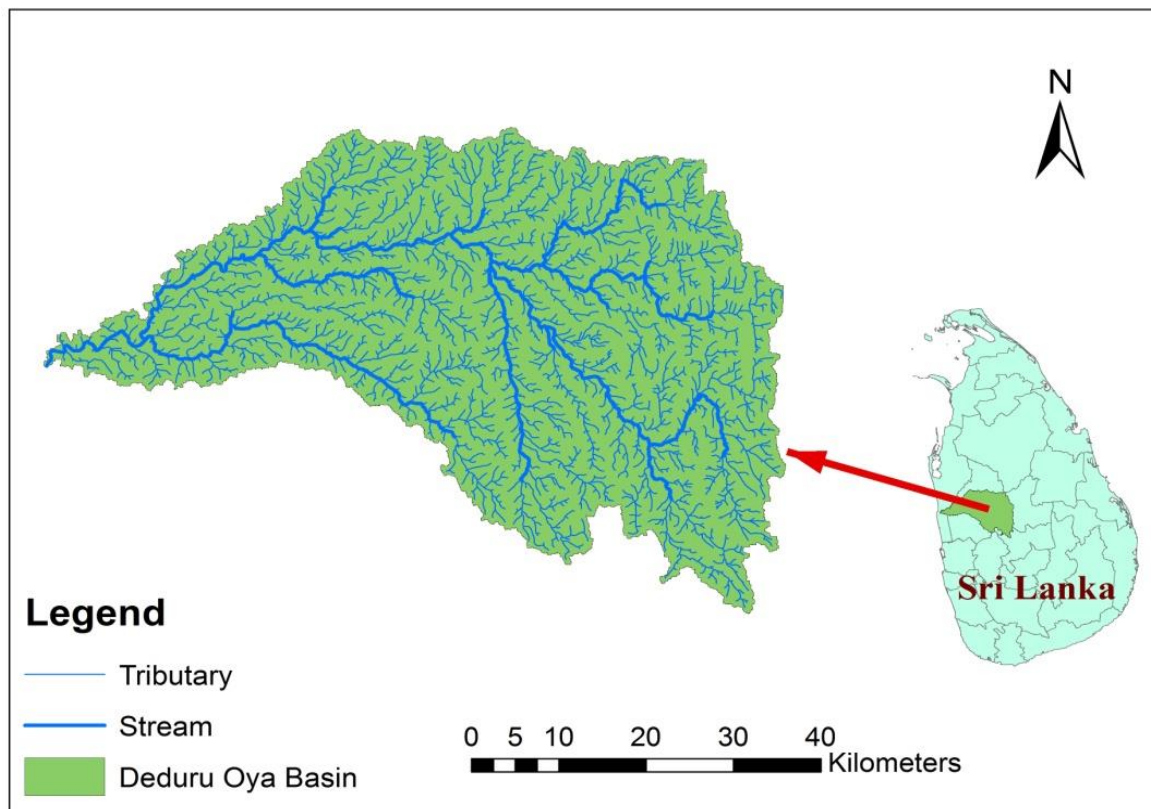


Figure 4.1: Study area map of Deduru Oya basin

The Geographic Information System (GIS) data for the basin selected for the research was collected from the Department of Survey, Sri Lanka. The boundary demarcation and the sub-catchments were checked by using contour/terrain data which are available in 1:50,000 topographic sheets with an elevation interval of 10 m. The stream networks were also identified using same scale map. The parameters of basin and sub-catchments such as

catchment and sub-catchment area, length of streams and slope were subsequently determined using Geographic Information System (GIS). The land use types map (1999 version) within the catchment was collected from same department.

The major tributaries of the Deduru Oya are Ratwila Ela, Dik Oya and Kospothu Oya in the upper reaches of the basin, Kimbulwana Oya, Hakwatuna Oya and Maguru Oya in the middle reaches of the basin which confluence with the upstream and the Kolamunu Oya and Thalagalla Ella meet the river in the downstream reach.

The basin receives about 50% of the annual rainfall during inter monsoon months (March, April, October and November), about 35% during Southwest monsoon months (May to September), while remaining 15% is received during Northwest monsoon months (December to February). The Deduru Oya basin can be affected by flash floods in some periods but also suffer from long periods of low flows with extended droughts (generally February, March, June, July, August and September).

4.2 Data Type, Sources and Resolution

The Department of Meteorology and Hydrology Division under Department of Irrigation, Sri Lanka is managing the data records in the basin for rainfall, streamflow and evaporation. The data available and used for the research study, their resolutions and sources are mentioned in the Table 4.1.

Table 4.1: Data availability and source for rainfall, streamflow and evaporation

Data type	Temporal/spatial resolution	Station name	Data period	Data source
Rainfall	Monthly	Kurunegala	1990 – 2013	Department of Meteorology
		Mahawa		
		Millawana		
		Polontalawa		
Evaporation	Monthly	Wariyapola	1990 – 2013	
		Mahawa		
Streamflow	Monthly	Chilaw	1990 – 2013	Hydrology Division

It is important to be aware of how the data has been collected and what data quality control methods have been applied to the data prior to the provision of the data set as this will influence the modeling results. The accuracy of the model depends upon the quality of input data available. Advances in scientific hydrology and practice of engineering hydrology depend on good, reliable and continuous measurements of hydrological variables. The hydrological data must be free of errors to avoid wrong or poor results of modeling for the decision making.

4.2.1 Rainfall data

The yield of runoff generated in the catchment depends upon the duration and intensity of rainfall occurred in the catchment. The reliable measurements of rainfall are critical for successfully calibrating a rainfall-runoff model to a catchment. The length of rainfall data used is 24 years of monthly from five available stations namely; Kurunegala, Mahawa, Millawana, Polontawala and Wariyapola. All the five stations are provided with the facility of automated recording rain gauges and all lie inside the basin boundary.

4.2.2 Thiessen mean rainfall

The basin is sub divided into five Thiessen areas as shown in the Figure 4.2 based on coverage of rainfall area by each station. According to Thiessen area, Thiessen mean rainfall was calculated and compared with the arithmetic rainfall value. In this model, Thiessen mean rainfall will be used as it gives the coverage of Thiessen area by that particular station. Thiessen weight was calculated by taking the ratio of Thiessen area of each station to the total basin area as depicted in the Table 4.2.

Table 4.2: Thiessen polygon areas and weight for each rain gauge station

Sl. no.	Rain gauging station	Thiessen area (km ²)	Thiessen Weight
1	Kurunegala	592.00	0.22
2	Mahawa	483.76	0.19
3	Milawana	430.69	0.17
4	Polontalawa	502.43	0.19
5	Wariyapola	588.92	0.23

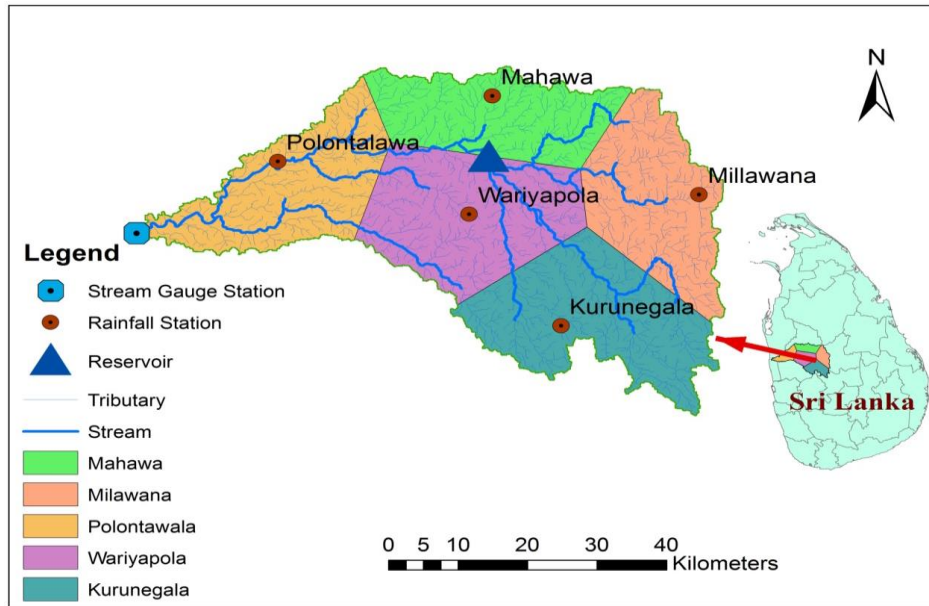


Figure 4.2: Thiessen polygon area map of Deduru Oya basin

Table 4.3: Location of gauging station for rainfall, evaporation and streamflow

Data name	Station name	Coordinate		Location relative to basin boundary
		Latitude	Longitude	
Rainfall	Kurunegala	7.47 N	80.37 E	
	Mahawa	7.75 N	80.42 E	
	Milawana	7.68 N	80.34 E	Inside boundary
	Polontalawa	7.72 N	80.00 E	
	Wariyapola	7.63 N	80.25 E	
Evaporation	Mahawa	7.68 N	80.34 E	Inside boundary
Streamflow	Chilaw	7.60 N	79.81 E	Main outlet of Basin

Table 4.3 shows the spatial distribution of gauging stations along with their location coordinates for five rainfall stations, one evaporation and streamflow station in the basin.

4.2.3 Streamflow

The reliable measurements of streamflow data are critical for successfully calibrating a rainfall-runoff model to a basin. There is only one stream gauge station in the basin having latest data as of 2013 with monthly temporal data resolution. The gauge station at Chilaw is

located at extreme outlet of the basin. The data for the period from 1990 to 2013 was collected and used for the modeling.

4.2.4 Evaporation

The monthly average pan evaporation data was collected from the Department of Meteorology from year 1990 to 2013 for the study. There is only one pan evaporation station available in the basin which is located at Mahawa station.

4.3 Data Checking

It is important to check the data for their accuracy, consistency and reliability before the development of any hydrologic model to ensure the credibility of the results. The monthly rainfall data were checked for consistency and compatibility using graphical/visual examination, and monthly and annual water balance, double mass curve method and statistical checks for homogeneity. The missing monthly rainfall data were calculated by using regression analysis method.

4.3.1 Station density of rainfall and streamflow

The spatial distribution of gauging stations were also checked and compared according to the guidelines of World Meteorological Organization (WMO) as mentioned in the Table 4.4. The rainfall stations are within the permissible limit, but the streamflow station is not within the permissible limit as per WMO standard.

Table 4.4: Station density of rainfall and stream gauging station

Gauge station	Number of station	Station density (km ² /station)	WMO standard (km ² /station)
Rainfall	5.00	519.55	575.00
Streamflow	1.00	2597.76	1875.00

4.3.2 Monthly rainfall and streamflow

The monthly rainfall and streamflow data which are to be used for the rainfall-runoff modeling was checked as follows:

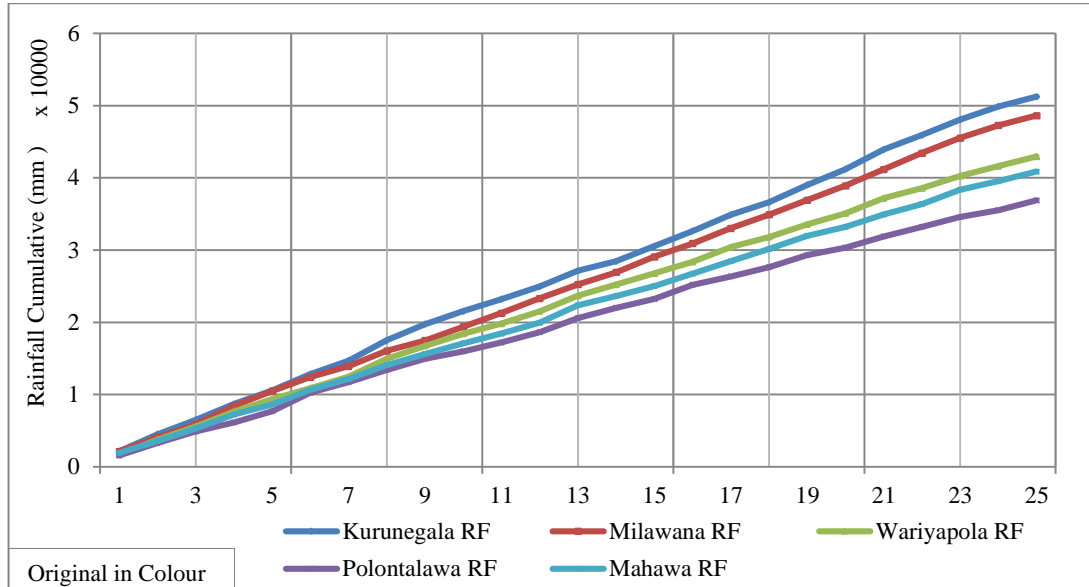


Figure 4.3: Single mass curve for monthly rainfall for year (1990-2013)

The Figure 4.3 shows single mass curve for five rainfall stations where Kurunegala is receiving highest rainfall followed by Millawana, Wariyapola, Mahawa and Polontalawa. There observed to exist small inconsistency in flow for up to about few months of the year in each station. However, in overall the cumulative pattern of rainfall is assumed to be in conformity with the condition for homogeneity.

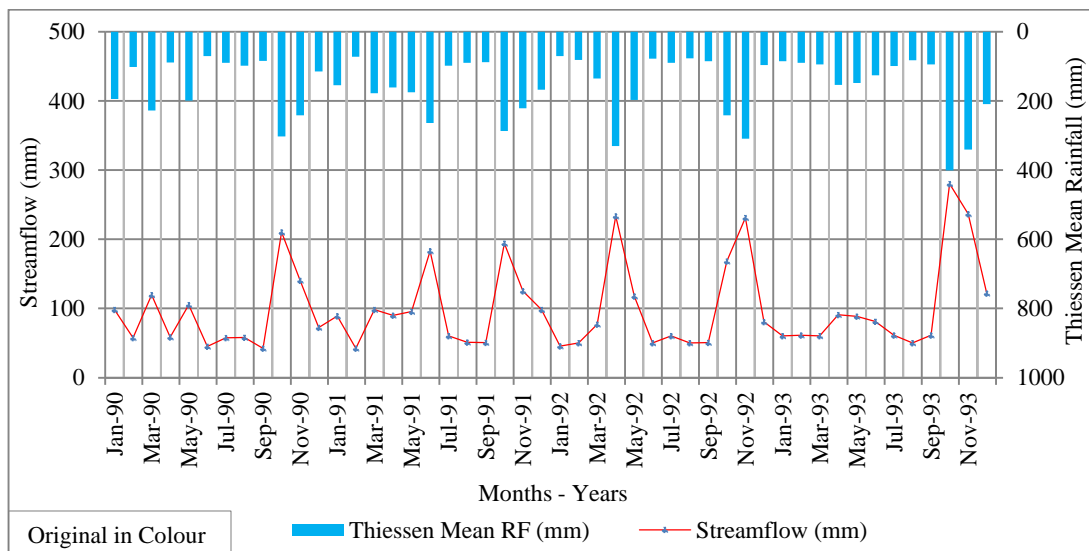


Figure 4.4: Thiessen mean rainfall and corresponding discharge for year (1990 - 1993)

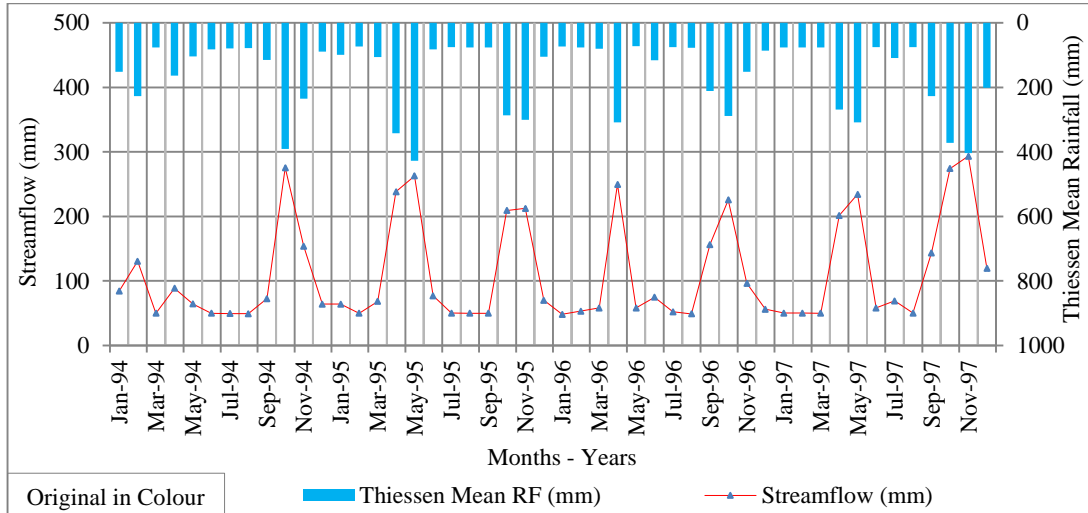


Figure 4.5: Thiessen mean rainfall and corresponding discharge for year (1994 - 1997)

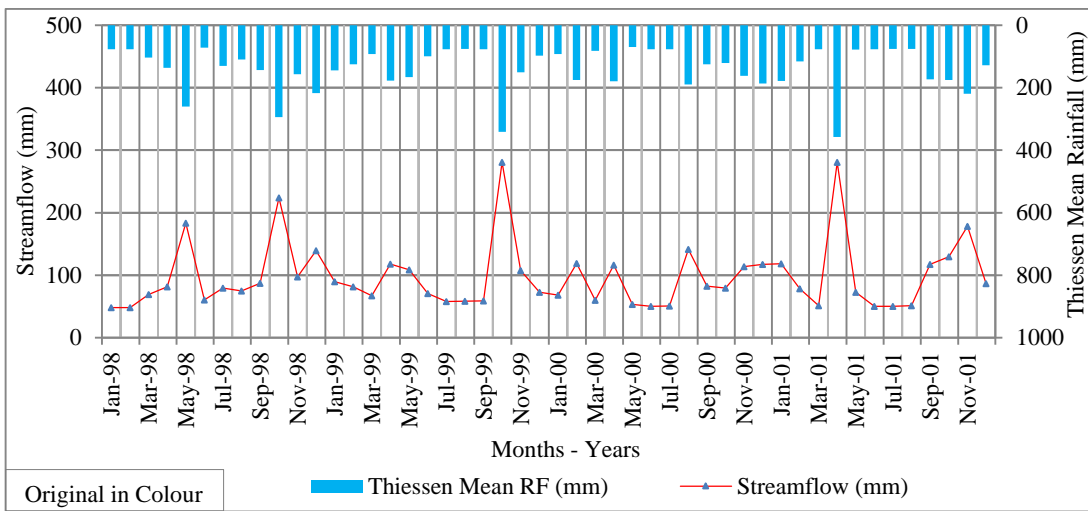


Figure 4.6: Thiessen mean rainfall and corresponding discharge for year (1998 - 2001)

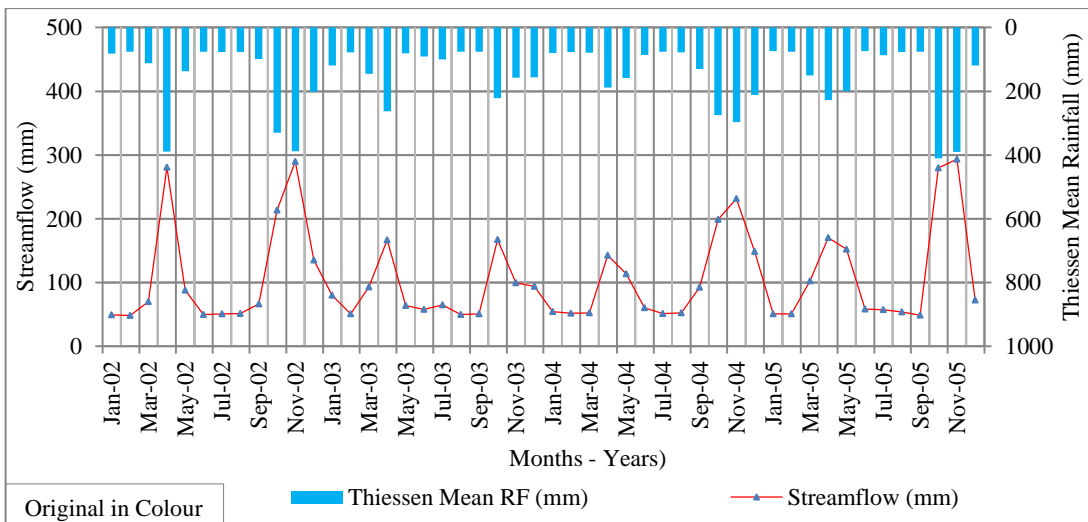


Figure 4.7: Thiessen mean rainfall and corresponding discharge for year (2002 - 2005)

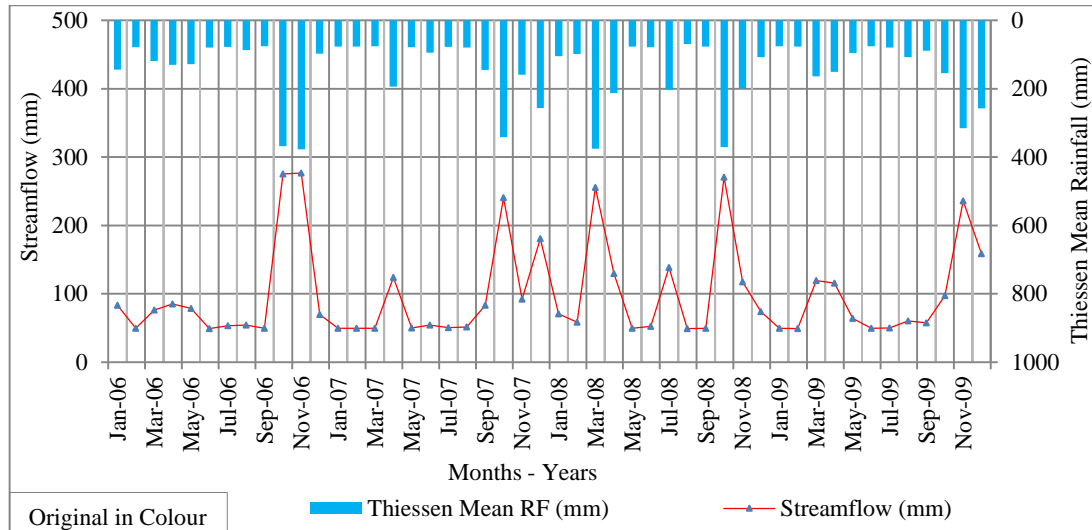


Figure 4.8: Thiessen mean rainfall and corresponding discharge for year (2006 – 2009)

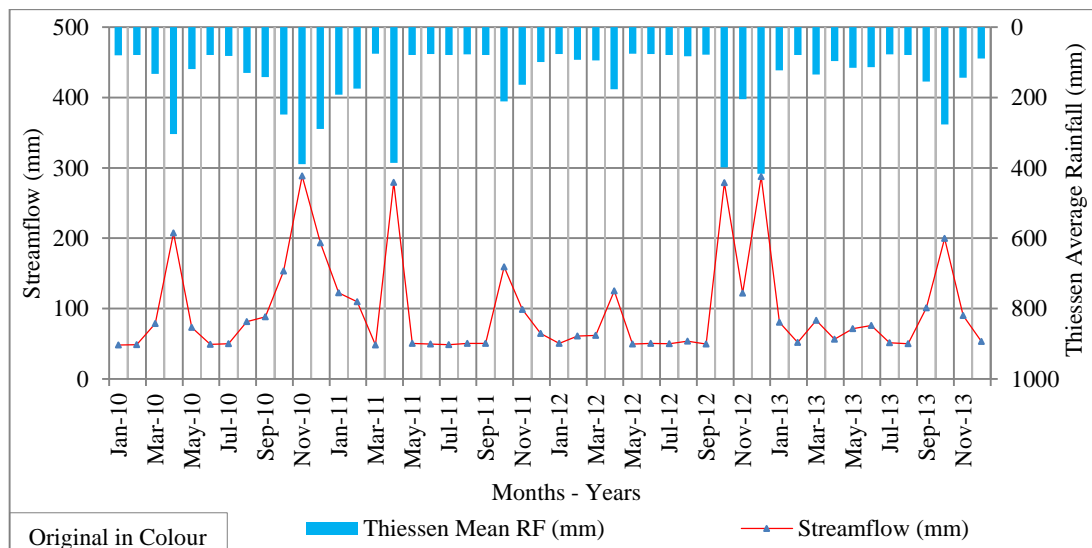


Figure 4.9: Thiessen mean rainfall and corresponding discharge for year (2010 – 2013)

The Thiessen mean rainfall and corresponding discharge for the year 1990 to 2013 are shown in the Figure 4.4 to 4.9. From the graphs, it can be noticed that the catchment has responded consistently to the intensity or depth of rainfall such that during the period of high rainfall there is high streamflow and vice versa in the catchment.

4.3.3 Annual rainfall and streamflow

The computation of the annual variation of rainfall using Thiessen mean and arithmetic mean method is shown in the Table 4.5 for the years 1990 to 2013. Comparison of rainfall values by two methods has shown small spatial variability.

Table 4.5: Thiessen mean and arithmetic annual rainfall with observed discharge

Year	Thiessen mean rainfall (mm/year)	Arithmetic mean method (mm/year)	Observed discharge (mm/year)
1990	1815.49	1907.89	1065.10
1991	1958.61	1932.61	1178.13
1992	1798.35	1787.12	1215.45
1993	1926.51	2000.75	1254.85
1994	1792.81	1726.03	1132.47
1995	2055.29	2054.64	1402.27
1996	1619.52	1580.70	1177.98
1997	2270.23	2215.08	1594.66
1998	1773.45	1719.62	1192.53
1999	1623.70	1571.22	1170.62
2000	1538.95	1502.60	1051.69
2001	1732.64	1688.23	1264.51
2002	2045.95	2120.11	1393.10
2003	1567.12	1460.08	1038.81
2004	1735.19	1671.43	1251.48
2005	1963.40	1843.34	1391.52
2006	1762.13	1846.86	1200.76
2007	1654.62	1601.47	1075.98
2008	1972.10	1937.82	1315.60
2009	1639.99	1582.42	1106.42
2010	2074.62	2078.66	1359.22
2011	1692.68	1681.06	1130.52
2012	1852.79	1850.37	1238.78
2013	1479.51	1410.43	963.88

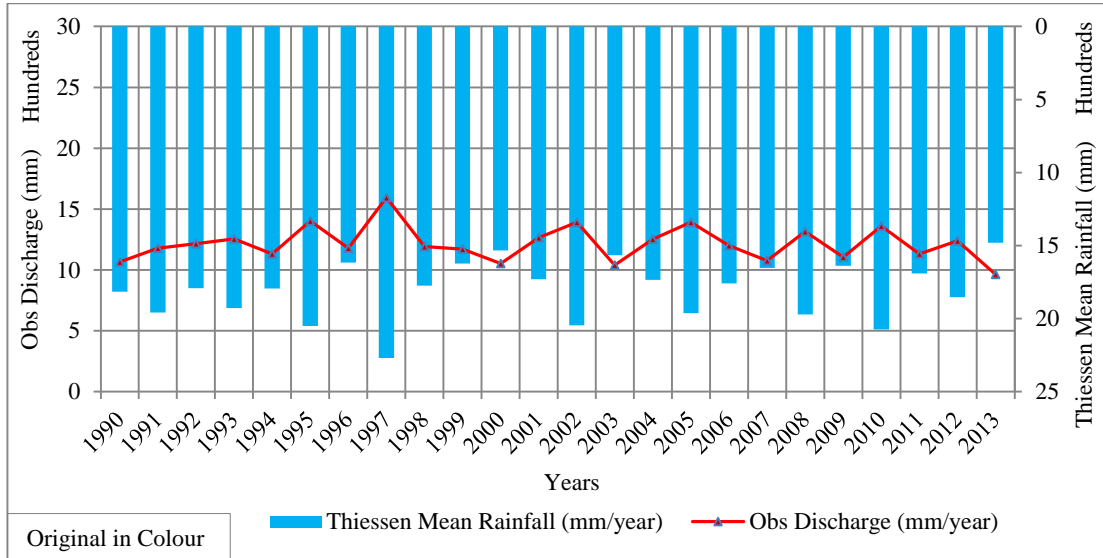


Figure 4.10: Thiessen mean rainfall and corresponding discharge for year (1990 – 2013)

Annual Thiessen mean rainfall and observed streamflow data were compared and checked by plotting each other as shown in the Figure 4.10. Visual checking on the streamflow was carried out it has responded corresponding to rainfall. It was found that during the data checking process there were few inconsistencies in the rainfall and streamflow. In some cases it was observed that the streamflow has not responded to individual rainfall events on same month. This is due to heavy and continuous rainfall in upstream of catchment at the end of month where the catchment has responded after few days. Therefore, the recorded values of discharge were included in the series derived for the next month.

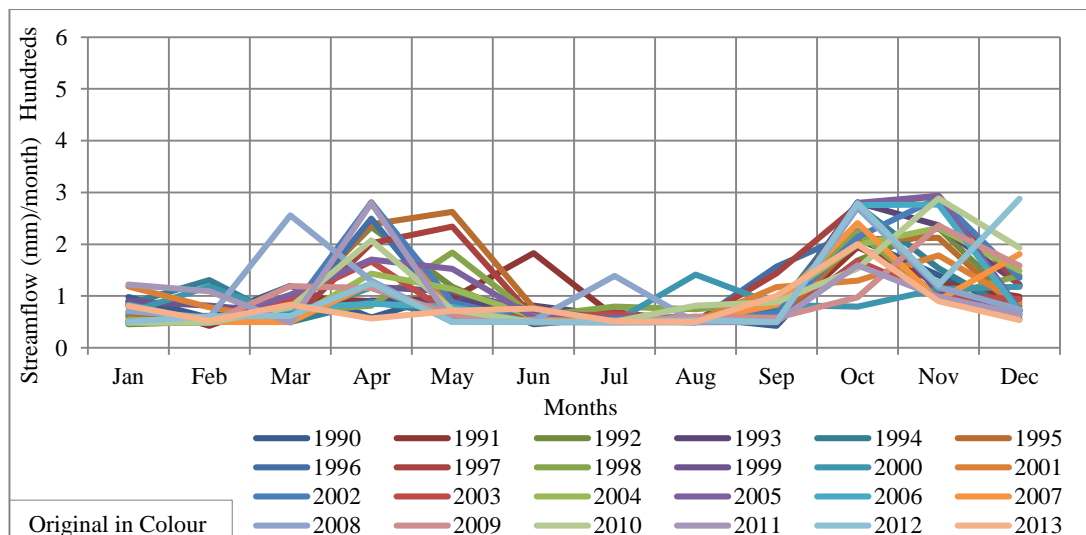


Figure 4.11: Monthly streamflow for year (1990 – 2013)

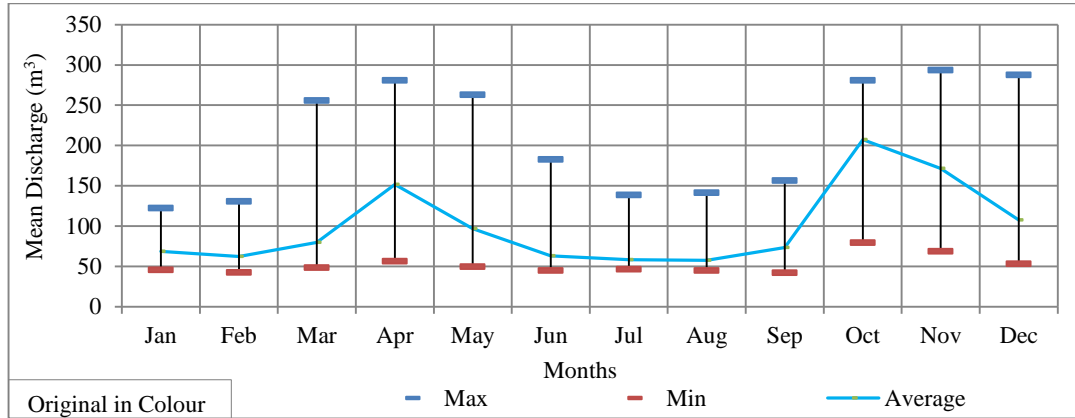


Figure 4.12: Monthly maximum, minimum and average values of mean discharge for year 1990 - 2013

The monthly mean streamflow is directly proportional to the rainfall as shown in the Figure 4.11. October and November months usually have received high rainfall compared to the rest of the months. In Sri Lanka, during Maha season from October to March, the catchment is receiving adequate rainfall for the reservoir storage to supply for the cultivation. The maximum, minimum and average values of streamflow are shown in the Figure 4.12.

Table 4.6: Time exceedance (%) corresponding to mean discharge (1990 - 2013)

Time	Time exceedance (%)	Mean discharge in descending order (mm)
1	8.33	98.35
2	16.67	97.21
3	25.00	85.05
4	33.33	80.88
5	41.67	77.35
6	50.00	70.73
7	58.33	70.61
8	66.67	68.51
9	75.00	64.60
10	83.33	64.55
11	91.67	63.32
12	100.00	62.86

The time exceedance in percentage was calculated and arranged with the mean discharge in descending order as shown in the Table 4.6, and then plotted the graph; mean discharge versus time exceedance (Flow duration curve) as shown in the Figure 4.13 to check the flow pattern. Based on the flow pattern, the mean streamflow is classified into three categories with respect to time exceedance (%) such that the flow equal to or less than 25% is high, greater than 25% and less than 75% is medium flow and equal to or greater than 75% is low flow as shown in the Figure 4.13.

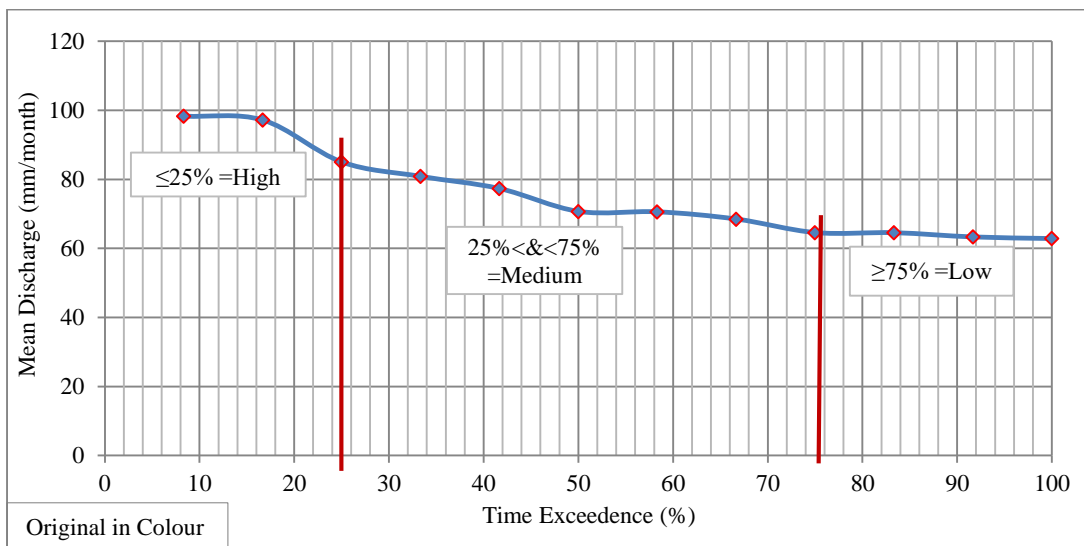


Figure 4.13: Classification of mean discharge for year (1990 – 2013)

4.3.4 Evaporation

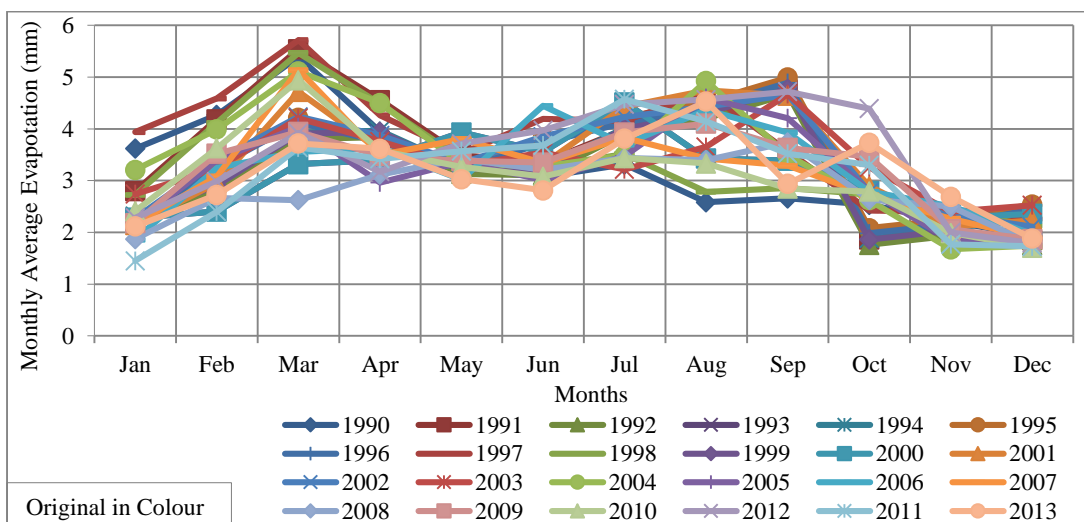


Figure 4.14: Monthly average evaporation for year (1990 – 2013)

The monthly average evaporation data was collected and plotted against the time (months) as shown in the Figure 4.14 for year 1990 to 2013 to check its pattern with rainfall and streamflow. In this regard, it is low during the wet season (Maha) due to high rainfall. In Deduru Oya basin, overall average rate of evaporation is 3.31 ± 2.22 mm (mean \pm standard deviation) per day for 24 years. The rate of evaporation is high during the dry season (Yala) where the water is being absorbed and lost through evaporation and transpiration process in the catchment. The Monthly maximum, minimum and average evaporation was calculated and compared for different years as shown in the Figure 4.15.

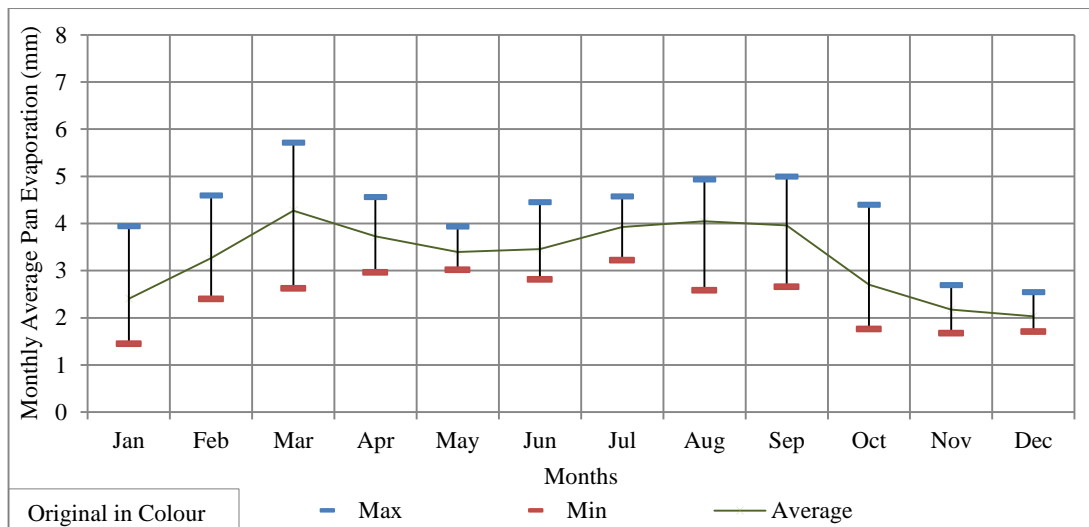


Figure 4.15: Monthly maximum, minimum and average evaporation rate for (1990 – 2013)

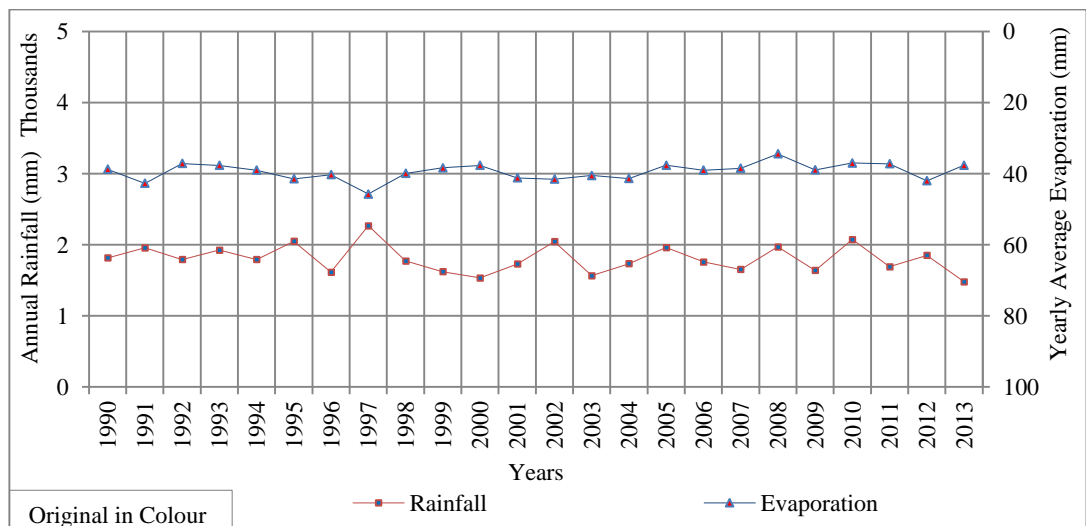


Figure 4.16: Comparison of annual rainfall and evaporation for year (1990 – 2013)

The Figure 4.16 shows the pattern of annual rainfall and evaporation for the year 1990 to 2013 such that the rate of evaporation is high during low rainfall period and vice-versa. The highest annual average evaporation is 45.72 mm in 1997 and the lowest value of 34.39 mm in 2008. In Sri Lanka, the value of pan coefficient used for water demand modeling is 0.8 according to Ponrajah (1984).

4.4 Runoff Coefficient Computation

The runoff coefficient (C) is a dimensionless ratio relating the amount of runoff to the amount of rainfall received in the catchment. Its value is larger for areas with low infiltration and high runoff, and the value is lower for permeable and well vegetated areas. It is important for flood control channel construction and for possible flood hazard zone delineation. A high runoff coefficient value may indicate flash flooding areas during storms as water moves fast overland on its way to a river channel or a valley floor.

In order to analyze the rainfall and stream data, the runoff coefficient can be calculated in three different ways, 1) using land use type with standard coefficient values, 2) rainfall with observed stream including baseflow contribution and 3) rainfall with streamflow excluding the baseflow contribution. These calculations were computed as follows:

4.4.1 Runoff coefficient calculation based on land use type

The runoff coefficient in the basin was calculated using the land use type map which is depicted in the Figure 4.17 and its area coverage shown in the Table 4.7, and the value of coefficient of each land use type according to the standard provided by Department of Irrigation, Sri Lanka (Ponrajah,1984). This calculated runoff coefficient is to compare with runoff coefficient which was calculated using rainfall and streamflow, and with model optimized runoff coefficient. The land use type map used for the runoff coefficient calculation is 1999 version, and presumably there could be slight variations in land use from that year afterwards due to development of various project related and other infrastructure in the basin. Therefore, the runoff coefficient may increase due to the increase in impervious surface and decrease in vegetation coverage. The calculated value of runoff coefficient is 0.38 as shown in the Table 4.8.

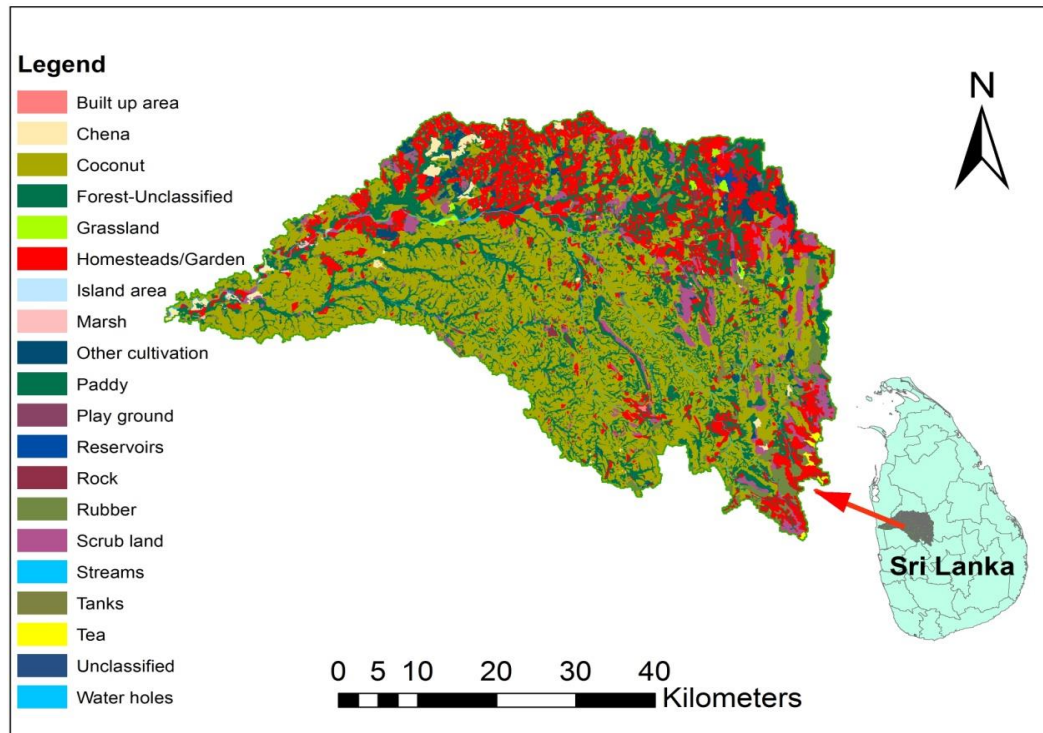


Figure 4.17: Land use type map of Deduru Oya basin

Table 4.7: Land use type and area coverage for Deduru Oya basin

Land use type	Area (km ²)	Land use type	Area (km ²)
Built-up Area	0.56	Play Ground	0.02
Chena	25.31	Reservoirs	3.88
Coconut	1131.39	Rocks	20.78
Forest-Unclassified	70.12	Rubbers	49.53
Grassland	7.19	Scrub Lands	133.65
Homesteads/Garden	443.11	Streams	20.28
Island area	0.01	Tanks	81.56
Marsh	2.15	Tea	4.56
Other Cultivation	49.89	Unclassified	0.01
Paddy	553.00	Water Holes	0.68

The maximum area coverage in the basin is coconut cultivations followed by paddy fields. In this regard, the runoff coefficient will be low as the surface area with high vegetation cover as the surface area is pervious and the infiltration will be high, and as a result certain quantity of runoff will be infiltrated into subsurface before it joins to stream channel and vice versa.

Table 4.8: Runoff coefficient calculation based on land use type in the basin

Land use type	Area (A , km²)	Coefficient (C)	A x C
Built-up Area	0.56	0.50	0.28
Chena	25.31	0.40	10.12
Coconut	1131.39	0.40	452.56
Forest-Unclassified	70.13	0.25	17.53
Grassland	7.19	0.35	2.52
Homesteads/Garden	443.12	0.40	177.25
Island area	0.01	0.25	0.00
Marsh	2.15	0.25	0.54
Other Cultivation	49.89	0.30	14.97
Paddy	553.00	0.35	193.55
Play Ground	0.02	0.30	0.01
Reservoirs	3.88	0.40	1.55
Rocks	20.79	0.60	12.47
Rubbers	49.54	0.35	17.34
Scrub Lands	133.65	0.30	40.10
Streams	20.29	0.25	5.07
Tanks	81.57	0.40	32.63
Tea	4.57	0.40	1.83
Unclassified	0.01	0.25	0.00
Water Holes	0.68	0.20	0.14
Total	2597.76		980.45
	Runoff coefficient (C) = $\sum(C \times A) / \sum A =$		0.38

4.4.2 Runoff coefficient computation using monthly observed streamflow and rainfall

The monthly observed streamflow and Thiessen mean rainfall from the period 1990 to 2013 was used to calculate the runoff coefficient taking the ratio of observed streamflow to Thiessen mean rainfall. The obtained values are within the ranges of 0.4 to 0.9. The calculated runoff coefficient was ranked into different categories and sorted out against its frequency as shown in the Table 4.9. The highest frequency of runoff coefficient is between 0.6 and 0.7 (Fig. 4.18).

Table 4.9: Runoff coefficient for monthly rainfall and observed streamflow for year (1990 - 2013)

Ranges of runoff coefficient	Frequency of runoff coefficient
0.100= \leq RC= \leq 0.2	0
0.201= \leq RC= \leq 0.3	0
0.301= \leq RC= \leq 0.4	0
0.401= \leq RC= \leq 0.5	9
0.501= \leq RC= \leq 0.6	36
0.601= \leq RC= \leq 0.7	180
0.701= \leq RC= \leq 0.8	61
0.801= \leq RC= \leq 0.9	2
0.901= \leq RC= \leq 1.0	0
Total	288

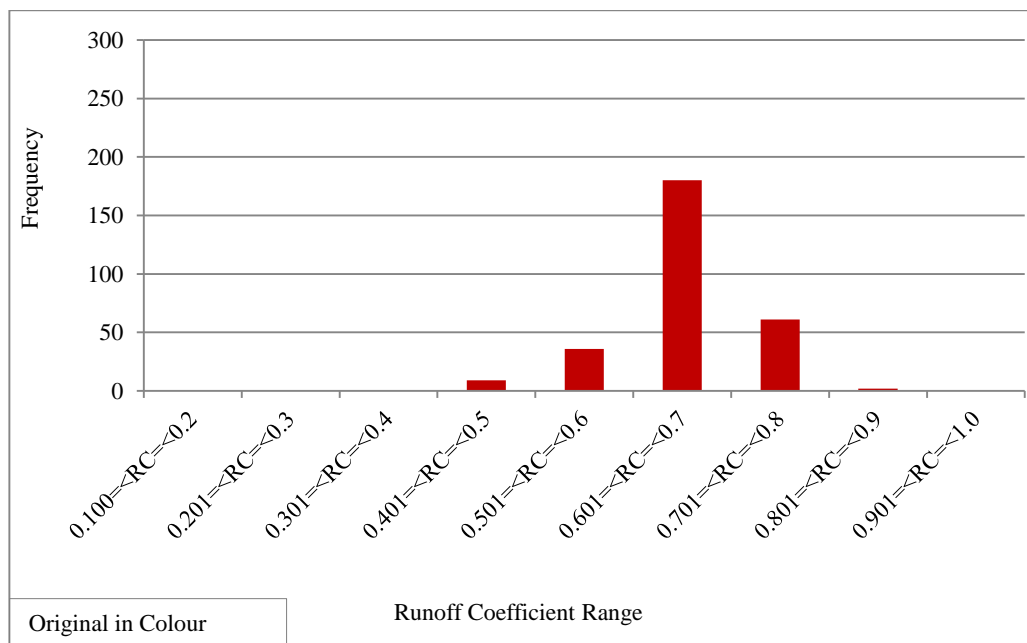


Figure 4.18: Runoff coefficient frequency for monthly rainfall and observed streamflow for year (1990 – 2013)

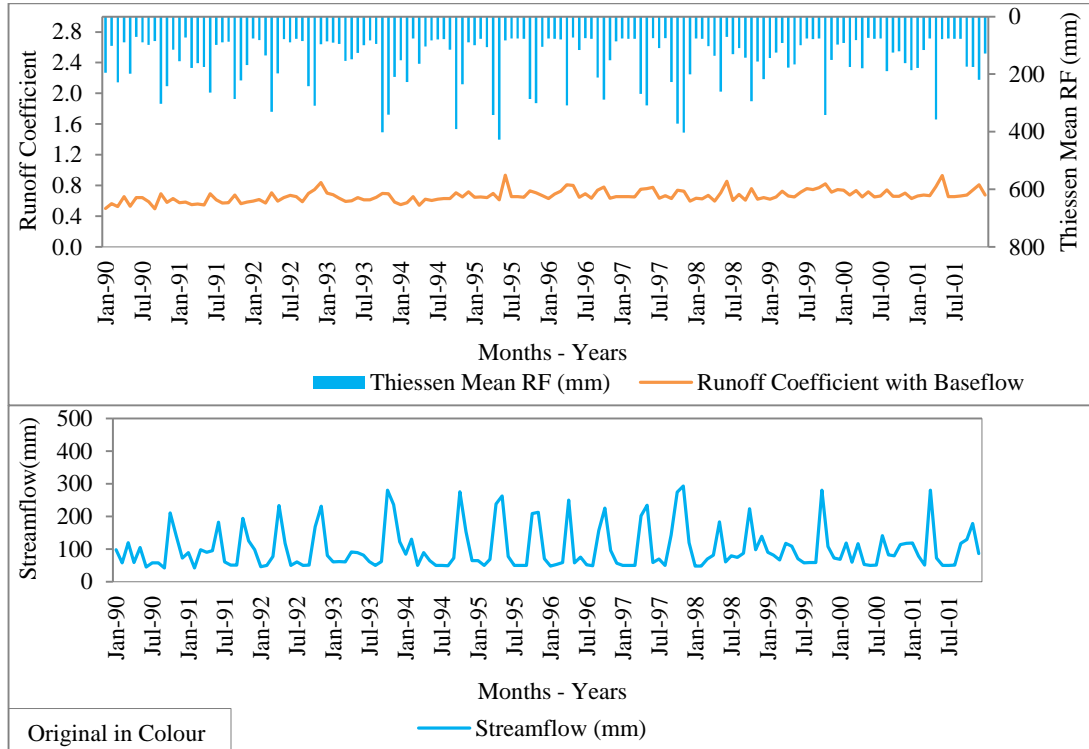


Figure 4.19: Comparison of monthly observed streamflow, Thiessen mean rainfall & runoff coefficient for year (1990 – 2001)

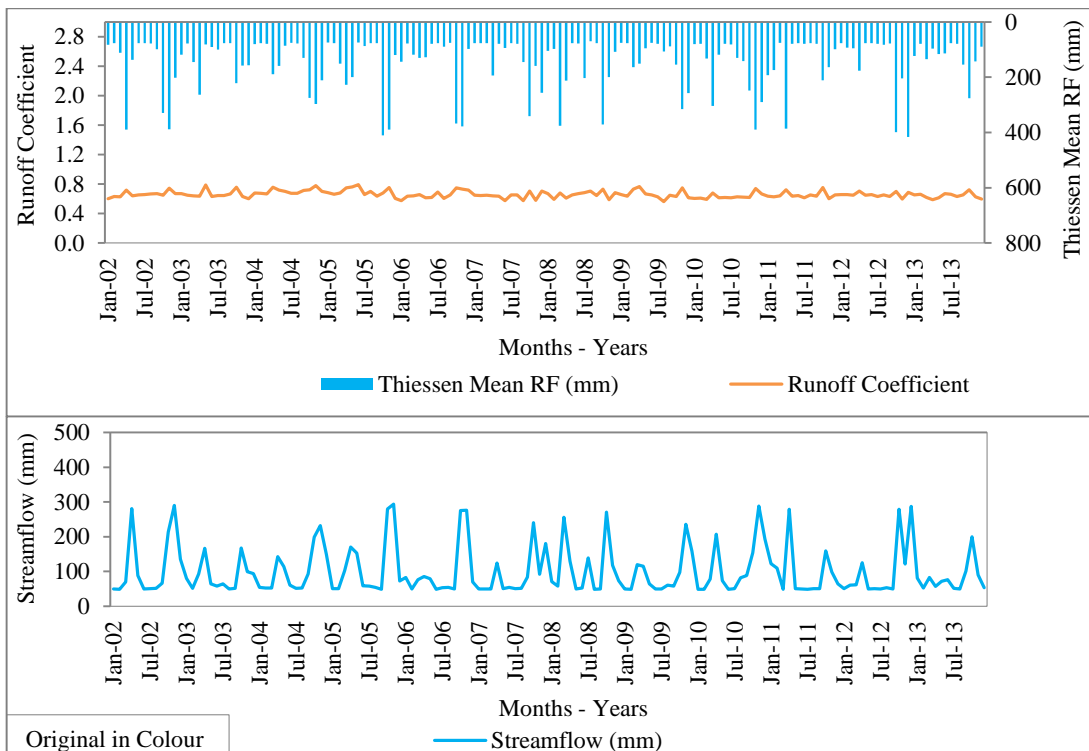


Figure 4.20: Comparison of monthly observed streamflow, Thiessen mean rainfall & runoff coefficient for year (2002 – 2013)

The Figure 4.19 and 4.20 shows the flow pattern of monthly observed streamflow, Thiessen mean rainfall and computed runoff coefficient. It is noted that all the three parameters are proportional to each other such that higher the rainfall is, the higher the streamflow and runoff coefficient. However, in few months, there is a shift in runoff coefficient as its value has presumably been shifted to the next month.

Table 4.10: Runoff coefficient for annual rainfall and streamflow (1990-2013)

Year	Thiessen mean rainfall (mm)	Observed discharge (mm)	Runoff coefficient
1990	1815.49	1065.10	0.59
1991	1958.61	1178.13	0.60
1992	1798.35	1215.45	0.68
1993	1826.83	1193.61	0.65
1994	1792.81	1132.47	0.63
1995	2055.29	1402.27	0.68
1996	1619.52	1177.98	0.73
1997	2270.23	1594.66	0.70
1998	1773.45	1192.53	0.67
1999	1623.70	1170.62	0.72
2000	1538.95	1051.69	0.68
2001	1732.64	1264.51	0.73
2002	2045.95	1393.10	0.68
2003	1567.12	1038.81	0.66
2004	1735.19	1251.48	0.72
2005	1963.40	1391.52	0.71
2006	1762.13	1200.76	0.68
2007	1654.62	1075.98	0.65
2008	1972.10	1315.60	0.67
2009	1639.99	1106.42	0.67
2010	2074.62	1359.22	0.66
2011	1692.68	1130.52	0.67
2012	1852.79	1238.78	0.67
2013	1479.51	963.88	0.65

Table 4.10 shows the annual rainfall and observed discharges which were used for runoff coefficient calculation. It is found that the ranges of runoff coefficient frequency is same like monthly, ranging between 0.6 to 0.7 as shown in the Figure 4.21. Annual rainfall, observed discharge and calculated runoff coefficient were compared and checked for any inconsistency by comparing the pattern as shown in the Figure 4.22.

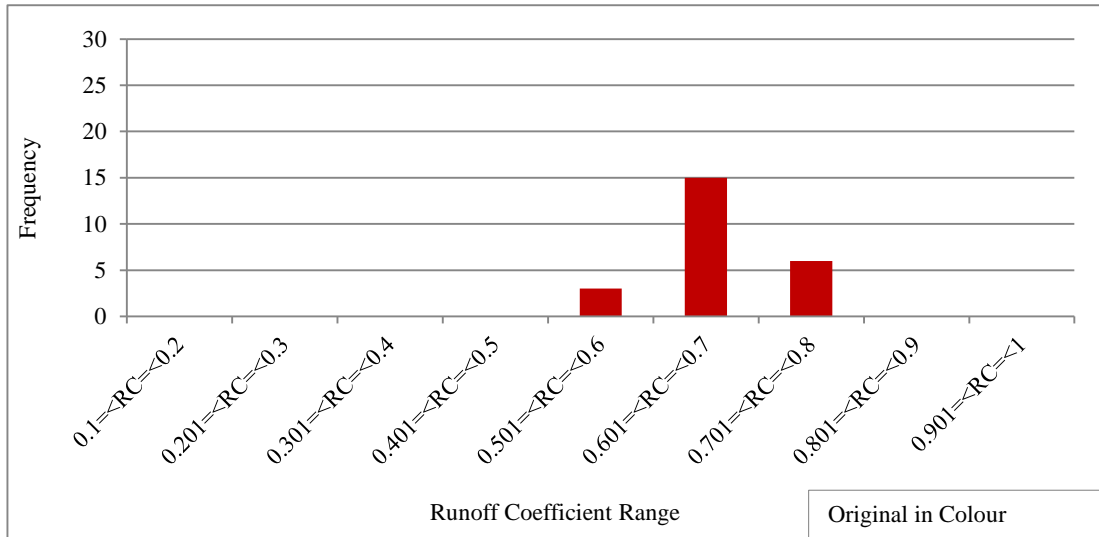


Figure 4.21: Runoff coefficient frequency for annual rainfall and observed streamflow for year (1990 – 2013)

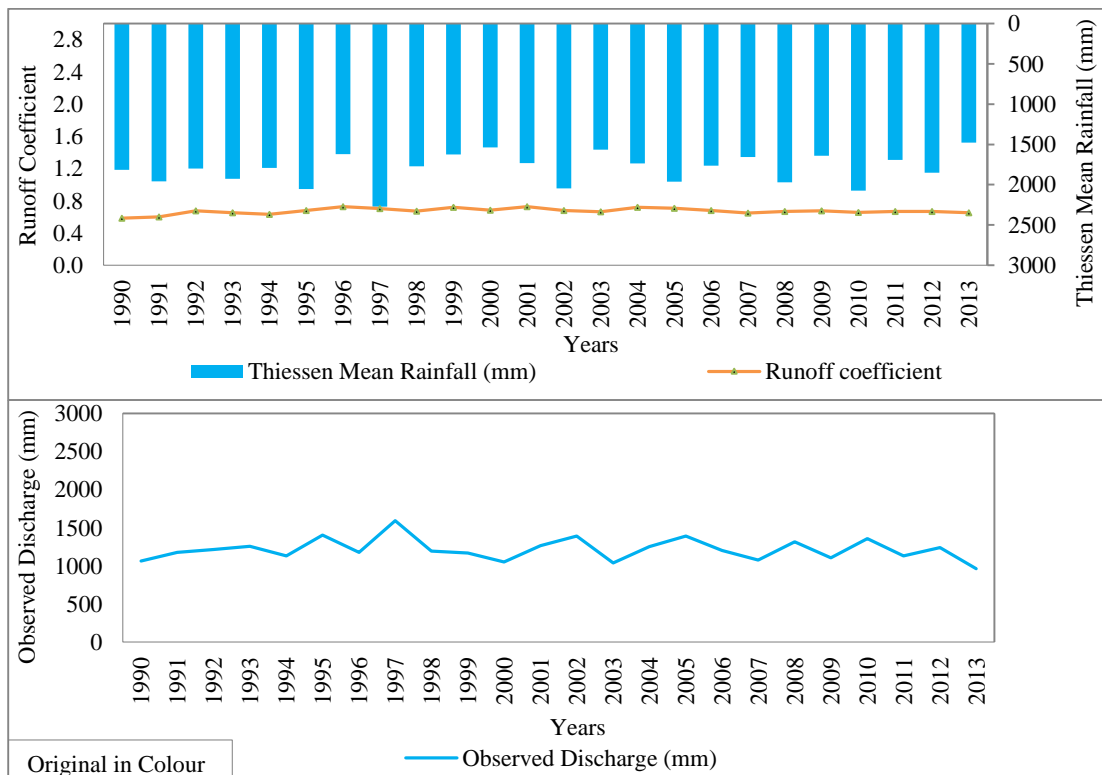


Figure 4.22: Comparison of annual Thiessen rainfall, observe discharge and runoff coefficient (1990 – 2013)

5 RESULTS AND ANALYSIS

5.1 Parameter Optimization

Rainfall-runoff models generally have a large number of parameters which are not directly measurable. Therefore, they need to be estimated through model calibration, i.e. by comparing the simulated outputs of the model to the observed outputs of the catchment. The optimization method will calibrate the rainfall-runoff model by finding the values for the model parameters that minimize or maximize the appropriate specific calibration criterion. The values of the parameter will depend on objective function(s) used for the calibration, data errors such as measurement errors and inadequate spatial and temporal resolution of the data.

The following objective functions were used to compare the measured and simulated streamflow:

5.1.1 Mean Ratio of Absolute Error (MRAE)

$$\text{MRAE} = \frac{\sum \frac{\text{ABS}(Q_{\text{obs}} - Q_{\text{sim}})}{Q_{\text{obs}}} \times 100}{n}$$

Where Q_{obs} = observed discharge, Q_{sim} = simulated discharge and n = number of observations. MRAE indicates the degree of matching of simulated and observed streamflow hydrographs (Wijesekera, 2000).

5.1.2 Nash-Sutcliffe Coefficient (NSC)

$$\text{NSC} = 1 - \frac{\text{sum}(Q_{\text{obs}} - Q_{\text{sim}})^2}{\text{sum}(Q_{\text{obs}} - Q_{\text{mean}})^2}$$

Where Q_{obs} = observed discharge, Q_{sim} = simulated discharge and Q_{mean} = mean of simulated discharge. It is used to assess the agreement between observations and simulations and indicates how well the plot of observed versus simulated data fits the 1:1 line (Moreda, 1999).

The three parameters used in the rainfall-runoff modeling were simultaneously or separately optimized in the following manner.

5.1.3 Initial Discharge (Delayed groundwater flow)

One of the parameters in the model called Initial Discharge has been optimized based on trial and error by tuning the values of all three parameters within the permissible range and visually checked the matching of hydrographs between simulated and observed discharge. After several trials, the values of objective functions used as an error estimate for the model indicated an optimum value as shown in the Table 5.1.

Table 5.1: Values of parameters and error estimates for optimizing initial discharge

Model	Data period	Parameters			Error estimates		
		RC	BCC	ID	MRAE	NSC	R ²
Calibration	1990 - 2001	0.55	0.06	4.5x10 ⁷ m ³ /month	0.19	0.9	0.96

Where;

RC is Runoff Coefficient

BCC is Baseflow Contribution Coefficient

ID is Initial Discharge

MRAE is Mean Ratio of Absolute Error

NSC is Nash-Sutcliffe Coefficient

R² is Coefficient of Determination

At the same time, the value of Initial Discharge parameter ($4.5 \times 10^7 \text{ m}^3/\text{month}$ or $17.36 \text{ m}^3/\text{s}$) was cross checked with the streamflow data collected during the field visits, and knowledge and information from local authorities. And it was found that the optimized discharge is in reasonable conformity in comparison to the field calculation where the depth, width and velocity of streamflow during dry season is approximately 0.8 m, 44 m and 0.5 m/s ($17.6 \text{ m}^3/\text{s}$). This obtained value of Initial Discharge was taken as constant for the period of modeling.

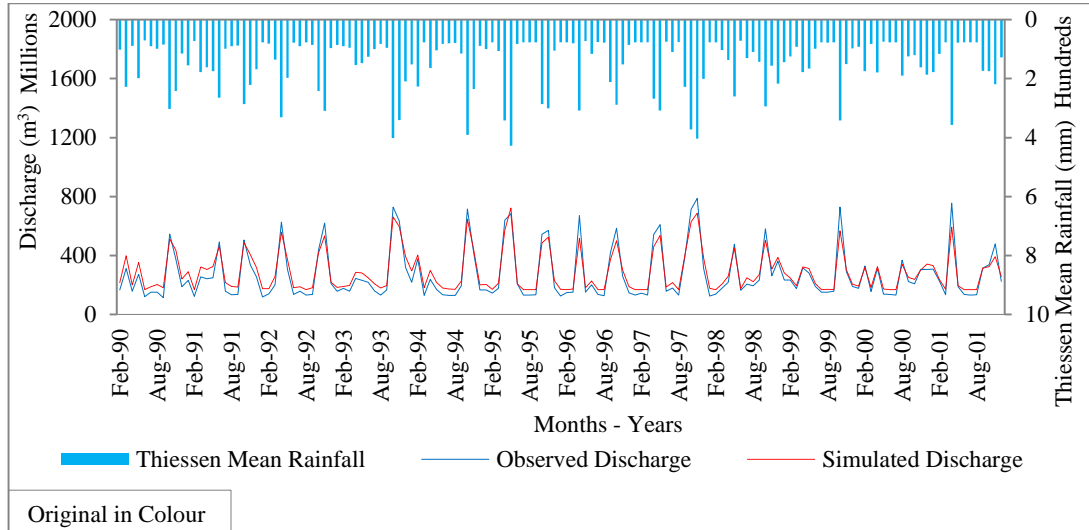


Figure 5.1: Calibration run with initial parameter (1990 - 2001)

The Figure 5.1 shows the hydrograph developed using the values of initial parameters. The pattern of hydrograph was not matched well and it can be improved further by optimizing the other parameters keeping one parameter (e.g. Initial Discharge) as constant.

5.1.4 Runoff coefficient and baseflow contribution coefficient

In order to improve the accuracy and reliability of hydrograph development for comparing simulated and observed discharge, these two parameters were further optimized keeping the value of Initial Discharge as constant. The same model error estimates were used to calibrate the dataset from 1990 to 2001 and to verify the model using dataset from 2002 to 2013. The process of optimization was carried out based on trial and error methods targeting to get minimum value of Mean Ratio of Absolute Error (MRAE) and maximum value of Nash-Sutcliffe Coefficient (NSC).

In order to optimize the parameters, the values of the selected two parameters were changed within the given ranges and their corresponding error estimates were calculated as shown in the Table 5.2.

Table 5.2: Ranges of parameter value for optimization

Model parameter		Error estimate	
RC	BCC	MRAE	NSC
0.1	1.928	0.399	0.353
0.2	0.896	0.305	0.666
0.3	0.553	0.300	0.777
0.4	0.216	0.200	0.858
0.5	0.070	0.173	0.914
0.6	0.014	0.200	0.903
0.7	0.002	0.300	0.839
0.8	-0.077	0.303	0.828
0.9	-0.078	0.400	0.695
1.0	-0.079	0.500	0.581

The optimum range of the two parameters, the Runoff Coefficient and Baseflow Contribution Coefficient was found to be at 0.5 and 0.072 respectively, where the value of MRAE is decreasing till 0.173 and then started to increase thereafter. At the same time, the NSC value has increased up to the point where the runoff coefficient is 0.5 and thereafter its value has started to decrease. Based on the above, the Runoff Coefficient value of 0.5 and Baseflow Contribution Coefficient value of 0.07 were selected for further optimization.

The value of Runoff Coefficient ranging from 0.1 to 1.0 at an interval of 0.1 (left column of Table 5.3) was used to calculate the optimum values of MRAE and NSC corresponding to the values of Baseflow Contribution Coefficient; 1.938, 0.896, 0.553, 0.216, 0.072, 0.014, 0.002, -0.077 and -0.078 (top row of Table 5.3).

The values of MRAE and NSC obtained by iterating the values of Runoff Coefficient and Baseflow Contribution Coefficient are shown in the Table 5.3 and 5.4. The lowest value of Mean Ratio of Absolute Error (MRAE) is 0.17 corresponding to 0.5 Runoff Coefficient (left column of Table 5.3) and 0.072 Baseflow Contribution Coefficient (top row of Table 5.3). Similarly, the highest value of Nash-Sutcliffe Coefficient (NSC) is 0.91 corresponding to same value of Runoff Coefficient (left column of Table 5.4) and 0.072 Baseflow Contribution Coefficient (top row of Table 5.4)

Table 5.3: Optimized values of Mean Ratio of Absolute Error (MRAE)

		Base flow contribution coefficient								
		1.928	0.896	0.553	0.216	0.072	0.014	0.002	-0.077	-0.078
Runoff coefficient	0.1	0.400	0.724	0.935	0.980	0.995	0.998	0.999	1.000	1.000
	0.2	0.826	0.300	0.567	0.784	0.893	0.911	0.918	0.949	0.949
	0.3	1.621	0.708	0.228	0.490	0.688	0.746	0.751	0.832	0.832
	0.4	2.419	1.196	0.439	0.200	0.440	0.577	0.603	0.707	0.706
	0.5	3.217	1.688	0.726	0.362	0.170	0.367	0.379	0.572	0.571
	0.6	4.015	2.181	1.025	0.576	0.298	0.200	0.198	0.417	0.413
	0.7	4.813	2.673	1.325	0.801	0.466	0.328	0.300	0.240	0.239
	0.8	4.985	3.166	1.625	1.026	0.643	0.483	0.449	0.310	0.353
	0.9	6.410	3.658	1.925	1.251	0.820	0.640	0.602	0.396	0.420
	1.0	7.208	4.151	2.225	1.476	0.997	0.797	0.755	0.499	0.502

Table 5.4: Optimized values of Nash-Sutcliffe Coefficient (NSC)

		Base flow contribution coefficient								
		1.928	0.896	0.553	0.216	0.072	0.014	0.002	-0.077	-0.078
Runoff coefficient	0.1	0.35	-0.02	0.08	0.01	0.01	0.00	0.00	0.00	0.00
	0.2	0.40	0.74	0.04	0.01	0.10	0.07	0.06	0.06	0.06
	0.3	-0.01	0.48	0.80	0.25	-0.02	0.04	0.04	0.02	0.02
	0.4	-0.07	0.14	0.72	0.86	0.42	0.11	0.06	0.06	0.06
	0.5	-0.06	-0.03	0.45	0.79	0.91	0.63	0.60	0.15	0.15
	0.6	-0.06	-0.07	0.22	0.58	0.85	0.90	0.90	0.55	0.56
	0.7	-0.06	-0.07	0.06	0.36	0.68	0.81	0.84	0.87	0.87
	0.8	-0.07	-0.06	-0.03	0.19	0.48	0.64	0.68	0.83	0.82
	0.9	-0.05	-0.06	-0.07	0.07	0.32	0.47	0.50	0.70	0.69
	1.0	-0.05	-0.06	-0.07	-0.01	0.19	0.33	0.36	0.58	0.58

The Runoff Coefficient of 0.5 obtained from initial trial run was further extended from 0.4 to 0.6 at an interval of 0.01 and iterated with a constant value (0.07) of Baseflow Contribution Coefficient as shown in the Table 5.5. The graph with the value of MRAE against Runoff Coefficient was plotted to find the minimum value of MRAE and the corresponding value of runoff coefficient was considered as the most appropriate or optimized parameter value for the model calibration and validation run to compare the observed discharge with simulated discharge. The graphical representation of MRAE and Runoff Coefficient is shown in Figure 5.2.

Table 5.5: Optimization of runoff coefficient with constant baseflow contribution coefficient

Parameter		Error estimate	
RC	BCC	MRAE	NSC
0.400	0.070	0.450	0.398
0.410	0.070	0.429	0.452
0.420	0.070	0.404	0.513
0.430	0.070	0.370	0.583
0.440	0.070	0.346	0.633
0.450	0.070	0.324	0.673
0.460	0.070	0.315	0.696
0.470	0.070	0.313	0.708
0.480	0.070	0.295	0.743
0.490	0.070	0.249	0.808
0.500	0.070	0.170	0.913
0.510	0.070	0.176	0.900
0.520	0.070	0.187	0.897
0.530	0.070	0.199	0.894
0.540	0.070	0.211	0.889
0.550	0.070	0.223	0.885
0.560	0.070	0.235	0.881
0.570	0.070	0.248	0.875
0.580	0.070	0.262	0.868
0.590	0.070	0.275	0.860
0.600	0.070	0.290	0.851

Where: RC = Runoff Coefficient, BCC = Baseflow Contribution Coefficient, $MRAE$ = Mean Ratio of Absolute Error and NSC = Nash-Sutcliffe Coefficient

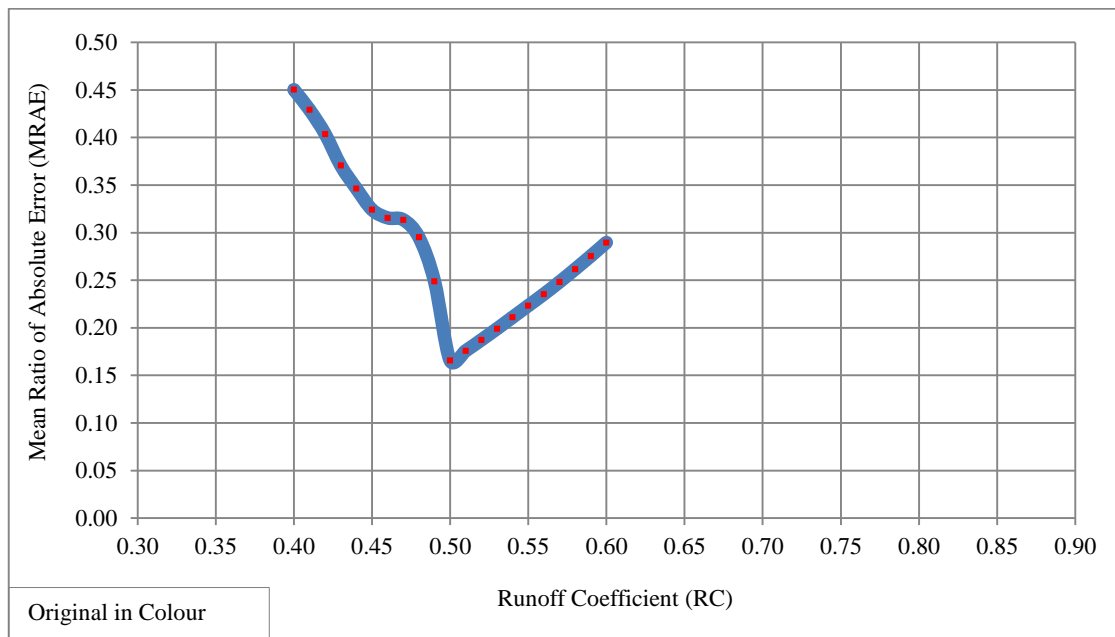


Figure 5.2: Graphical representation of optimized value of MRAE and runoff coefficient

5.2 Model Calibration and Validation

The purpose of calibration process in modeling is to test the model with known input and output values, aiming at the adjustment and evaluation of the parameters used. In contrast to calibration, validation is to compare the model results with an independent dataset. The three parameters were optimized to obtain the best fit hydrograph between observed and simulated discharges. The best set of parameters with minimum error values were considered as optimized parameters of an event. Out of the hydrological dataset of 24 years, the data from 1990 to 2001 were used for calibration and those of 2002 to 2013 for validation of the model.

In order to optimize the parameters used for modeling, error estimates like Root Mean Square Error (RMSE), Mean Ratio of Absolute Error (MRAE), Nash-Sutcliffe Coefficient (NSC) and Arithmetic Mean of the Error (BIAS) were computed as indicators. Out of those indicators, Mean Ratio of Absolute Error (MRAE) and Nash-Sutcliffe Coefficient (NSC) were selected for the parameter optimization. According to their accuracy, they have been frequently used as error indicators as per the literature review by Perera and Wijesekera (2011) and Moreda (1999).

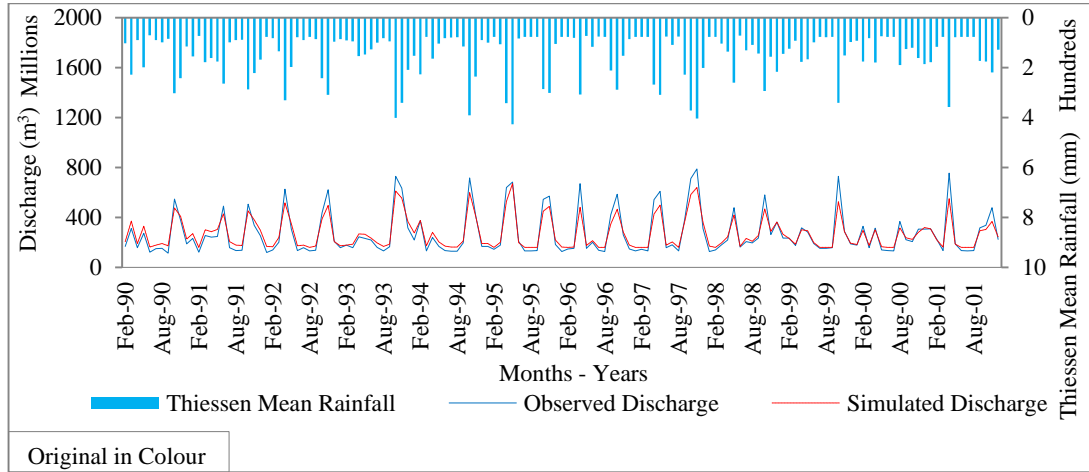


Figure 5.3: River discharge and Thiessen mean rainfall for calibration run (1990 - 2001)

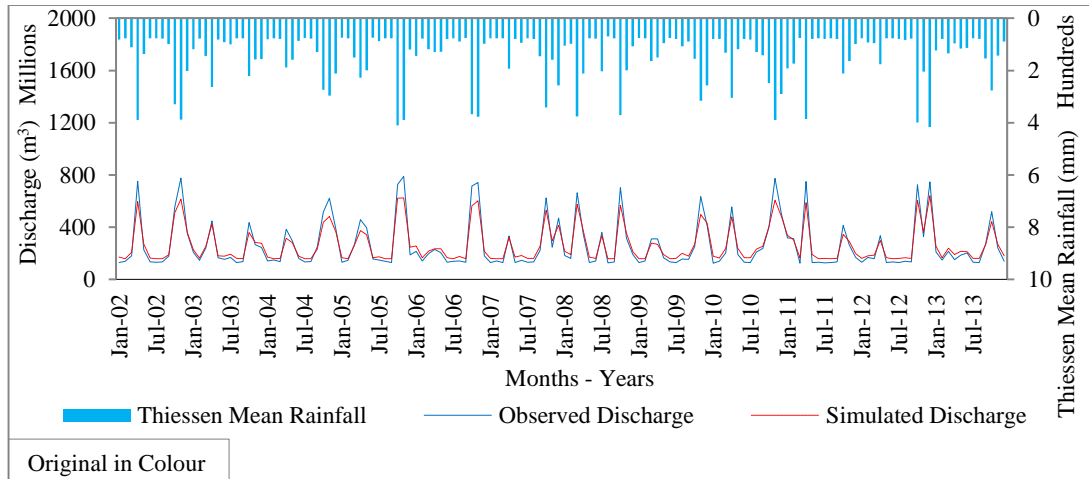


Figure 5.4: River discharge and Thiessen mean rainfall for validation run (2002 - 2013)

Using the optimized parameters values; that is Runoff Coefficient of 0.5, Baseflow Contribution Coefficient of 0.07 and an Initial Discharge of $4.5 \times 10^7 \text{m}^3/\text{month}$, the model was calibrated for the period from 1990 to 2013 as shown in the Figure 5.3. In the same manner, the model was validated using the same three parameter values for the period from 2002 to 2013 as shown in the Figure 5.4 and Table 5.6.

Table 5.6: Results for calibration and validation run

Model	Data period	Error estimate		
		MRAE	NSC	R ²
Calibration run	1990 - 2001	0.17	0.91	0.98
Validation run	2002 - 2013	0.19	0.90	0.96

The MRAE values for calibration and validation model runs for the year 1990 - 2001 and 2002 - 2013 are 0.17 and 0.19, respectively. The above obtained values are within the permissible range (between 0.0 and 1.0, inclusive of 1.0). Therefore, it is acceptable for model computation which indicates an error of 17% and 19%, respectively. The result shows that the calibration result is better than the validation result. The value of Nash-Sutcliffe Coefficient for calibrated and validated is 0.91 and 0.90 which are near to optimal value (1.0) indicating a good fit or result. The values of Coefficient of Determination (R^2) for calibration and validation are 0.98 and 0.96 which show the degree of co-linearity or measure of quality of prediction between observed and simulated discharges. The values obtained are acceptable as it is greater than 0.5 according to Santhi et al. (2001) and Van Liew et al. (2003).

5.3 Flow Duration Curve for Calibration and Validation Run

The Figure 5.5 and 5.6 shows the flow duration curves for calibration and validation model runs. The percent exceedance probability curve illustrates how well the model reproduces the frequency of measured flows throughout the calibration and validation periods. The agreement between observed and simulated frequencies for the desired constituent indicates adequate simulation over the range of the condition examined (Singh et al., 2004).

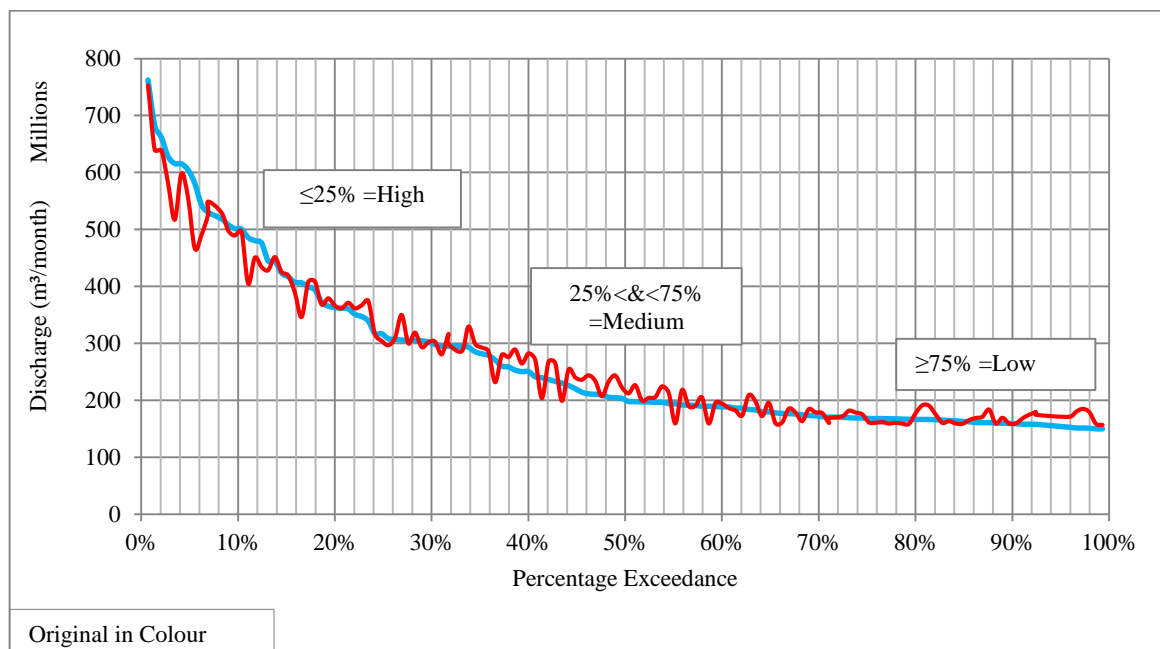


Figure 5.5: Flow duration curve for calibration run (1990 - 2001)

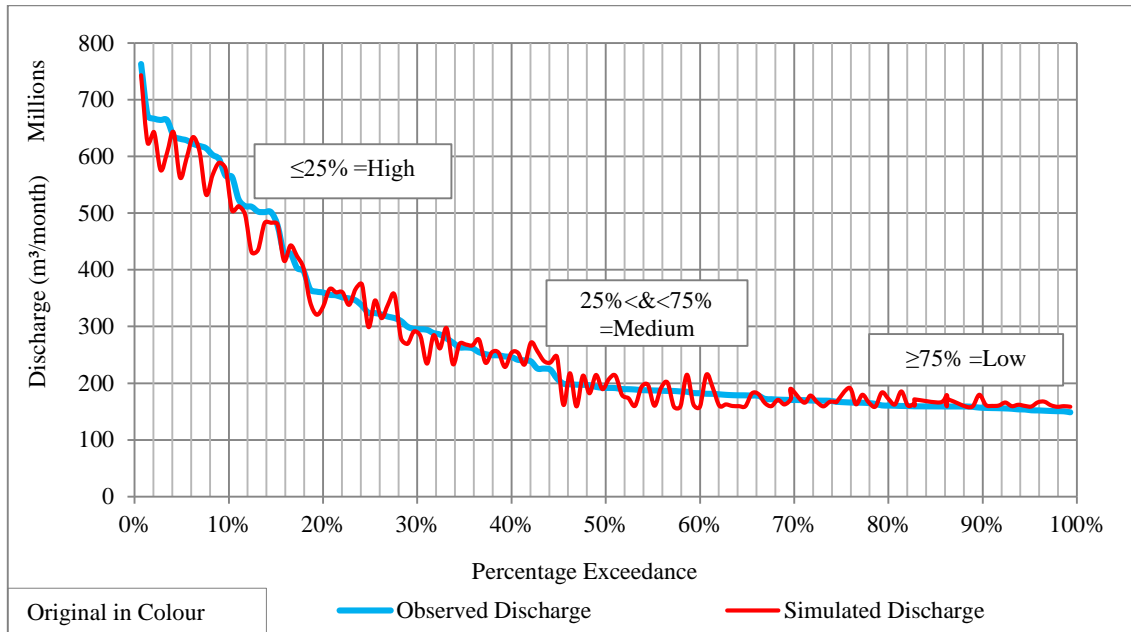


Figure 5.6: Flow duration curve for validation run (2002 - 2013)

Table 5.7: High and low flow errors for calibration run (1990 – 2001)

Flow type	Time exceedance (%)	Error estimate	
		MRAE	NSC
High flow	$\leq 25\%$	0.14	0.64
Medium flow	$25\% < \& < 75\%$	0.12	0.75
Low flow	$\geq 75\%$	0.24	0.12

Table 5.8: High and low flow error for validation run (2002 - 2013)

Flow type	Time exceedance (%)	Error estimate	
		MRAE	NSC
High flow	$\leq 25\%$	0.14	0.69
Medium flow	$25\% < \& < 75\%$	0.13	0.76
Low flow	$\geq 75\%$	0.25	0.11

The comparison of flow duration curves for each case was carried out to analyze and check the behavior of the model parameters. The flow duration for each case was divided into three regions as high flow, medium flow and low flow such that the high flows were taken as the streamflow, which occurred for less than or equal to 25% of time, and low flow was taken as flow which occurred for more than or equal to 75% of the time and the balance region was identified as medium flow as shown in the Table 5.7 for calibration run and Table 5.8 for validation runs.

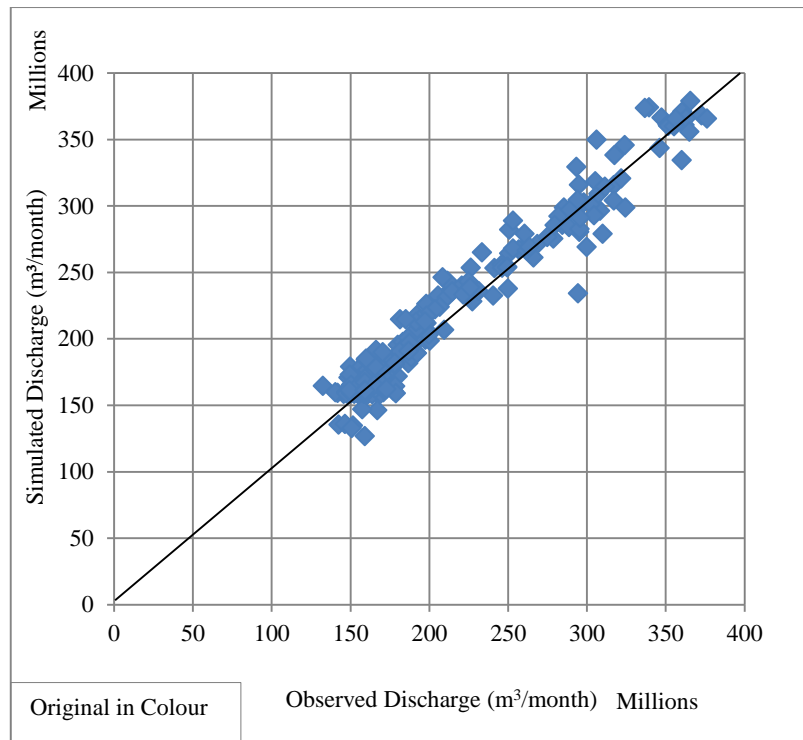


Figure 5.7: Monthly water balance for observed and simulated discharge (1990 - 2013)

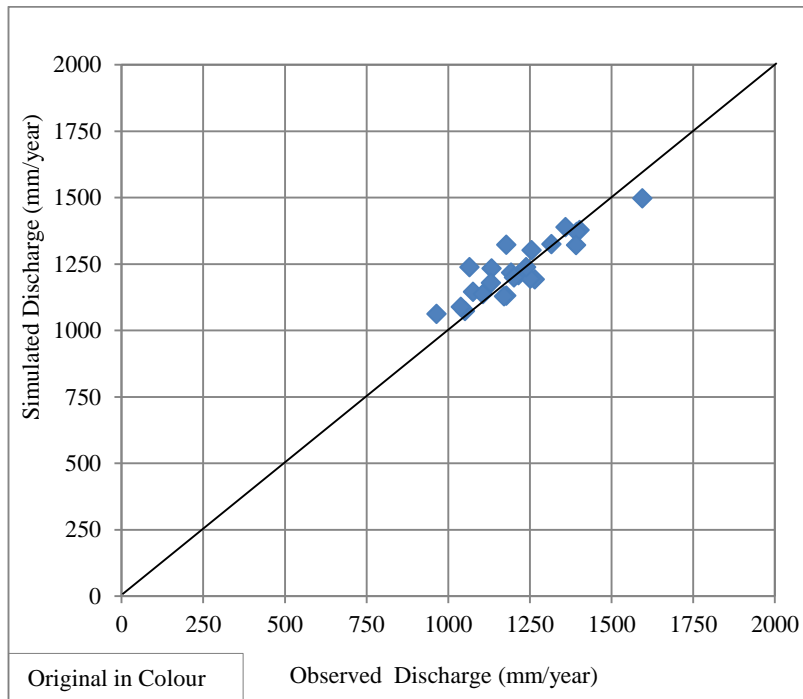


Figure 5.8: Annual water balance for observed and simulated discharge (1990 - 2013)

The monthly and annual water balance for the simulated and observed discharge was compared to see the matching of estimations made during consequent model runs. The correlation pattern of estimated values is shown in the Figures 5.7, 5.8 and 5.9.

Table 5.9: Annual observed and simulated water balance (1990 – 2013)

Year	Rainfall (mm/year)	Obs discharge (mm/year)	Obs discharge water balance (mm)	Sim discharge (mm/year)	Sim discharge water balance (mm)
1990	1815.49	1065.10	750.39	1238.83	576.65
1991	1958.61	1178.13	780.48	1322.55	636.05
1992	1798.35	1215.45	582.91	1208.34	590.01
1993	1926.51	1254.85	671.67	1302.18	624.33
1994	1792.81	1132.47	660.34	1234.12	558.69
1995	2055.29	1402.27	653.02	1378.83	676.46
1996	1619.52	1177.98	441.54	1131.81	487.72
1997	2270.23	1594.66	675.57	1498.01	772.21
1998	1773.45	1192.53	580.92	1218.33	555.13
1999	1623.70	1170.62	453.08	1128.42	495.28
2000	1538.95	1051.69	487.27	1073.13	465.82
2001	1732.64	1264.51	468.14	1193.37	539.27
2002	2045.95	1393.10	652.85	1371.66	674.30
2003	1567.12	1038.81	528.31	1089.44	477.68
2004	1735.19	1251.48	483.71	1195.15	540.04
2005	1963.40	1391.52	571.88	1321.79	641.62
2006	1762.13	1200.76	561.37	1199.72	562.41
2007	1654.62	1075.98	578.64	1145.59	509.03
2008	1972.10	1315.60	656.50	1325.24	646.86
2009	1639.99	1106.42	533.56	1137.58	502.41
2010	2074.62	1359.22	715.40	1389.43	685.20
2011	1692.68	1130.52	562.16	1179.53	513.15
2012	1852.79	1238.78	614.01	1238.52	614.27
2013	1479.51	963.88	515.63	1062.81	416.70

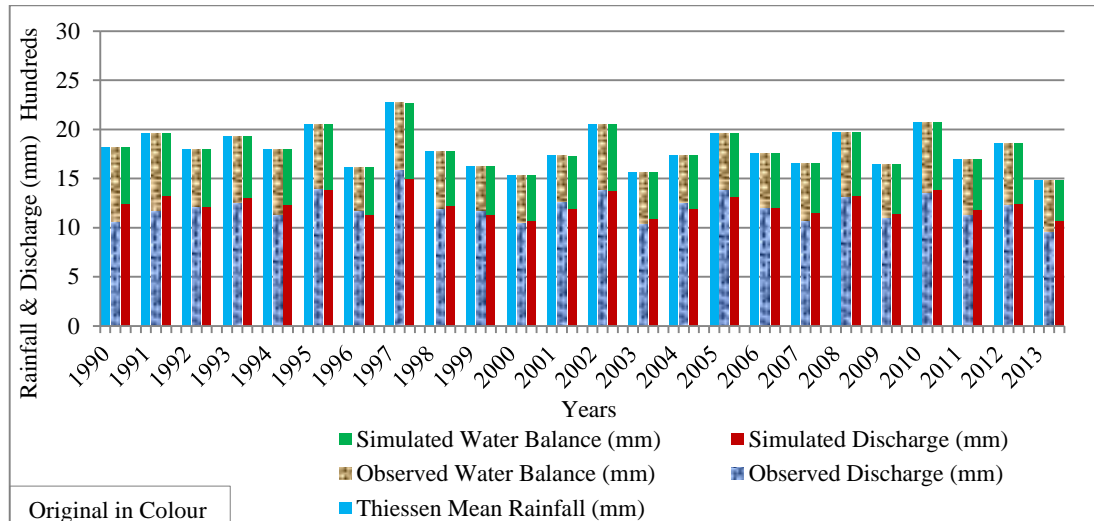


Figure 5.9: Comparison of annual observed and simulated water balance (1990 – 2013)

5.4 Runoff Coefficient Computation using Monthly Simulated Streamflow (exclusive of baseflow) and Rainfall

The baseflow was separated from the simulated discharge and the runoff coefficient was calculated using monthly rainfall to analyze the runoff coefficient without baseflow. The highest frequency of runoff coefficient is between the ranges of 0.3 to 0.4 with frequency of 199 out of 288 as shown in the Table 5.10 and Figure 5. 10. It indicates that the runoff coefficient estimated is less when the baseflow contribution was not taken into account.

Table 5.10: Runoff coefficient for monthly streamflow without baseflow and rainfall

Ranges of runoff coefficient	Frequency of runoff coefficient
0.100=<RC=<0.2	0
0.201=<RC=<0.3	13
0.301=<RC=<0.4	119
0.401=<RC=<0.5	83
0.501=<RC=<0.6	36
0.601=<RC=<0.7	35
0.701=<RC=<0.8	2
0.801=<RC=<0.9	0
0.901=<RC=<1.0	0
Total	288

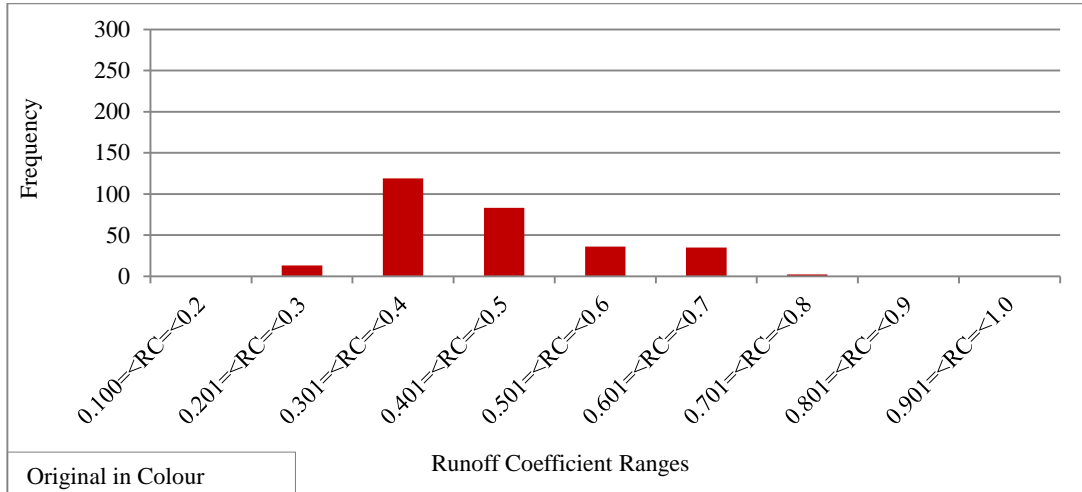


Figure 5.10: Runoff coefficient frequency for monthly rainfall and simulated discharge (exclusive of baseflow) for year (1990 – 2013)

The monthly simulated discharge excluding baseflow, rainfall and calculated runoff coefficient were compared and checked for the pattern of flow as shown in the Figure 5.11 and 5.12. Higher the rainfall, the higher streamflow and runoff coefficient were estimated and vice-versa. It was noted that there exists a shift in streamflow and runoff coefficient due to continuous and heavy rainfall at end of month under consideration.

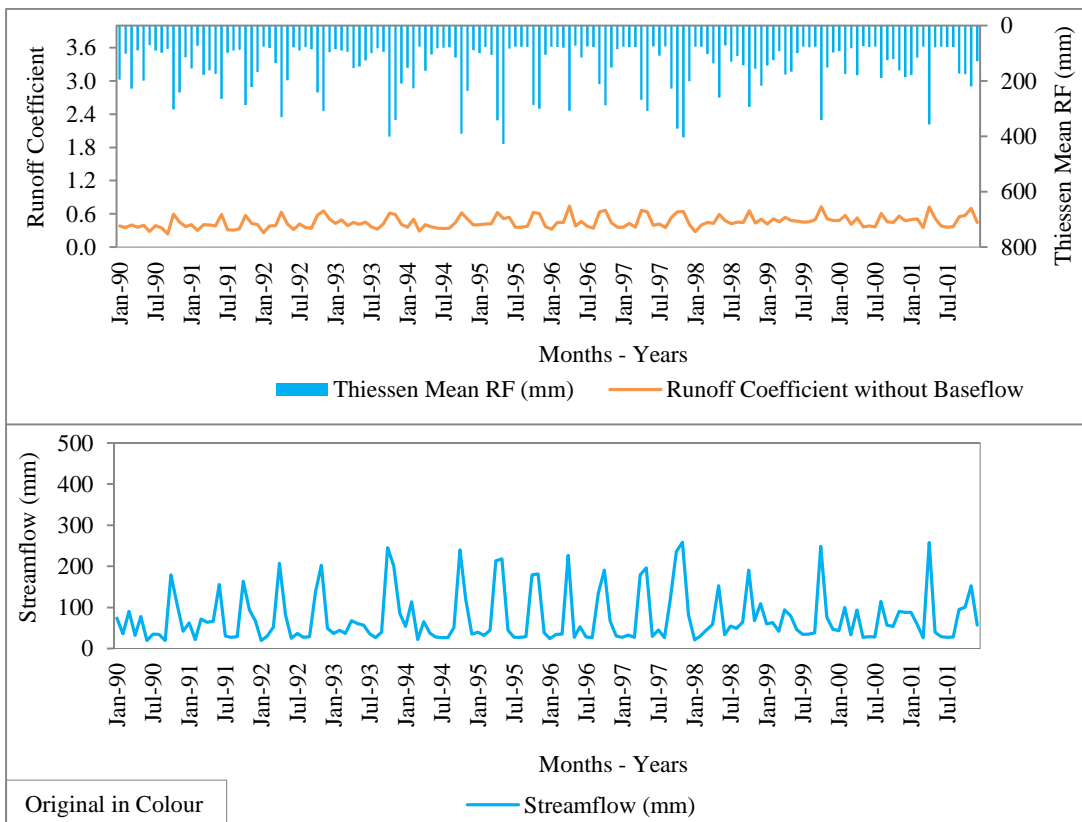


Figure 5.11: Comparison of monthly observed streamflow (without baseflow), rainfall and runoff coefficient (1990-2001)

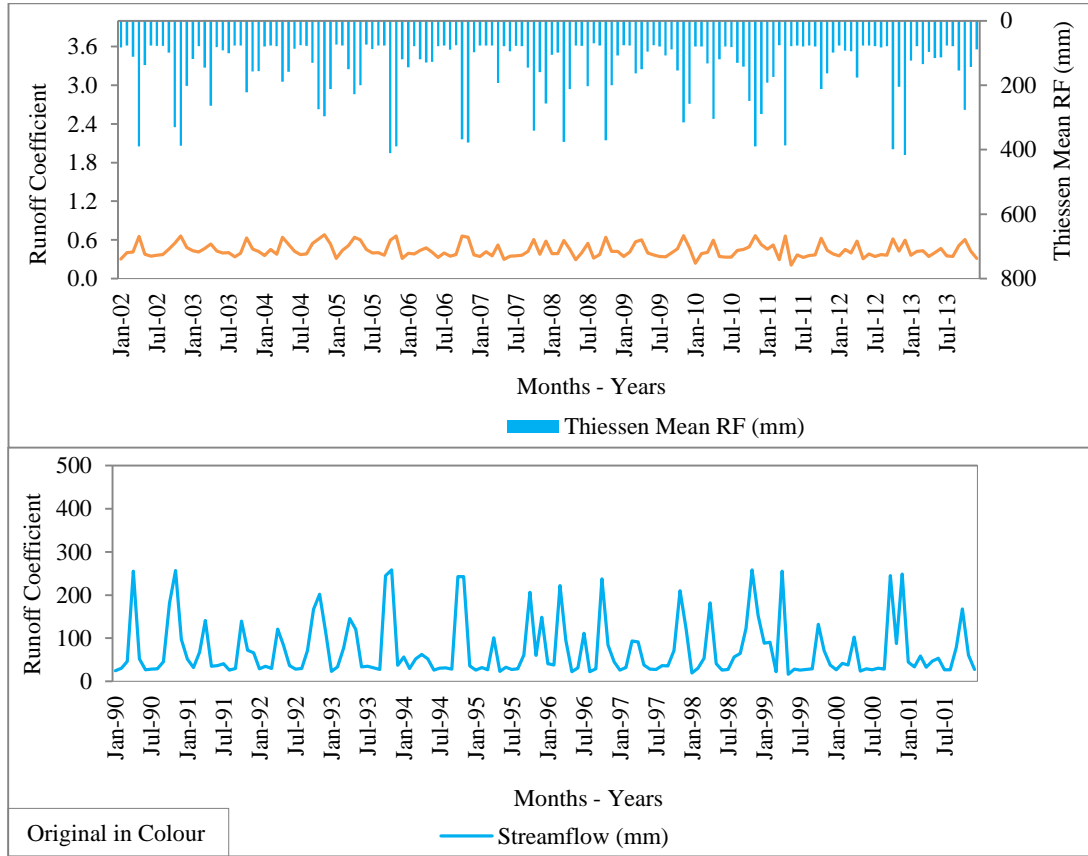


Figure 5.12: Comparison of monthly observed streamflow (without baseflow), rainfall & runoff coefficient (2002-2013)

5.5 Runoff Coefficient Computation using Annual Rainfall & Simulated Discharge (without baseflow)

Table 5.11: Runoff coefficient for annual rainfall & simulated discharge (without baseflow)

Year	Rainfall (mm/year)	Discharge (mm/year)	Runoff coefficient
1990	1815.49	749.87	0.41
1991	1958.61	854.53	0.44
1992	1798.35	901.48	0.50
1993	1926.51	938.31	0.49
1994	1792.81	821.06	0.46
1995	2055.29	1075.69	0.52
1996	1619.52	878.99	0.54
1997	2270.23	1260.51	0.56
1998	1773.45	877.11	0.49
1999	1623.70	865.42	0.53
2000	1538.95	759.47	0.49
2001	1732.64	962.59	0.56
2002	2045.95	1072.62	0.52
2003	1567.12	737.63	0.47
2004	1735.19	947.23	0.55
2005	1963.40	1067.49	0.54
2006	1762.13	889.44	0.50
2007	1654.62	774.95	0.47
2008	1972.10	980.13	0.50
2009	1639.99	809.53	0.49
2010	2074.62	1033.54	0.50
2011	1692.68	825.12	0.49
2012	1852.79	928.09	0.50
2013	1479.51	657.31	0.44

Using annual rainfall and simulated discharge without baseflow, the runoff coefficient was calculated taking into account the ratio of annual rainfall to simulated discharge excluding the baseflow as shown in the Table 5.11.

Table 5.12: Runoff coefficient frequency for annual rainfall & simulated discharge (without baseflow)

Ranges of runoff coefficient	Frequency of runoff coefficient
0.100= \leq RC= \leq 0.2	0
0.201= \leq RC= \leq 0.3	0
0.301= \leq RC= \leq 0.4	0
0.401= \leq RC= \leq 0.5	16
0.501= \leq RC= \leq 0.6	8
0.601= \leq RC= \leq 0.7	0
0.701= \leq RC= \leq 0.8	0
0.801= \leq RC= \leq 0.9	0
0.901= \leq RC= \leq 1.0	0
Total	24

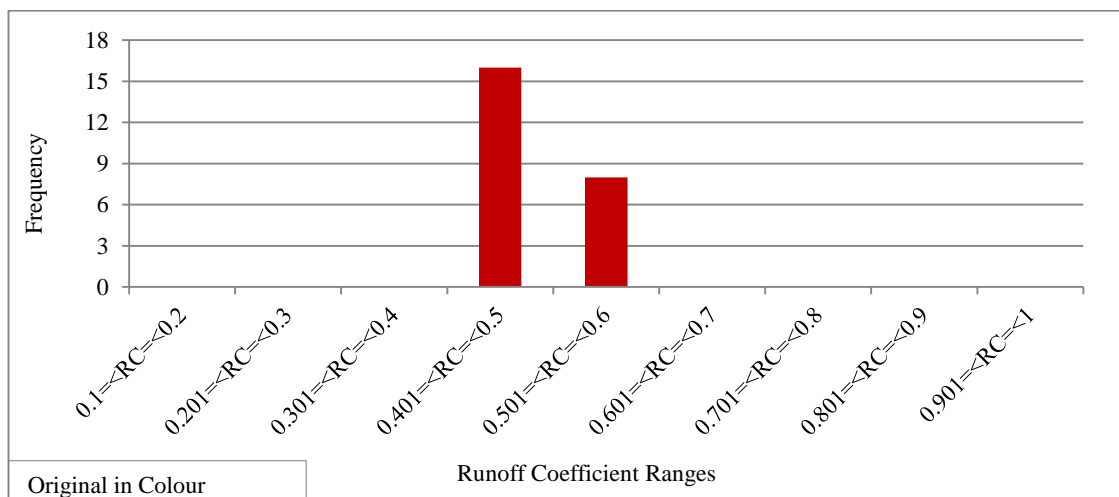


Figure 5.13: Runoff coefficient frequency for annual rainfall and simulated discharge (without baseflow) (1990 - 2013)

The ranges and its frequency of runoff coefficient were calculated using annual rainfall and simulated discharge which is exclusive of baseflow. The maximum frequency of runoff coefficient lies between the ranges of 0.4 to 0.5 as shown in the Table 5.12 and Figure 5.13.

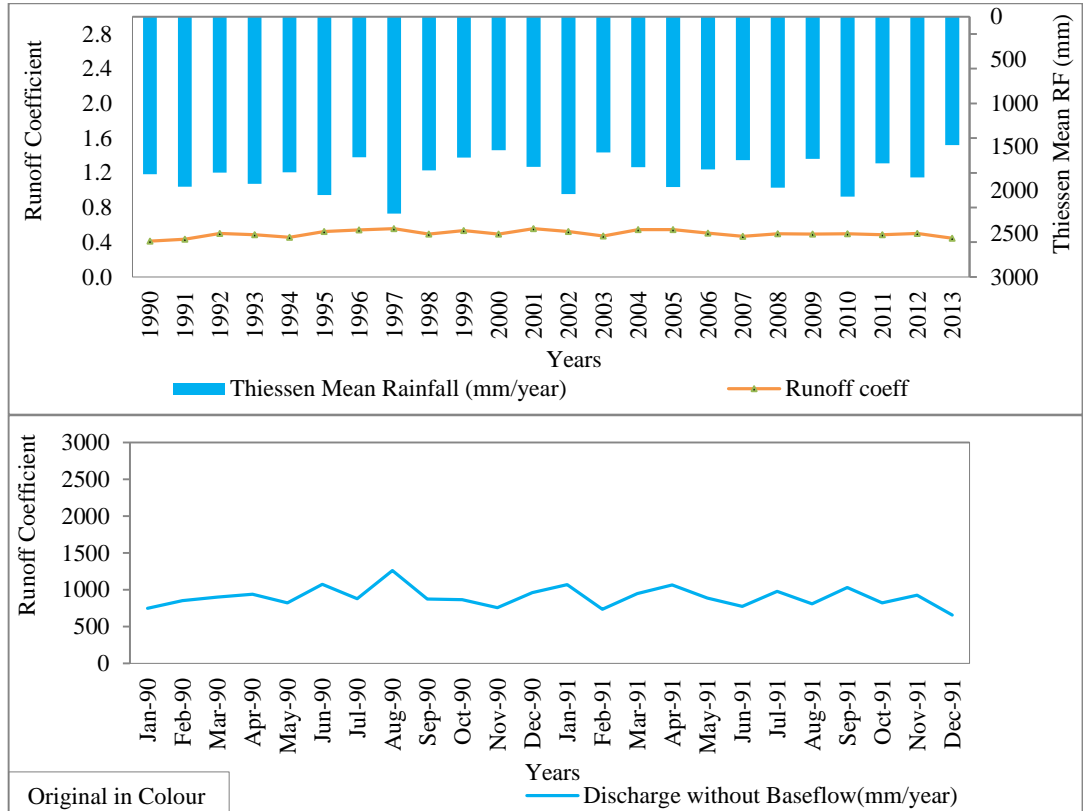


Figure 5.14: Comparison of annual rainfall, discharge (without baseflow) and runoff coefficient (1990 – 2013)

The Figure 5.14 shows the comparison of annual rainfall, simulated discharge (exclusive of baseflow) and runoff coefficient. It is observed that the pattern of flow is same such that higher rainfall has high streamflow and runoff coefficient at same time period.

5.6 Comparison of Runoff Coefficient with and without Baseflow

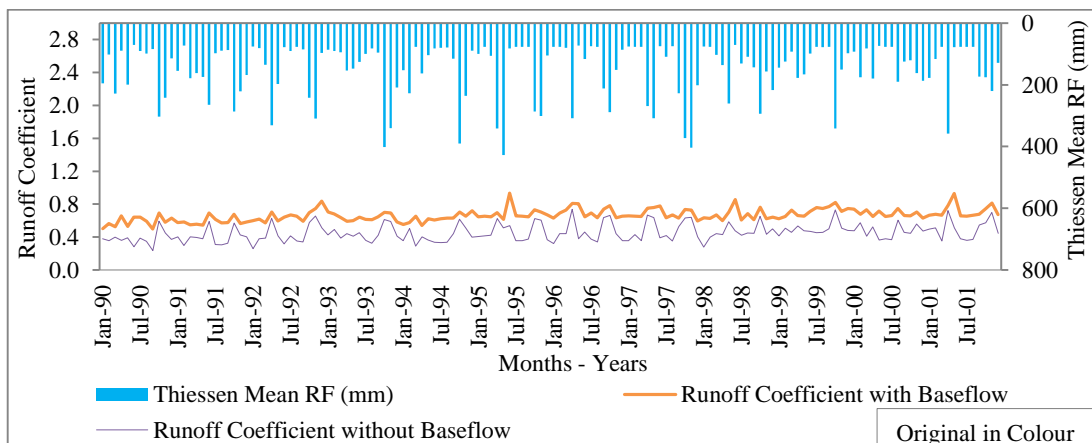


Figure 5.15: Comparison of runoff coefficient with and without baseflow (1990 – 2001)

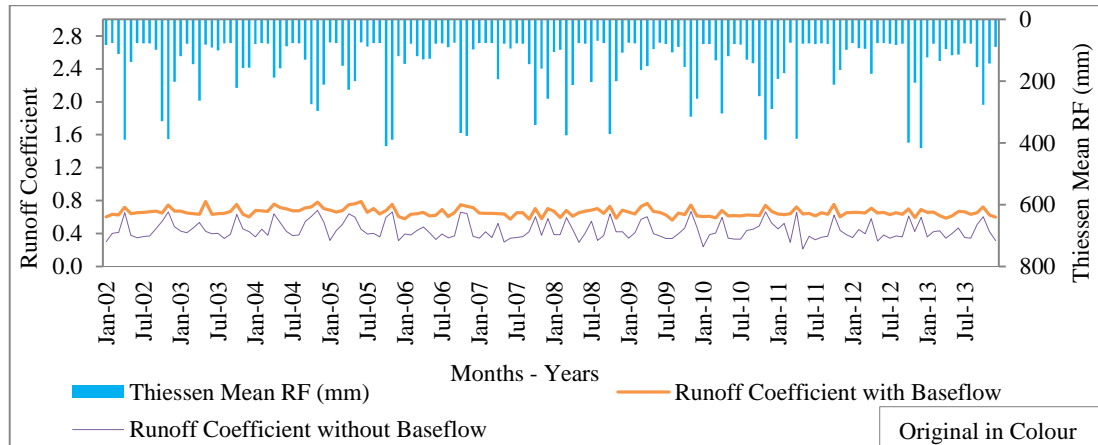


Figure 5.16: Comparison of runoff coefficient with and without baseflow (2002 – 2013)

The Figure 5.15 and 5.16 shows the runoff coefficient for monthly rainfall and simulated discharge with and without baseflow. It was computed by taking the ratio of simulated discharge to rainfall such that the values of runoff coefficient for streamflow without baseflow are high during peak rainfall. This is due to high volume of runoff flowing over the basin and over saturation of subsurface where the infiltration is minimized.

5.7 Scenario Analysis

Based on the same values of modeled parameters, the scenario analyses were carried out for the water resources assessment in the basin. The Hydrology Division of the Irrigation Department has stopped to record the stream discharge since 2014, which is after commissioning of existing Deduru Oya reservoir. Therefore, it is not possible to validate the results of scenario analysis. However, the scenario analysis relating to study was carried out to observe the scenarios in the basin and at the same time it will provide as a reference and scope for the future researchers in the same field.

5.7.1 Discharge simulation for sub-catchments

The basin was divided into two sub-catchments; upper and lower sub-catchment as shown in the Figure 5.17. Other than Initial Discharge parameter, the value of parameters was taken as the same as of optimized parameters which were used for modeling. The value of Initial Discharge parameter was taken according to area of particular sub-catchment. The discharge from the upper sub-catchment was simulated considering the Thiessen mean rainfall. The coverage of area in each sub-catchment is shown in the Table 5.13.

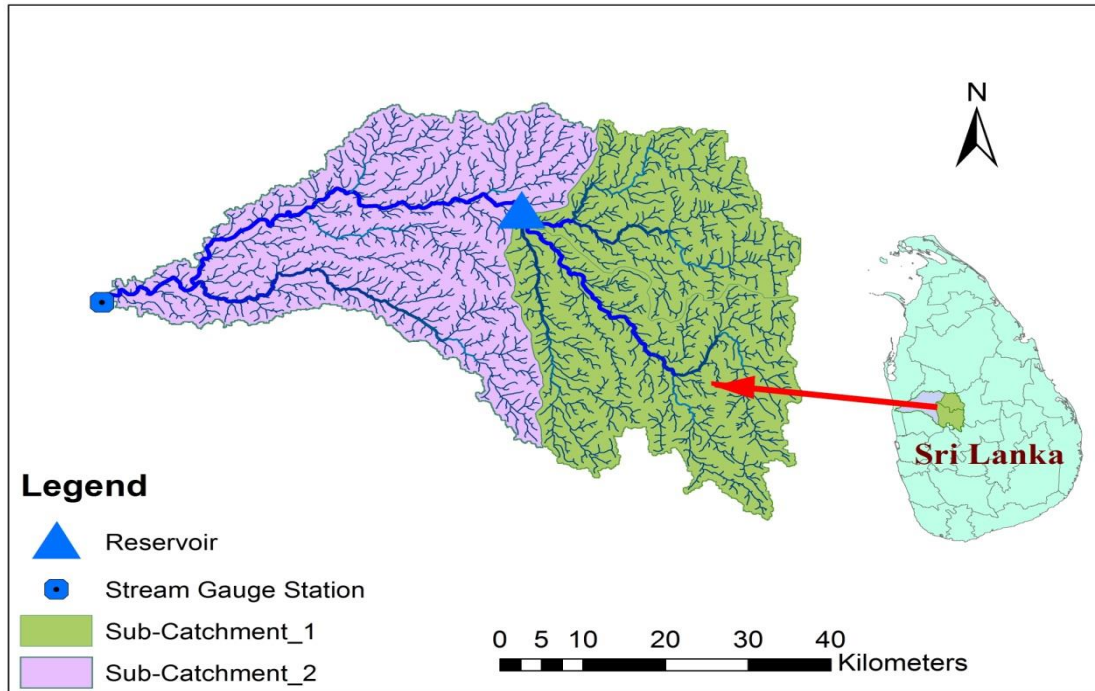


Figure 5.17: Sub-catchments map of Deduru Oya basin

Table 5.13: Area coverage of sub-catchments in Deduru Oya basin

Sl. No.	Catchment	Area (km ²)
1	Entire basin	2597.76
2	Sub-catchment-1 (upstream)	1371.99
3	Sub-catchment-2 (downstream)	1225.77

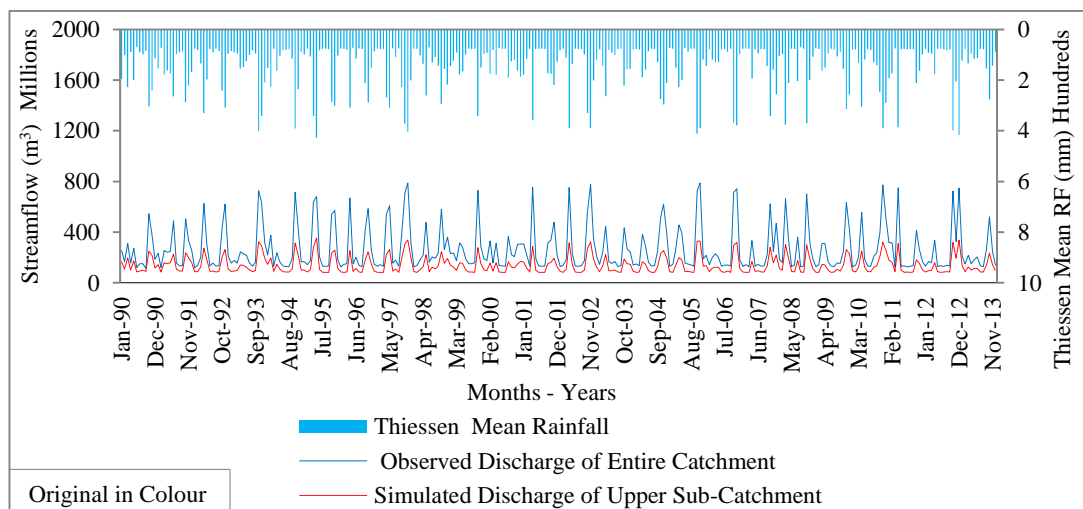


Figure 5.18: Hydrograph for observed discharge of entire basin and simulated discharge for upper sub-catchment (1990 – 2013)

The Figure 5.18 shows the hydrograph for upper sub-catchment which was modeled using same parameter values of Runoff Coefficient (0.5) and Baseflow Contribution Coefficient

(0.07). But the Initial Discharge was changed to $2.38 \times 10^7 \text{ m}^3/\text{month}$ according to its area. These simulated discharges were passed to the lower sub-catchment (1225.77 km^2) as an inflow. In the same manner, using same values of other two modeled parameters and Initial Discharge value of $2.12 \times 10^7 \text{ m}^3/\text{month}$, the discharge from the lower sub-catchment which is inclusive of discharge simulated for upper catchment as an inflow was calculated at the same outlet of observed discharge. The hydrograph was developed for observed and simulated discharge to compare its flow pattern as shown in the Figure 5.19.

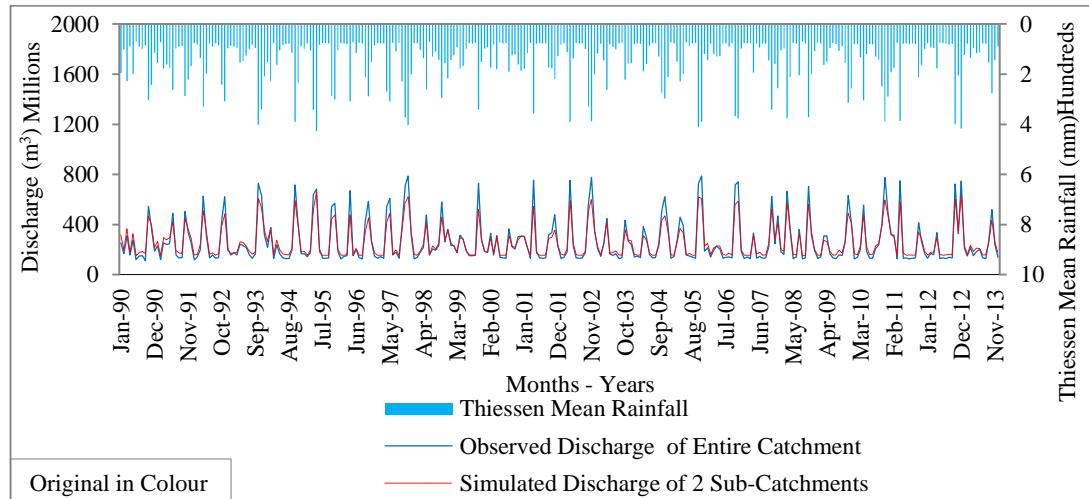


Figure 5.19: Hydrograph for observed discharge of entire basin and sum of two sub-catchments discharge (1990 – 2013)

The summation of discharge for two sub-catchments was validated with the observed discharge. As compared to simulation of discharge for entire basin, the simulated discharge based on sub-catchment wise flows using the same values of parameters has led to better performance of the model. The difference in model performance for discharge simulation is shown in the Table 5.14. The value of MRAE has reduced to 0.15 from 0.17 whereas the value of NSC and R^2 has remained same.

Table 5.14: Difference in model performance for discharge simulations considering entire basin and sub-catchments

Catchment	Error estimate		
	MRAE	NSC	R^2
Entire basin	0.17	0.91	0.98
Sub-catchments	0.15	0.91	0.98

5.7.2 Model extension for discharge simulation

There is no recorded streamflow data with effect from 2014 till to date to validate the simulated discharge. However, this simulated discharge maybe used for the water resources planning and assessment. Sharifi (1996) has stated that the short streamflow can be used to calibrate the model and then streamflow can be extended as long as the rainfall record is available. Therefore, to compute the discharges, the monthly rainfall of same stations from 2014 to August, 2015 was collected from the Department of Meteorology.

In order to analyze the difference in discharges with and without reservoir, the model has been extended based on same value of three parameters from 2014 to August, 2015 as shown in the Figure 5.20. This is to fill the gap of discharge simulation till October, 2014 as the existing reservoir was started to function with effect from November, 2014.

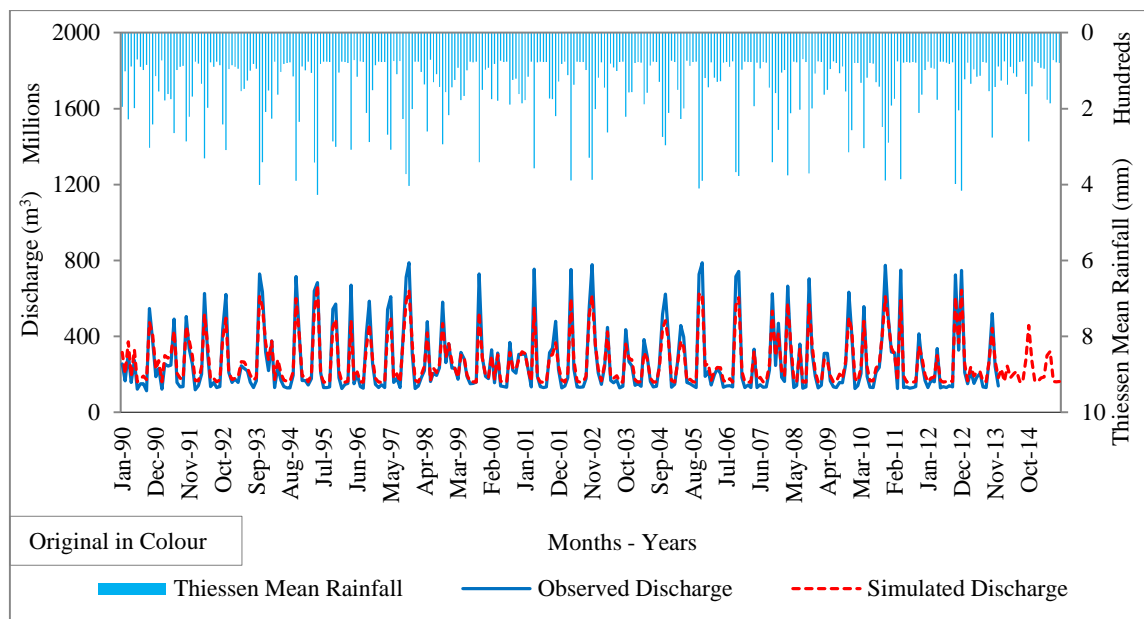


Figure 5.20: Simulated discharge from 1990 to August, 2015

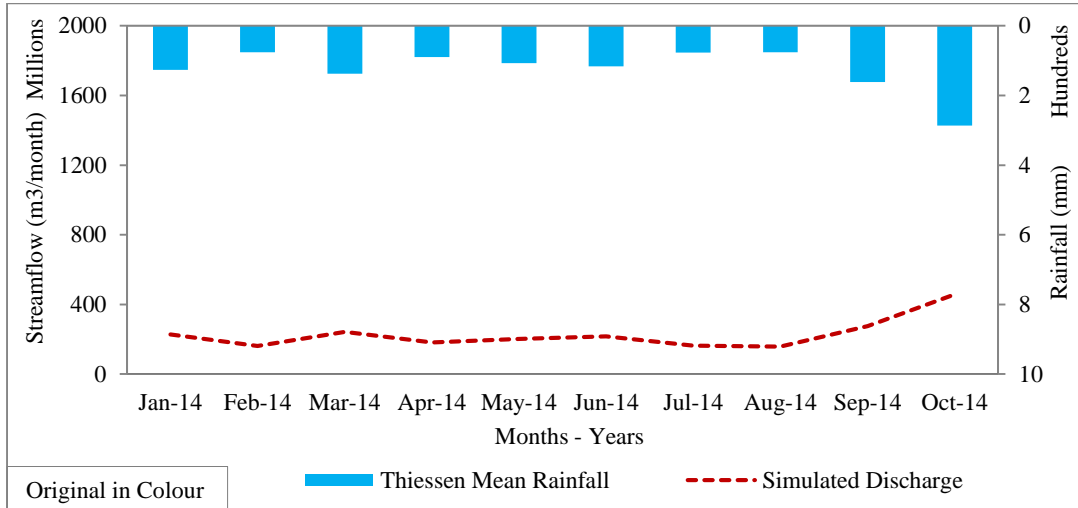


Figure 5.21: Simulated discharge with rainfall from January to October, 2014

Table 5.15: Comparison of simulated discharge with observed discharge from January to October, 2014

Months	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct
Observed discharge, m ³ in million (2013)	209	149	216	152	185	197	133	129	271	519
Observed discharge m ³ in million (2012)	187	169	161	183	129	181	129	139	196	524
Simulated discharge m ³ in million (2014)	228	161	243	177	202	216	162	157	176	458

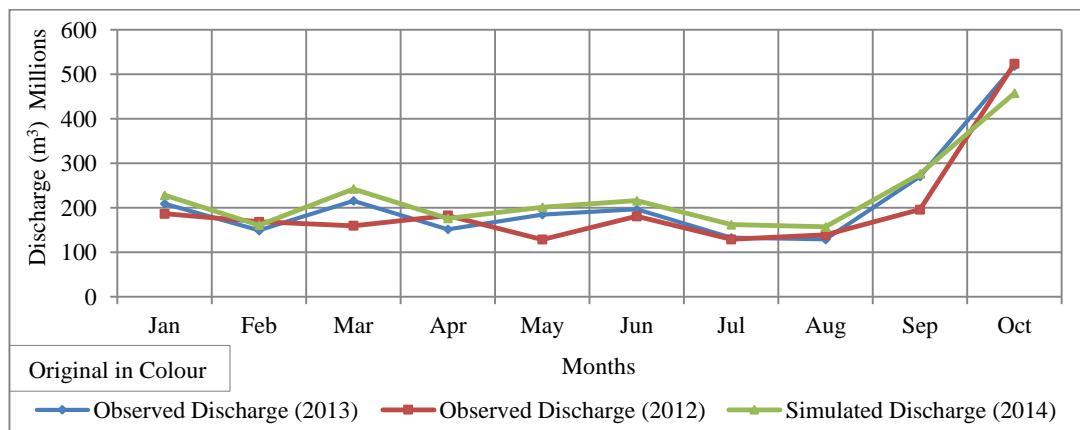


Figure 5.22: Comparison of simulated discharge with previous years' observed discharge

A separate graph between rainfall and simulated discharge from January to October, 2014 has been extracted from the Figure 5.20 as shown in the Figure 5.21. It is found that the basin have responded to the rainfall where the streamflow is high when the rainfall is high and vice versa. The simulated discharge was compared with observed discharge of year 2012 and 2013 as shown in the Table 5.15 and Figure 5.22 to check the flow pattern.

Table 5.16: Discharge through gates and sluices of reservoir

Months - Years	Discharge through gates (m³)	Discharge through sluices (m³)
Nov-14	133.00	7.50
Dec-14	87.62	5.59
Jan-15	24.27	5.35
Feb-15	29.13	5.64
Mar-15	47.92	8.72
Apr-15	97.31	5.65
May-15	65.34	8.16
Jun-15	79.39	2.25
Jul-15	80.85	4.84
Aug-15	30.62	8.04

The existing Deduru Oya reservoir was commissioned and started to function from November, 2014 and the water has been discharged through sluice and gate openings. The water discharged through gate openings flows to downstream channel and the water discharged through sluices is for the irrigation. The quantity of water discharged through gates and sluices were collected for the study from Irrigation office of Wariyapola Division, Sri Lanka as shown in the Table 5.16. According to Ponrajah (1984), 20% of water quantity used for irrigation can be reused as a return flow to the downstream. Therefore, 20% of water discharged through sluices has been added to downstream as an inflow and simulated the discharge incorporating the lower sub-catchment. The discharges comparing with and without reservoir for the period November, 2014 to August, 2015 is shown in the Figure 5.23.

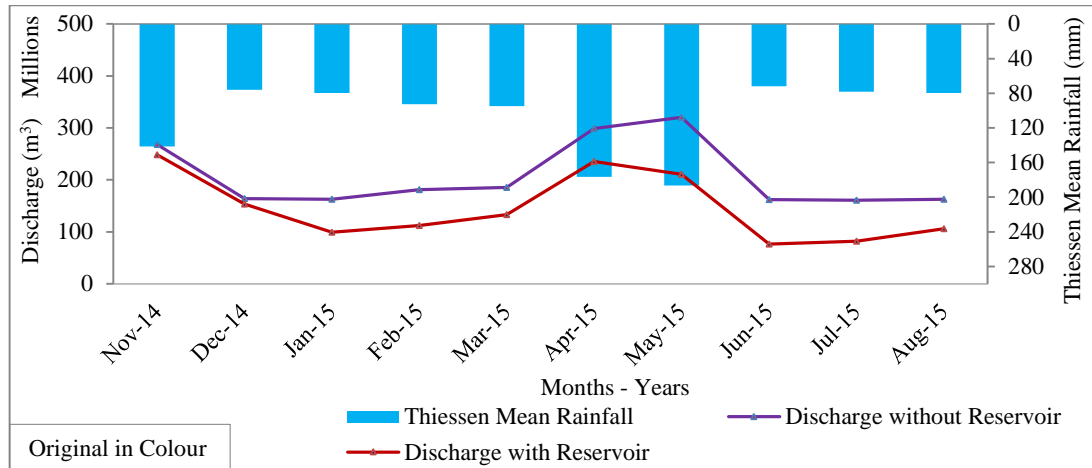


Figure 5.23: Comparison of rainfall, discharge with and without reservoir

5.7.3 Flood control by the reservoir

Table 5.17: Difference in discharge due to presence of existing reservoir

Months- Years	No- '14	Dec- '14	Jan- '15	Feb- '15	Mar- '15	Apr- '15	May- '15	Jun- '15	Jul- '15	Aug- '15
Discharge with reservoir (m ³ in million)	267	163	162	180	185	298	320	162	160	162
Discharge without reservoir (m ³ in million)	239	155	999	113	135	240	211	766	811	106

As shown in the Table 5.17, considering the scenario without existing reservoir till August, 2015 a total of $2062 \times 10^6 \text{ m}^3$ water within 10 months (November, 2014 to August, 2015) was passed through the outlet of entire basin and with existing reservoir a total of $1467 \times 10^6 \text{ m}^3$. Hence, 70.69% of water quantity has been stored by the existing reservoir and the flood peak in May, 2015 was reduced by 66.04% in relation to the flood effect for the downstream.

6 DISCUSSION

6.1 Data Checking

The data checking process has provided agreeable results with a maximum number of missing rainfall data at Millawana station. The monthly rainfall in the basin was found to be between the range of 69.45 mm - 427.35 mm and annually between 1,469.96 mm – 2,270.23 mm. Out of five rain gauge stations, Kurunegala station located in the most upstream receives the highest rainfall. The monthly streamflow varied between ranges of 109.55 MCM - 762.60 MCM and annually in the range of 2,503.93 MCM – 4,142.54 MCM. The monthly average evaporation diverged between the range of 1.45 mm - 5.71 mm and between 34.39 mm - 45.72 mm for the annual series.

The runoff coefficient for entire basin which was calculated using land use types corresponding to its standard coefficient according to Department of Irrigation, Sri Lanka is 0.38. Comparing to optimized runoff coefficient (0.5) and average runoff coefficient of basin which was calculated using monthly rainfall and observed discharge (0.66) is higher than the runoff coefficient calculated based on land use types. This is because of infrastructure developments taking place in the basin where the land surfaces have become more impervious (low infiltration), and as a result the losses of runoff has reduced and it contributes to increased runoff and subsequent flooding in the downstream. Determining of runoff coefficient and its variation with the major parameters is important for water resources assessments giving due consideration to the soil, slope and land use variations in the basin.

6.2 Rainfall and Streamflow Data Error

The rainfall and streamflow contain some errors due to errors in meteorological input data and errors in recorded observations. Consequently, the data input to rainfall-runoff model leads to an accumulated error in model output where the parameter values are optimized for calibration. However, the error in rainfall data is at times compensated by the errors in the parameter values. The quality and length of the data used for model calibration matters on how close the model is actually able to simulate the long-term and short-term hydrological behavior of the catchment.

6.3 Catchment Runoff Generation

Understanding the catchment yield, and how this varies in time and space, particularly in response to climate variability, i.e. seasonally, inter-annually, etc., is important for the modelers and planners. It is useful for estimating the relative contributions of individual catchments to water availability over the sub-catchments of a basin scale and for estimating how this catchment yield and predicting its change in water availability over the time in response to changes in the catchment such as increasing development in land use and land management.

For this study, the runoff generation in a basin was based on two main components; (1) surface runoff and (2) subsurface runoff. The surface runoff is generated by the consideration of Thiessen mean rainfall over the catchment area with the multiplication of runoff coefficient. In case of subsurface runoff, it has included the groundwater contribution to the channel system as rapid groundwater flow in the upper part of initially unsaturated subsurface and as delayed groundwater flow in the lower part of the saturated subsurface. In the model, the delayed groundwater flow was added with the rapid groundwater (previous and present month runoff) flow with the multiplication of Baseflow Contribution Coefficient. Therefore, the streamflow consists of both surface and subsurface runoff which enables the model to simulate high flows and dry flow conditions individually and more effectively.

6.4 Model Parameter Optimization

The three parameters of the model have been optimized manually based on trial and error method. The value of Mean Ratio of Absolute Error (MRAE) and Nash-Sutcliffe Coefficient (NSC) for calibration and verification are 0.17 and 0.19, and 0.91 and 0.90, respectively. The obtained values are within the permissible limits and they were used for the model calibration and validation. The optimized parameter values of model might have involved error due to spatial and temporal distribution of basin, inconsistency and variation in the input data, method of optimization and the types of objective function used. Commonly, there is a significant decrease in model efficiency on validation period compared to the calibration one (Klemes, 1986).

6.5 Model Calibration and Validation

The calibration scheme has included optimization of Mean Ratio of Absolute Error (MRAE) and Nash-Sutcliffe Coefficient (NSC) as objective function that has measured the different aspects of the hydrograph: (1) overall water balance, (2) overall shape of the hydrograph, (3) peak flows, and (4) low flows. The process of model calibration was done manually where a trial-and error parameter adjustment was made. The goodness-of-fit of the calibrated model was performed based on the optimized parameter values and visual judgment by comparing the simulated and the observed hydrographs as well. The monthly time series data from 1990 to 2001 was used for the calibration and compared with the observed discharge. The calibrated model is capable in finding the characteristics of streamflow satisfactorily. By using the monthly long term rainfall, the model with the calibrated parameters can be used for estimating streamflow at the basin outlet for the water resource assessment and subsequent planning purposes.

At the same time, the model verification is a very important step because it gives information about the real functioning of the model unlike the calibration. The dataset from 2002 to 2013 was used for the model verification such that the model parameters obtained in the calibration step were used for the evaluation in the verification phase for reliability and accuracy of model prediction. The variability of the simulated hydrograph indicates the potential errors.

6.6 Model Performance

Generally, the model has predicted the streamflow well, though minor difficulties in matching of simulated and observed monthly flows were encountered. The model performed reasonably well over the calibration period by reproducing the observed flow volumes and simulating the observed peaks in terms of timing and quantity. The predictive ability of this approach was demonstrated by comparing the simulated streamflow against the observed values. The values of coefficient of determination (R^2) of calibration and validation are 0.98 and 0.96 which are near to 1.0 (optimal value) and it indicates a good measure of the prediction quality.

6.7 Model Extension for the Scenario Analysis

The objective of the model extension is for the demonstration of the effects of desired flood management interventions and to quantify potential benefits through inundation extent and depth reduction in the downstream due to reservoir construction in the upstream. This approach was undertaken to overcome the long term data inadequacies in precipitation and streamflow time series pertaining to the required spatial and temporal resolutions. The results of streamflow simulation for the extended period has shown a reasonable quantitative agreement when it was compared with the flow pattern of stream for the previous period and response of catchment for rainfall in the same period. Analysis results indicated that due to retention/detention by the reservoir, there exists a significant impact leading to a reduced discharge in the downstream of the basin. However, during the extreme event conditions, it was observed that the peak flow was unaffected and the discharge is high as the gates and sluices were opened to release the water for the safety of the dam and to limit the upstream inundation depths, extents and durations.

6.8 Water Resources Assessment

Due to rapid increase in population, economic and technical developments, the water resources are being highly over exploited and threatened. Therefore, careful management of this invaluable natural resource is a major concern for watershed managers, in order to protect it from further degradation and prevent depletion of resources for a sustainable future. In particular, the streamflow is a key consideration in water resources management as reduction in rainfall events leading to extended dry spells contributes to periods without runoff in the catchment. The quantity of water flowing over the channel matters for the water resources utilization as well as the design and planning of river training works especially in downstream of basin.

7 CONCLUSIONS

1. Rainfall runoff model comprising of three parameters was developed, calibrated and verified with good reproduction of observed stream flows.
2. Optimized values of runoff coefficient, baseflow contribution coefficient and initial discharge are 0.5, 0.07 and 4.5×10^7 m³/month.
3. Mean Ratio of Absolute Error (MRAE) during calibration is 0.17 while the same at validation is 0.19 which is slightly weaker than the correlation observed during calibration (Both lie within the acceptable and permissible range).
4. Nash-Sutcliffe Coefficient (NSC) for calibration and validation is 0.91 and 0.90, which lies between 0 and 1, and it is acceptable.
5. Both monthly and annually computed runoff coefficient are maximum within the range of 0.6 to 0.7 with 180 and 15 frequencies of occurrence.
6. Simulation of discharge following sub-catchment wise approached has improved the model performance by 2%.
7. Using a selected extreme rainfall event (November, 2014 to August, 2015) of the basin, the model has demonstrated that the incorporation of a reservoir has stored 70.69% of the flood water volume and could reduce the flood peak by 66.04% for an extreme event observed in May, 2015.
8. The calibrated and validated rainfall-runoff model with optimized parameters provides a tool for water resources planning and decision making processes in the basin.
9. The model results can be extended to predict future stream flows based on a known rainfall data set in the basin.
10. The modelling approach can be applied to similar basins in Sri Lanka and elsewhere for water resources planning and management.

8 FURTHER RECOMMENDATIONS

1. Model for streamflow estimation is dependent on data accuracy and data resolutions, thus a systematic approach to improve data accuracy and resolutions is recommended.
2. Choice of the set of data and objective function to be used for model is a subjective decision which influences the values of the model parameters and the performance of the model. Thus, careful selection of appropriate data sets with required accuracy and resolutions for modeling is recommended.
3. Further research is recommended incorporating adequate hydrological and reservoir operation data to continue the research as the functioning of the reservoir is commenced not even a year ago and such data is presently not available.
4. Data management by the Department of Meteorology and Hydrology Division needs to be improved in future for the betterment of research progress and increased accuracy in results.
5. As a contribution from this research project, the research results can be implemented for the water resources assessment and decision making purposes in the basin, and also in basins elsewhere with similar characteristics.

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Appendix – A
Data Checking

Appendix-A: Data checking

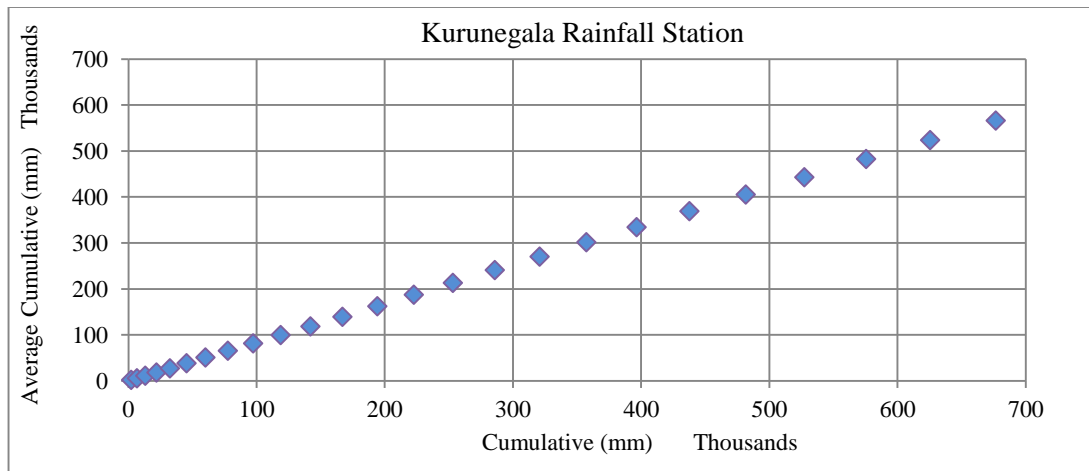


Figure A 1: Double mass curve for Kurunegala station

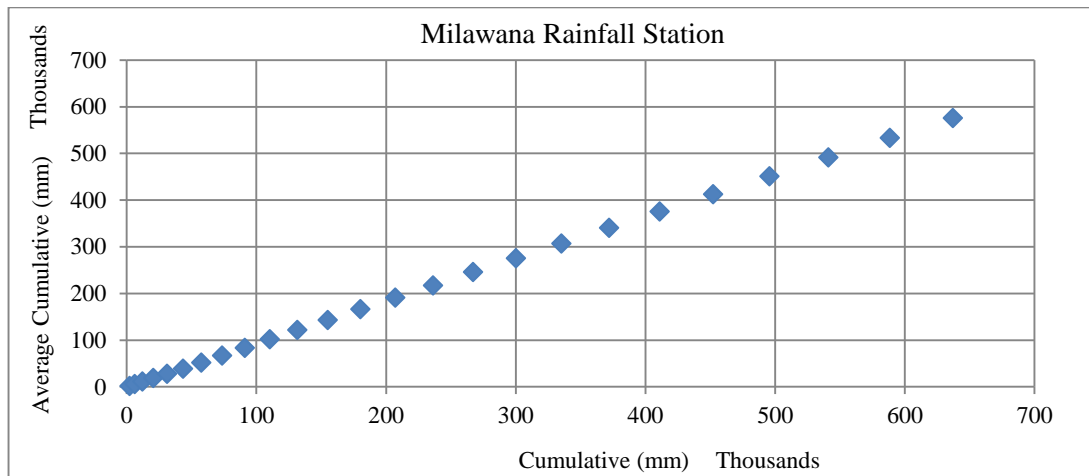


Figure A 2: Double mass curve for Milawana station

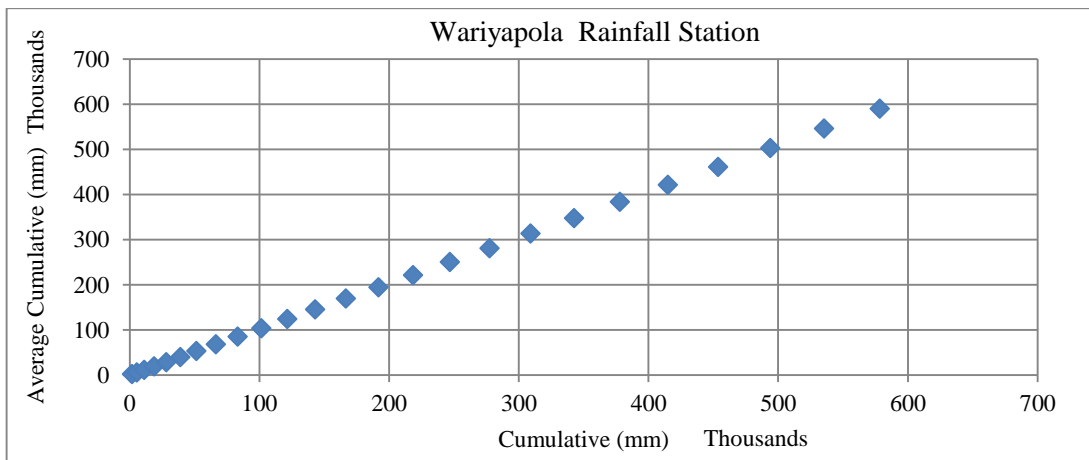


Figure A 3: Double mass curve for Wariyapola station

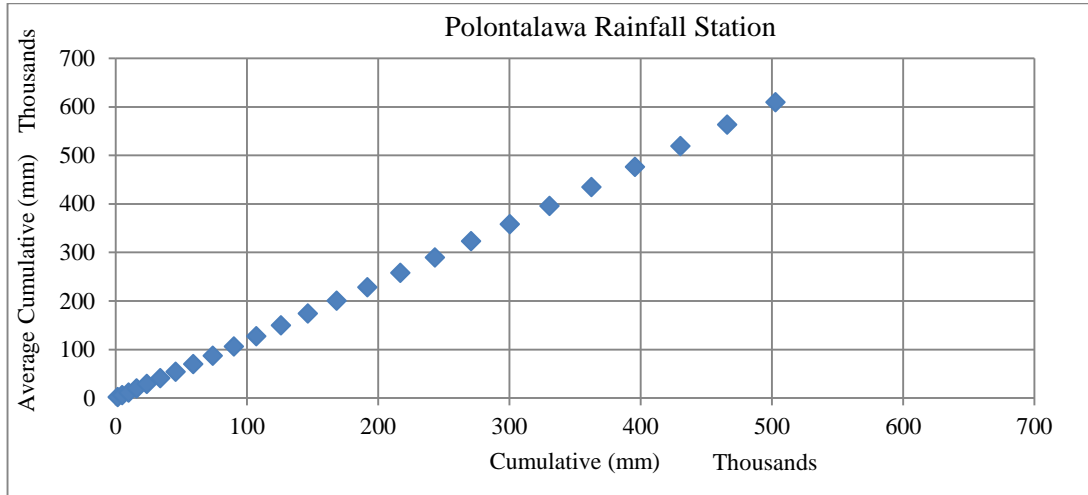


Figure A 4: Double mass curve for Polontalawa station

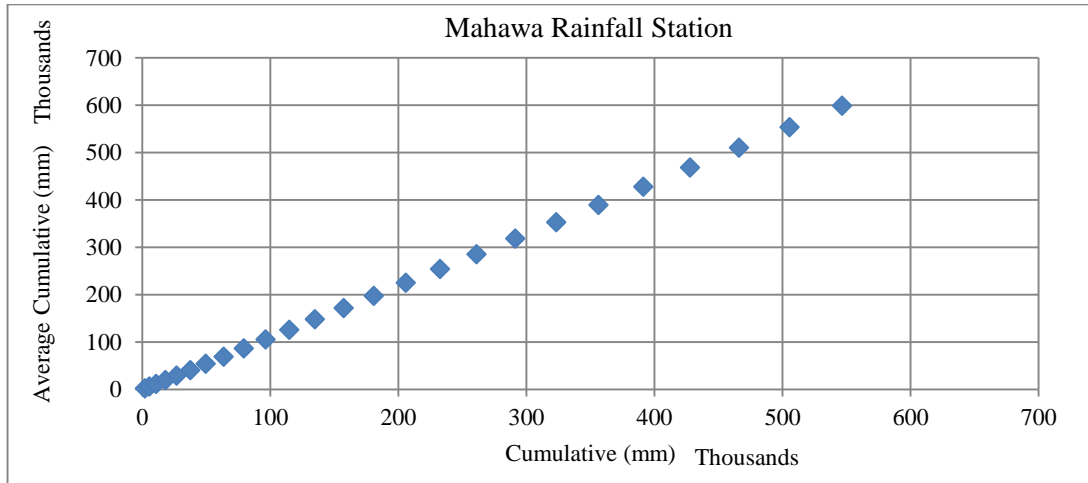


Figure A 5: Double mass curve for Mahawa station

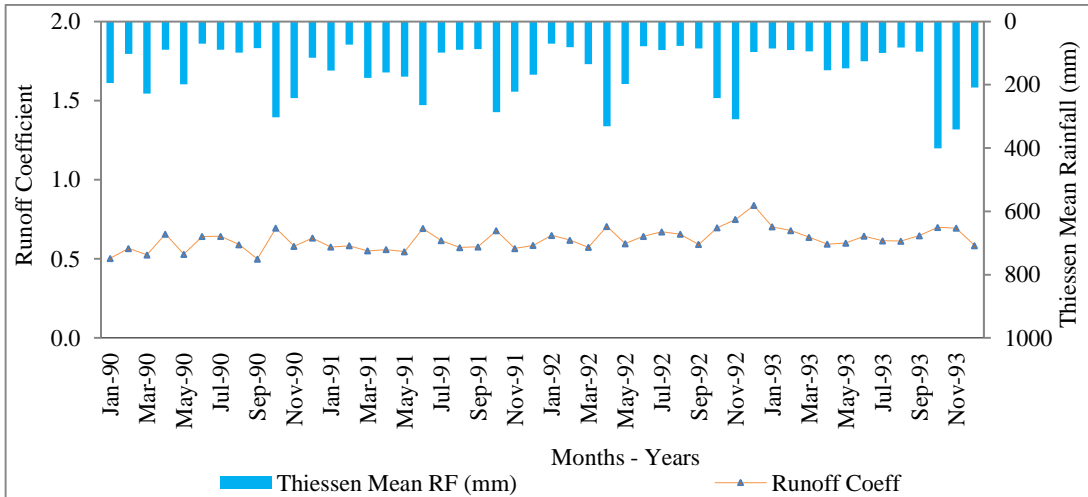


Figure A 6: Comparison of rainfall and runoff coefficient (1990 - 1993)

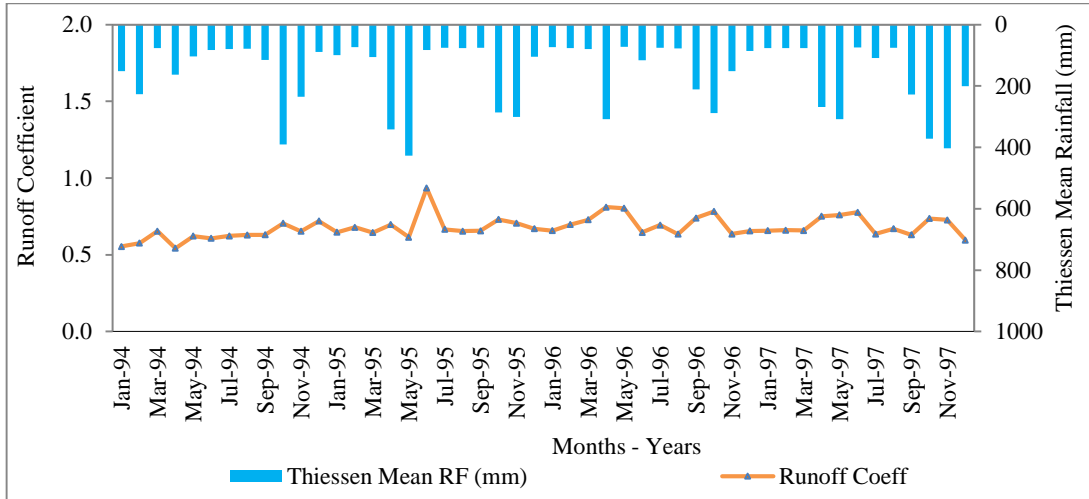


Figure A 7: Comparison of rainfall and runoff coefficient (1994 - 1997)

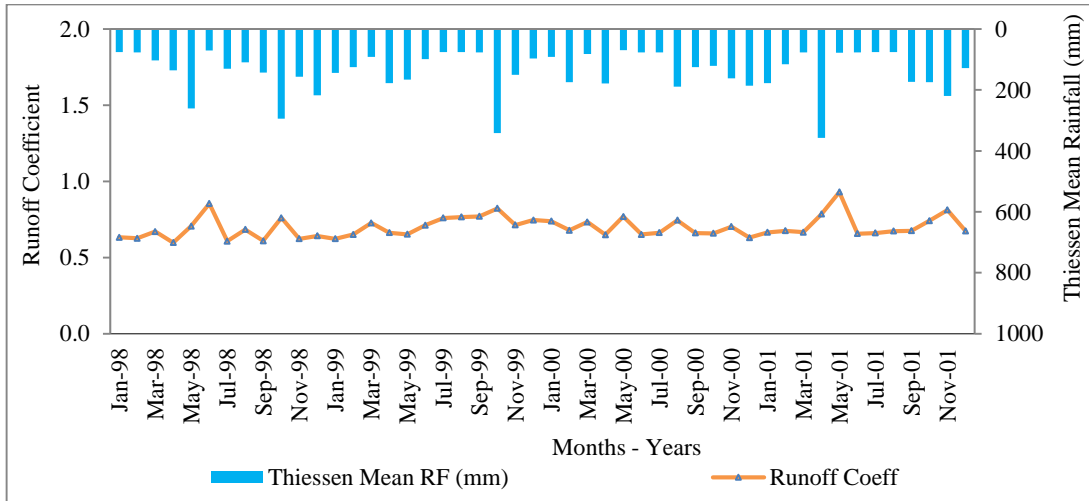


Figure A 8: Comparison of rainfall and runoff coefficient (1998 - 2001)

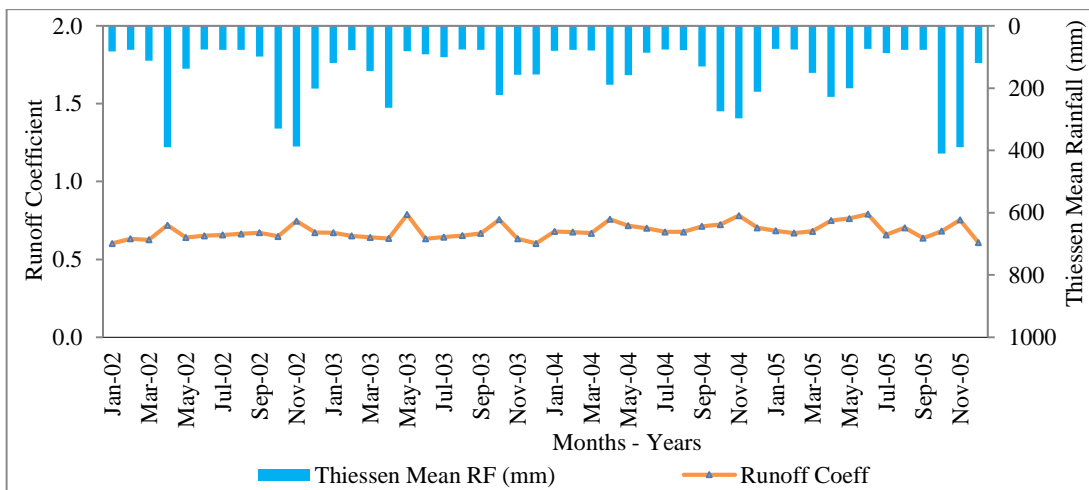


Figure A 9: Comparison of rainfall and runoff coefficient (2002 - 2005)

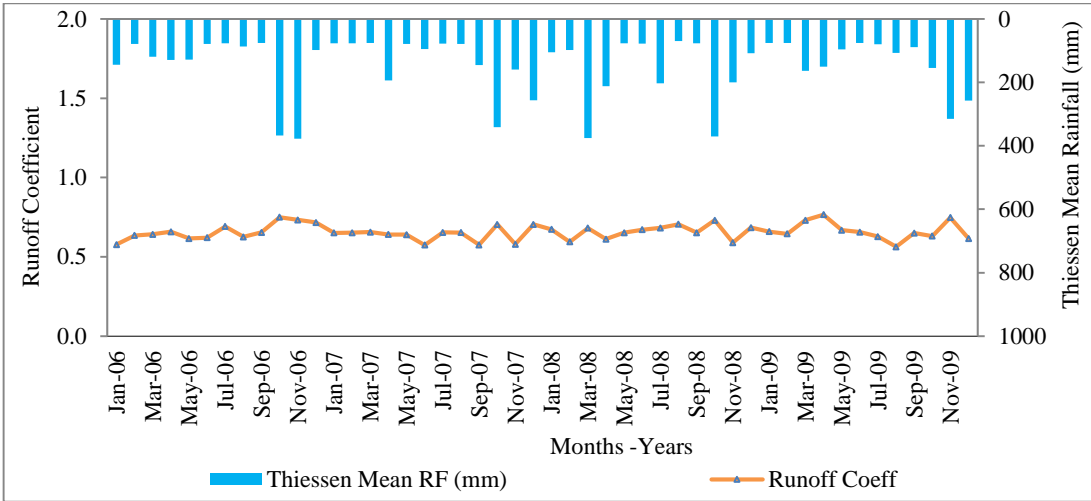


Figure A 10: Comparison of rainfall and runoff coefficient (2006 - 2009)

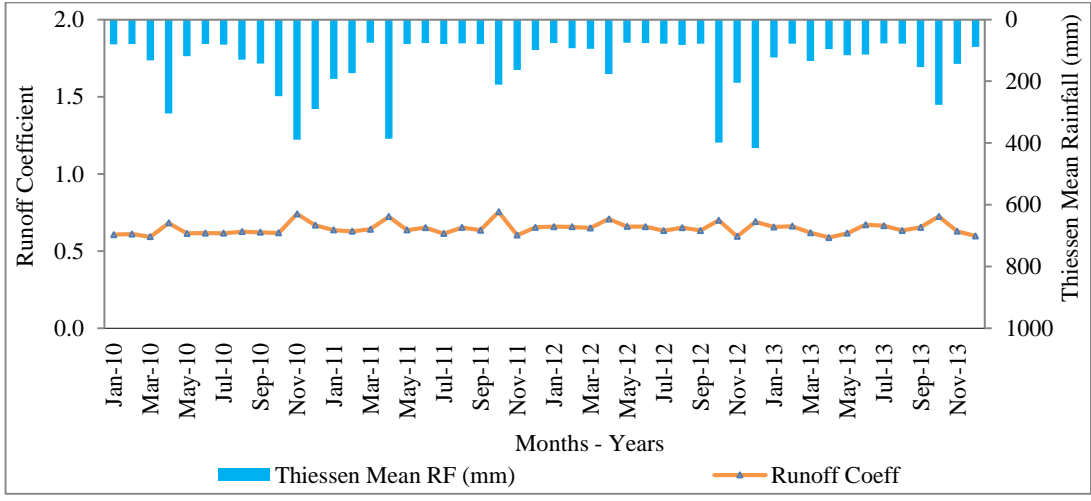


Figure A 11: Comparison of rainfall and runoff coefficient (2010 - 2013)

Appendix – B
Calibration and Validation

Appendix-B: Calibration and validation

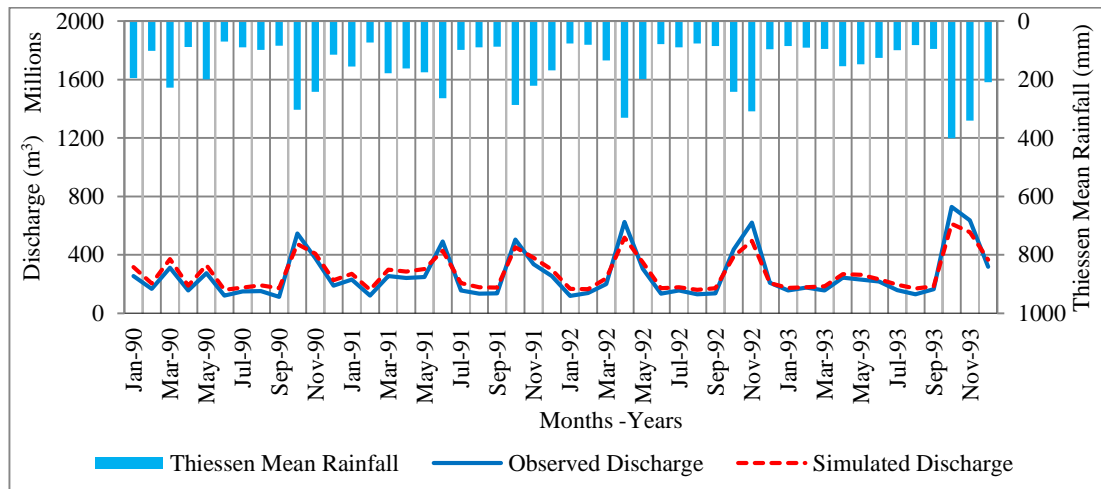


Figure B 1: Comparison of simulated and observed discharge (1990 - 1993)

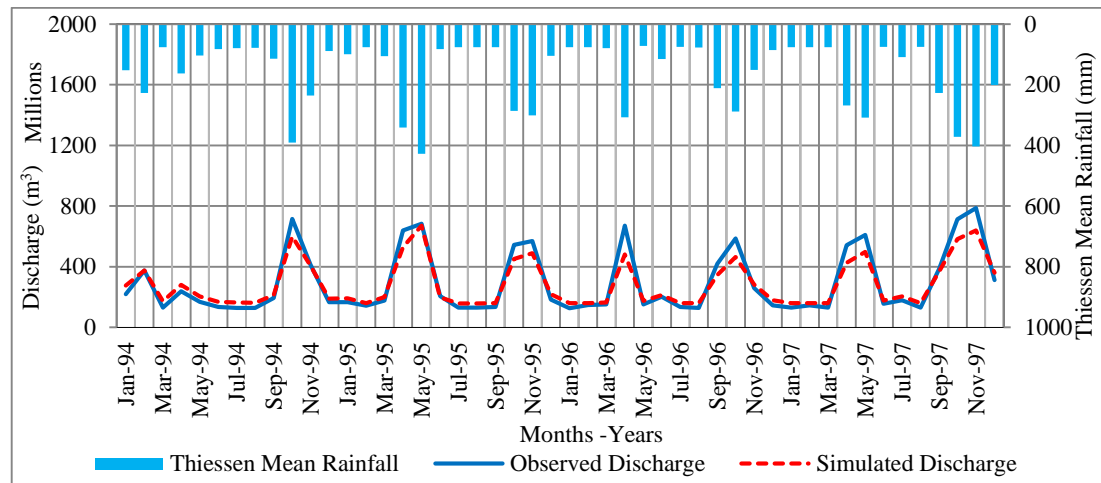


Figure B 2: Comparison of simulated and observed discharge (1994 - 1997)

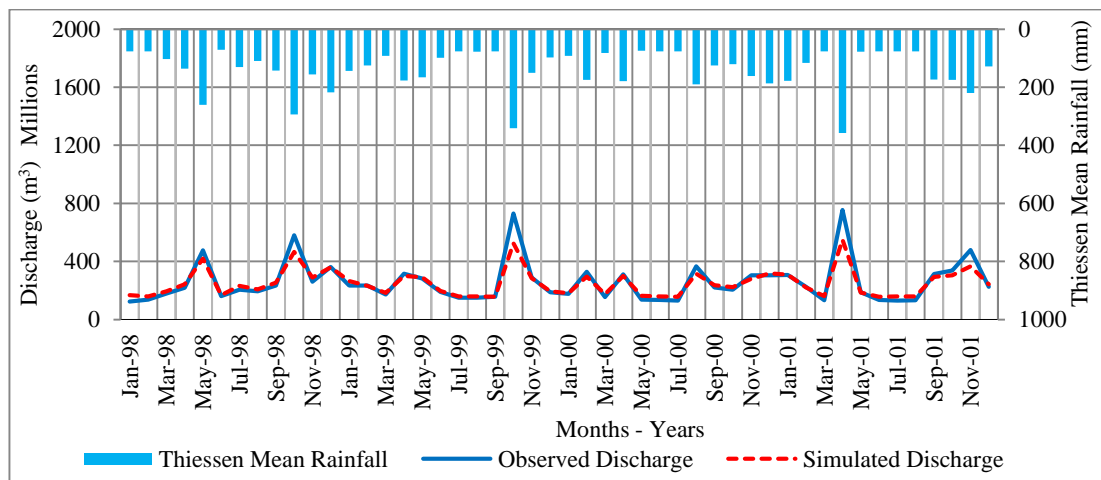


Figure B 3: Comparison of simulated and observed discharge (1998 - 2001)

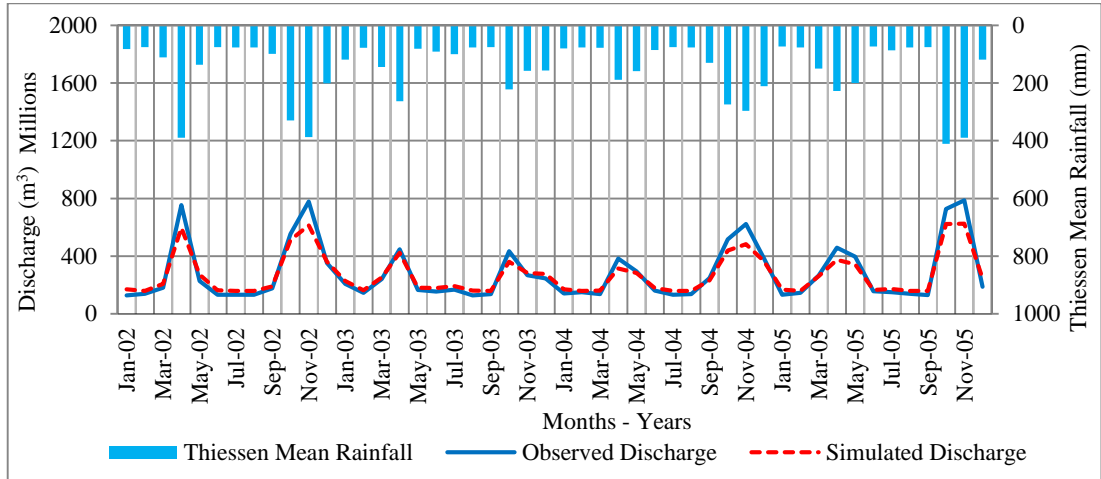


Figure B 4: Comparison of simulated and observed discharge (2002 - 2005)

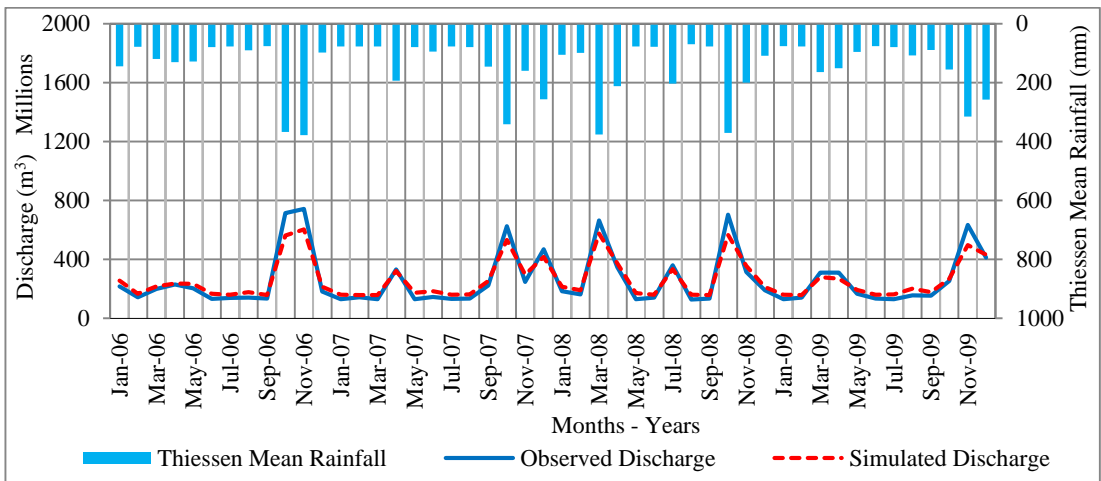


Figure B 5: Comparison of simulated and observed discharge (2006 - 2009)

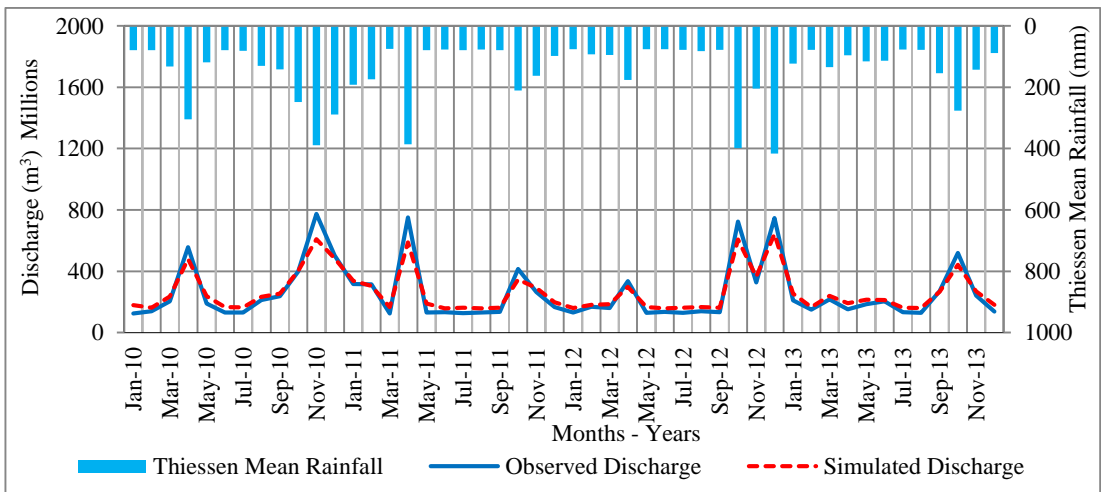


Figure B 6: Comparison of simulated and observed discharge (2010 - 2013)

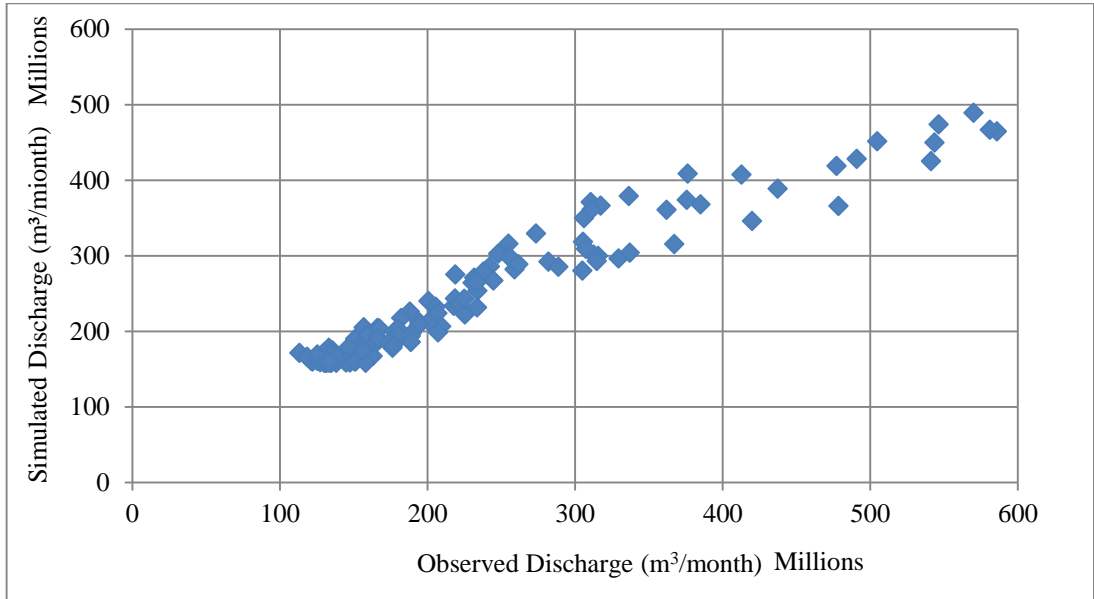


Figure B 7: Correlation between observed and simulated discharge (1990 - 2001)

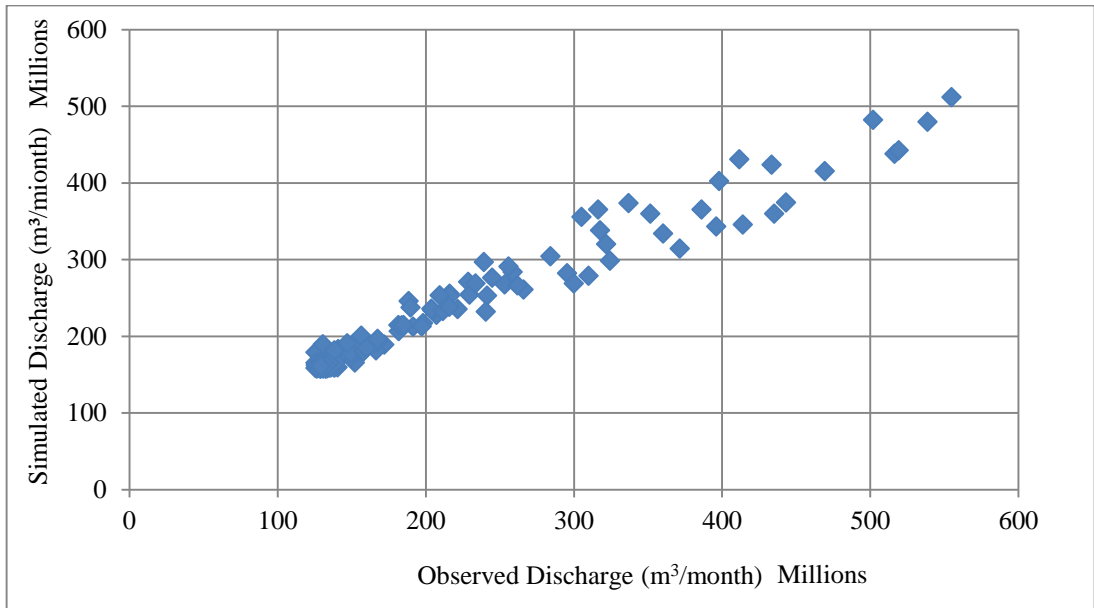


Figure B 8: Correlation between observed and simulated discharge (2002 - 2013)

Appendix – C

Discharge Simulation for Sub-catchments

Appendix-C: Discharge simulation for sub-catchments

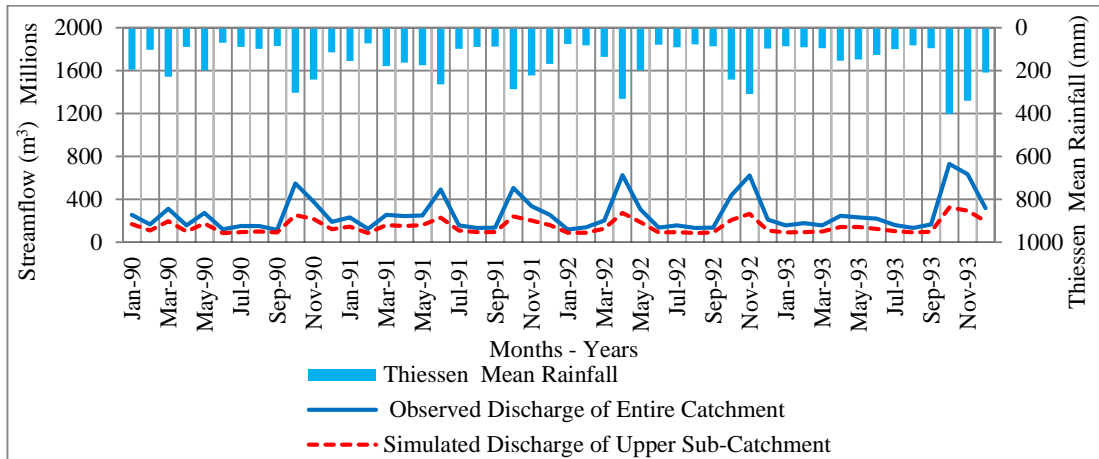


Figure C 1: Observed discharge of entire catchment & simulated discharge of upper sub-catchment (1990 - 1993)

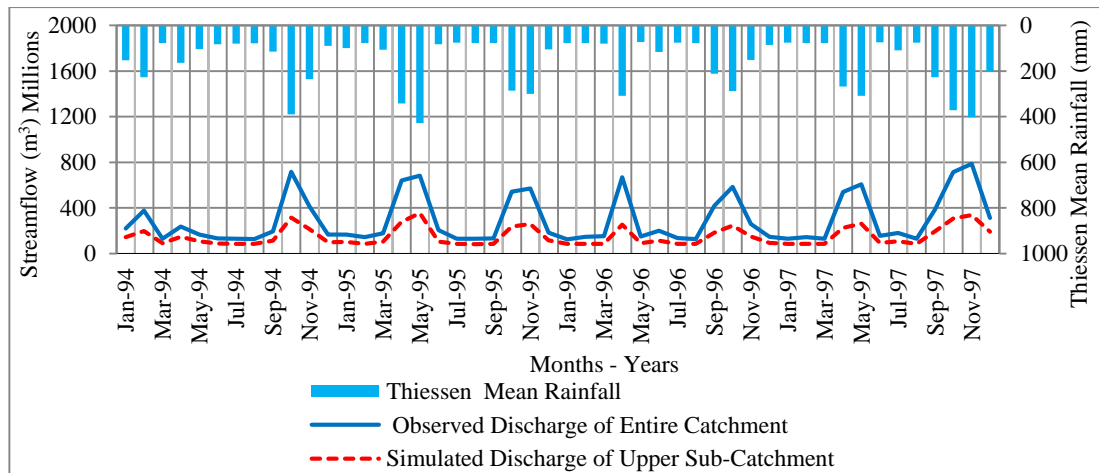


Figure C 2: Observed discharge of entire catchment & simulated discharge of upper sub-catchment (1994 - 1997)

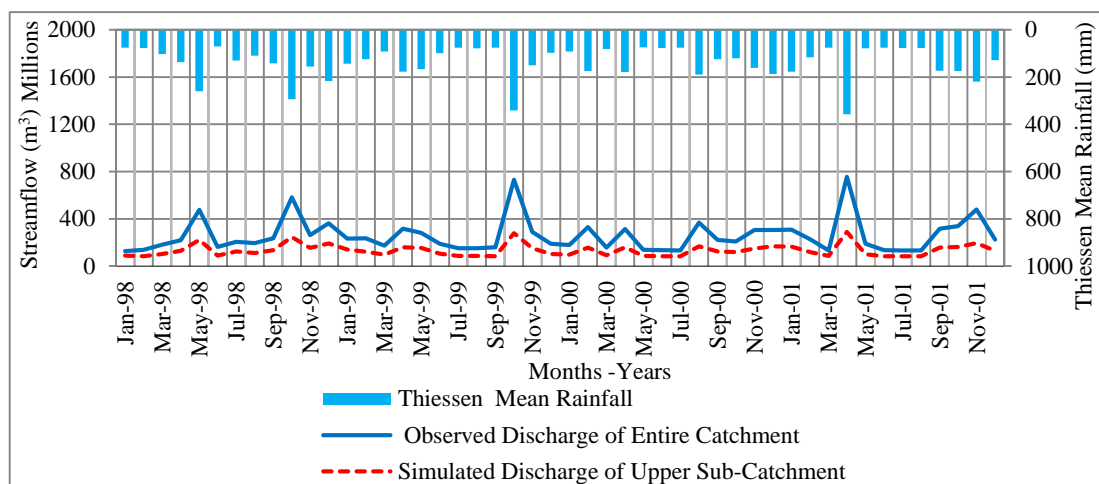


Figure C 3: Observed discharge of entire catchment & simulated discharge of upper sub-catchment (1998 - 2001)

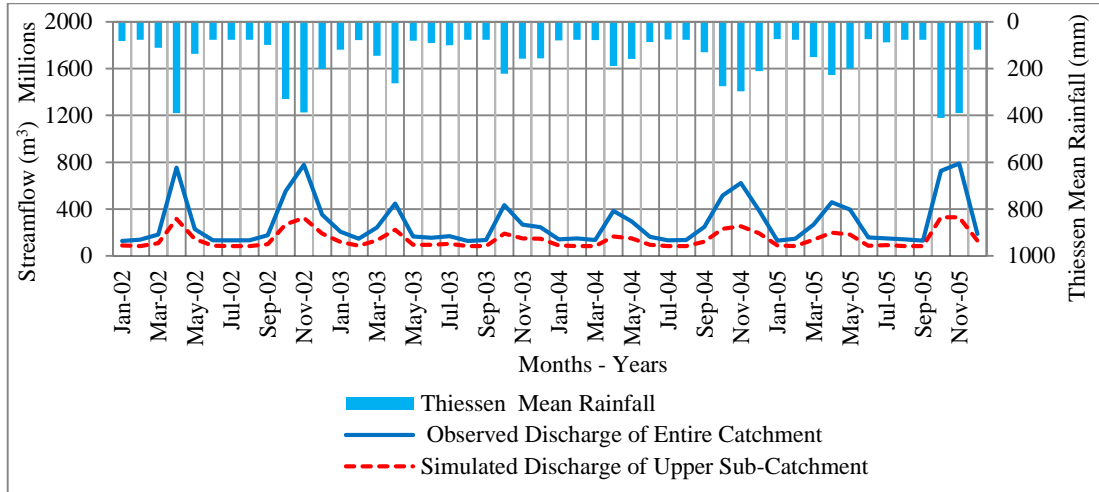


Figure C 4: Observed discharge of entire catchment & simulated discharge of upper sub-catchment (2002 - 2005)

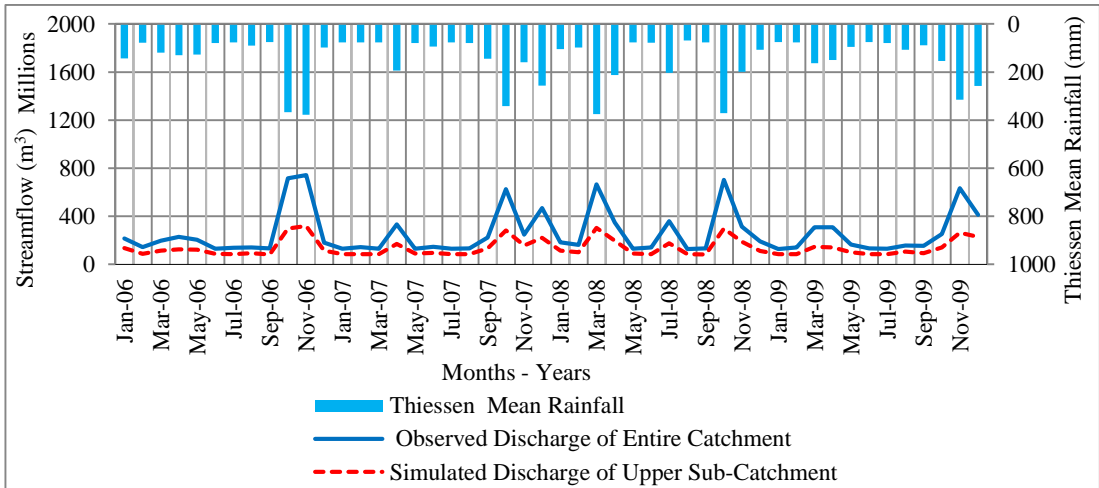


Figure C 5: Observed discharge of entire catchment & simulated discharge of upper sub-catchment (2006 - 2009)

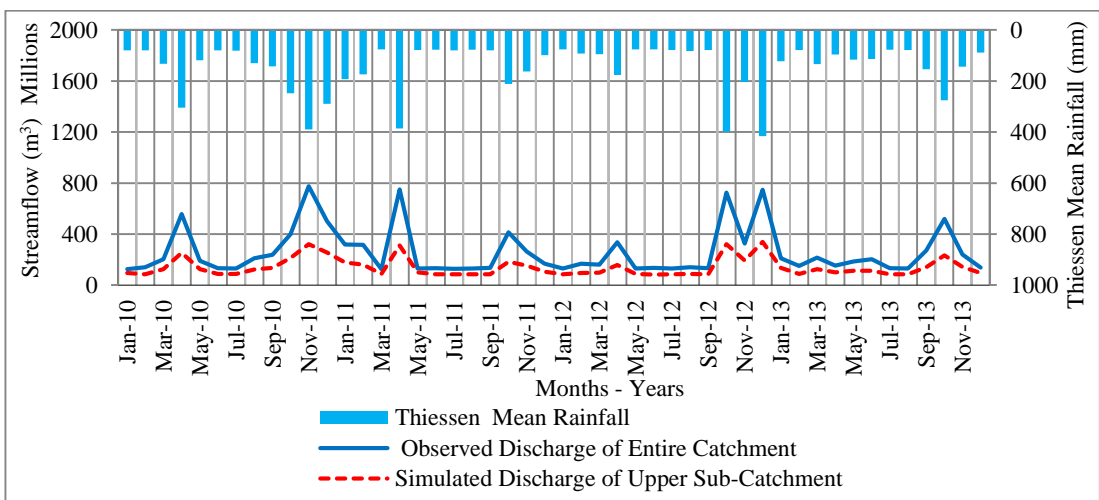


Figure C 6: Observed discharge of entire catchment & simulated discharge of upper sub-catchment (2010 - 2013)

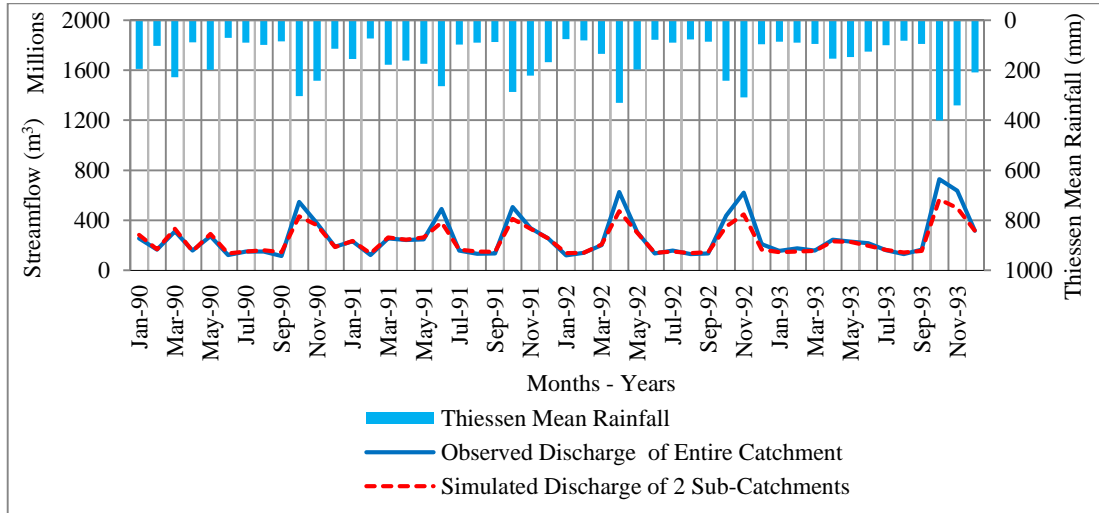


Figure C 7: Observed discharge of entire catchment & simulated discharge of 2 sub-catchment (1990 - 1993)

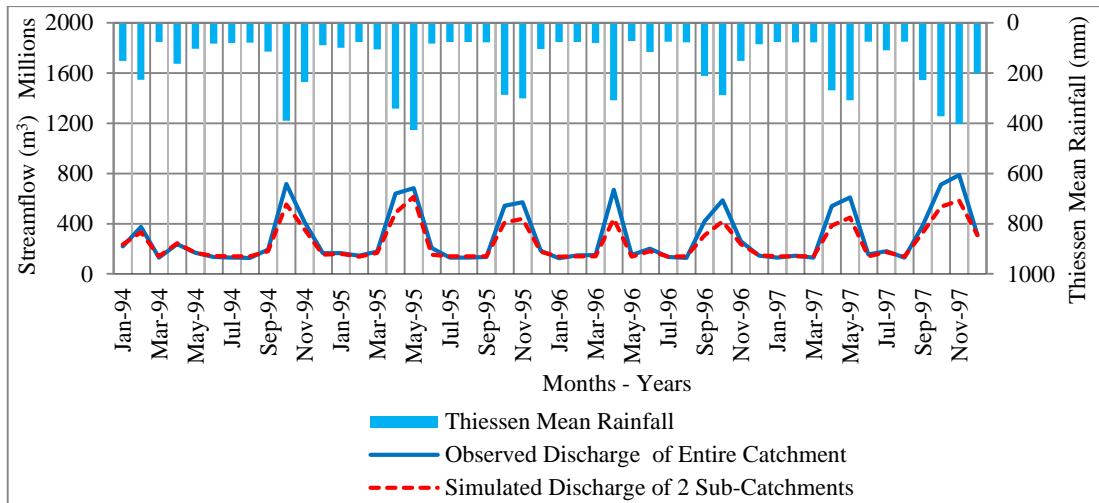


Figure C 8: Observed discharge of entire catchment & simulated discharge of upper sub-catchment (1994 - 1997)

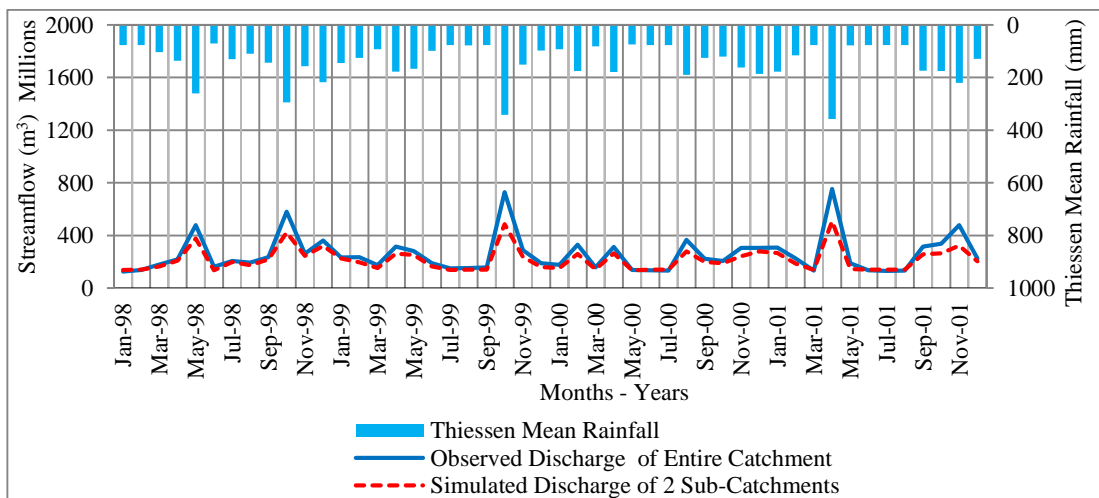


Figure C 9: Observed discharge of entire catchment & simulated discharge of upper sub-catchment (1998 - 2001)

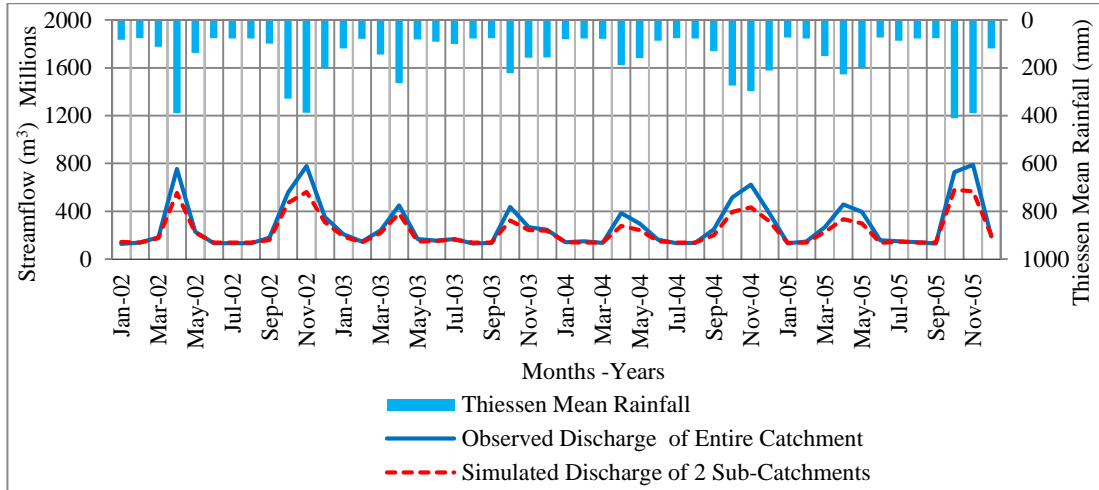


Figure C 10: Observed discharge of entire catchment & simulated discharge of upper sub-catchment (2002 - 2005)

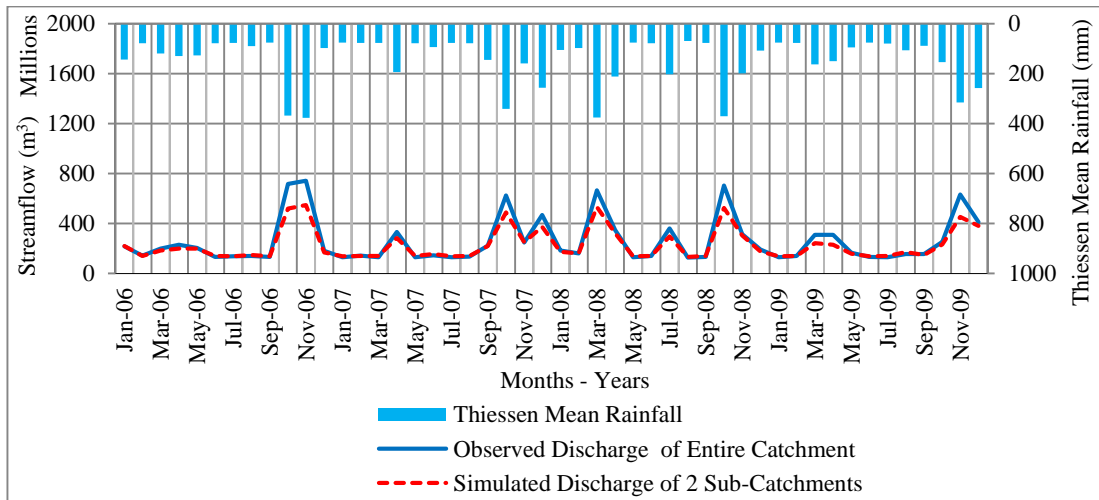


Figure C 11: Observed discharge of entire catchment & simulated discharge of upper sub-catchment (2006 - 2009)

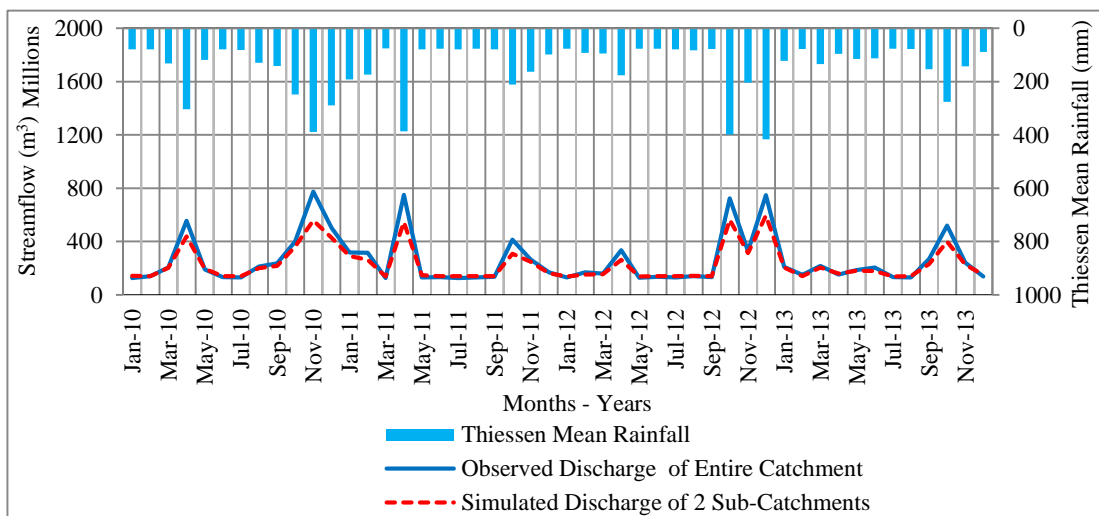


Figure C 12: Observed discharge of entire catchment & simulated discharge of upper sub-catchment (2010 - 2013)

Table C1: Observed and simulated water balance

Year	Thiessen mean rainfall (mm)	Observed discharge (mm)	Observed water balance (mm)	Simulated discharge (mm)	Simulated water balance (mm)
1990	1815.49	1065.10	750.39	1238.83	576.65
1991	1958.61	1178.13	780.48	1322.55	636.05
1992	1798.35	1215.45	582.91	1208.34	590.01
1993	1926.51	1254.85	671.67	1302.18	624.33
1994	1792.81	1132.47	660.34	1234.12	558.69
1995	2055.29	1402.27	653.02	1378.83	676.46
1996	1619.52	1177.98	441.54	1131.81	487.72
1997	2270.23	1594.66	675.57	1498.01	772.21
1998	1773.45	1192.53	580.92	1218.33	555.13
1999	1623.70	1170.62	453.08	1128.42	495.28
2000	1538.95	1051.69	487.27	1073.13	465.82
2001	1732.64	1264.51	468.14	1193.37	539.27
2002	2045.95	1393.10	652.85	1371.66	674.30
2003	1567.12	1038.81	528.31	1089.44	477.68

2004	1735.19	1251.48	483.71	1195.15	540.04
2005	1963.40	1391.52	571.88	1321.79	641.62
2006	1762.13	1200.76	561.37	1199.72	562.41
2007	1654.62	1075.98	578.64	1145.59	509.03
2008	1972.10	1315.60	656.50	1325.24	646.86
2009	1639.99	1106.42	533.56	1137.58	502.41
2010	2074.62	1359.22	715.40	1389.43	685.20
2011	1692.68	1130.52	562.16	1179.53	513.15
2012	1852.79	1238.78	614.01	1238.52	614.27
2013	1479.51	963.88	515.63	1062.81	416.70

Appendix – D

**Comparison of Rainfall, Simulated Discharge (exclusive of baseflow) and
Runoff Coefficient**

Appendix-D: Comparison of rainfall, simulated discharge (exclusive of baseflow) and runoff coefficient

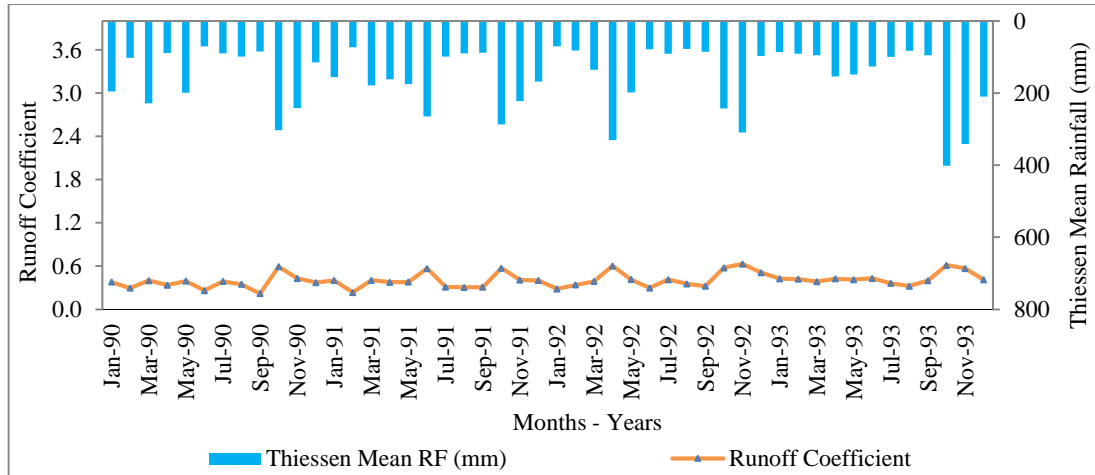


Figure D 1: Comparison of rainfall & runoff coefficient (without baseflow) (1990 - 1993)

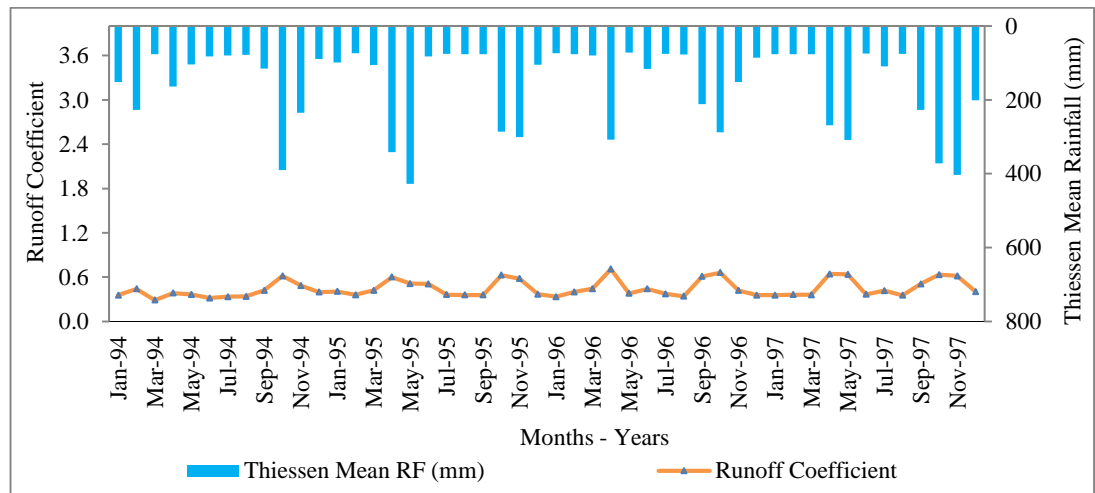


Figure D 2: Comparison of rainfall & runoff coefficient (without baseflow) (1994 - 1997)

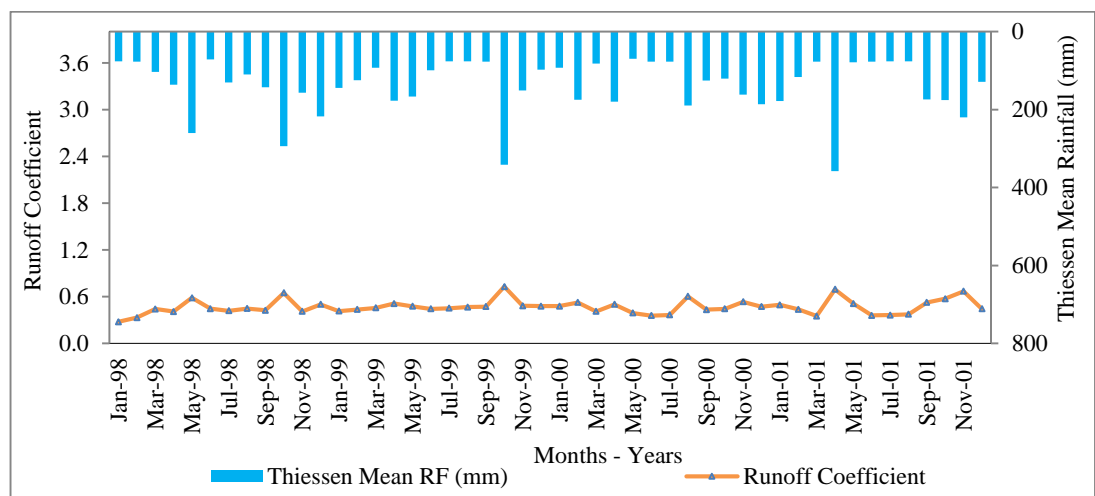


Figure D 3: Comparison of rainfall & runoff coefficient (without baseflow) (1998 - 2001)

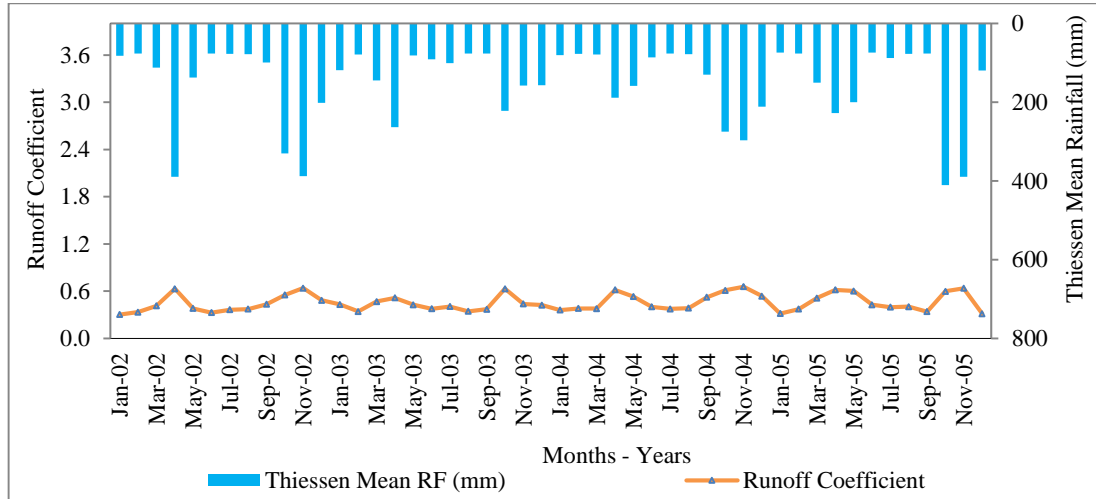


Figure D 4: Comparison of rainfall & runoff coefficient (without baseflow) (2002 - 2005)

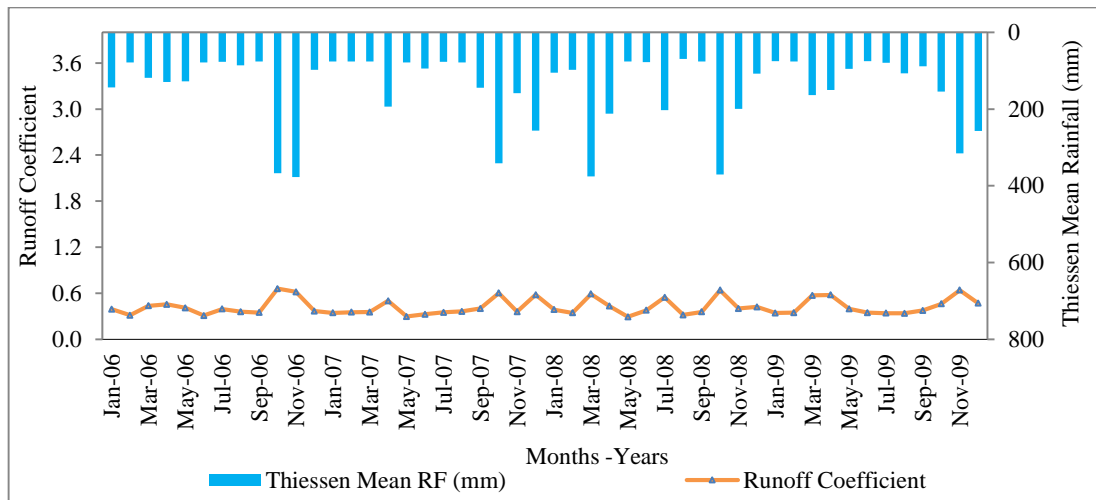


Figure D 5: Comparison of rainfall & runoff coefficient (without baseflow) (2006 - 2009)

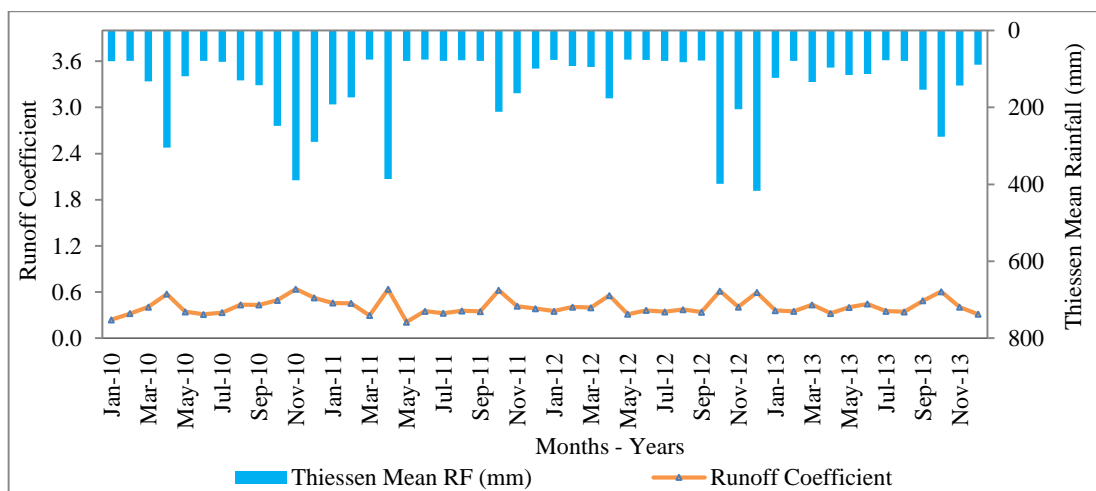


Figure D 6: Comparison of rainfall & runoff coefficient (without baseflow) (2010 - 2013)

Appendix – E
Runoff Coefficient for Land Use Type

Appendix-E: Runoff coefficient of land use types

Table E 1: Coefficient of land use type

Land Use	C	Land Use	C
Business: Downtown areas Neighborhood areas	0.70 - 0.95 0.50 - 0.70	Lawns:	
		Sandy soil, flat, 2%	0.05 - 0.10
		Sandy soil, avg., 2-7%	0.10 - 0.15
		Sandy soil, steep, 7%	0.15 - 0.20
		Heavy soil, flat, 2%	0.13 - 0.17
		Heavy soil, avg., 2-7%	0.18 - 0.22
		Heavy soil, steep, 7%	0.25 - 0.35
Residential: Single-family areas Multi units, detached Multi units, attached Suburban	0.30 - 0.50 0.40 - 0.60 0.60 - 0.75 0.25 - 0.40	Agricultural land:	
		Bare packed soil	
		*Smooth	0.30 - 0.60
		*Rough	0.20 - 0.50
		Cultivated rows	
		*Heavy soil, no crop	0.30 - 0.60
		*Heavy soil, with crop	0.20 - 0.50
		*Sandy soil, no crop	0.20 - 0.40
		*Sandy soil, with crop	0.10 - 0.25
		Pasture	
*Heavy soil	0.15 - 0.45		
*Sandy soil	0.05 - 0.25		
Woodlands	0.05 - 0.25		
Industrial: Light areas Heavy areas	0.50 - 0.80 0.60 - 0.90	Streets:	
		Asphaltic	0.70 - 0.95
		Concrete	0.80 - 0.95
		Brick	0.70 - 0.85
Parks, cemeteries	0.10 - 0.25	Unimproved areas	0.10 - 0.30
Playgrounds	0.20 - 0.35	Drives and walks	0.75 - 0.85
Railroad yard areas	0.20 - 0.40	Roofs	0.75 - 0.95

Source: The Clean Water Team Guidance Compendium for Watershed Monitoring and Assessment
State Water Resources Control Board 5.1.3 FS-(RC) 2011