A MONTHLY WATER BALANCE MODEL FOR EVALUATION OF CLIMATE CHANGE IMPACTS ON THE STREAMFLOW OF GINGANGA AND KELANI GANGA BASINS, SRI LANKA

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DECLARATION

I declare that this is my own work and this thesis does not incorporate without acknowledgement any material previously submitted for a Degree or Diploma in any other University or institute of higher learning and to the best of my knowledge and belief it does not contain any material previously published or written by another person expect where the acknowledgment is made in text.

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The above candidate has carried out research for the Master's thesis under my supervision.

....

Professor N.T.S. Wijesekera Date

This Thesis is gratefully dedicated to my family.

For their endless love, support and encouragement

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ABSTRACT

The availability and distribution of freshwater resources will be greatly affected by climate change and the vulnerability to water scarcity of affected populations currently experience could increase. Studies relating climate change and hydrology are becoming prevalent but few published studies focus on changes in Sri Lanka streamflow. There is ample evidence to suggest that the climate of South Asian region has already changed. Climate change or its increased variability is expected to alter the timing and magnitude of runoff. As a result it has important implications for existing water resources systems as well as for future water resources planning and management. A two-parameter monthly water balance model is adopted to simulate the runoff for the evaluation of climate change impacts on the streamflow of two major catchments in Kelani Ganga and Gin Ganga basins in Sri Lanka. The model was successfully calibrated and verified for Kelani Ganga & Gin Ganga basins showing that average values of 0.485 and 1110.50 mm for parameters c & SC respectively could simulate monthly streamflow with average MRAE 0.088 and average Nash-Sutcliffe efficiency 0.957. Application results show that the model efficiencies are high in both the calibration and verification periods. This study demonstrated the models capability and applicability to evaluate the climate change impacts on the streamflow and also to forecast for future scenarios. It is suggested that this two parameter model can be easily and efficiently incorporated in the climate impact studies to simulate monthly runoff and as well as in the water resources planning program.

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LIST OF ABBREVIATIONS

Abbreviation	Description
c	Parameter c
C	Runoff Coefficient
CC	Climate Change
DSD	Divisional Secretary Divisions
E	Nash–Sutcliffe coefficient
E (t)	Actual Evapotranspiration
EP (t)	Pan Evaporation
GCM	Global Circulation Model
IM1	Inter Monsoon 1
IPCC	Intergovernmental Panel on Climate Change
K	Pan Coefficient
MAR	Mean Annual Rainfall
MRAE	Mean Ratio of Absolute Error
MSE	Mean Square Error
NEM	North East Monsoon
P (t)	Rainfall
Q (t)	Runoff
RAEM	Ratio of Absolute Error to Mean
RE	Relative Error
RMSE	Root Mean Square Error
S (t)	Soil Moisture Content
SC	Field capacity of the catchment
SWM	South West Monsoon
TPMWBM	Two Parameter Monthly Water Balance Model
WMO	World Meteorological Organization

1 INTRODUCTION

1.1 General

The Intergovernmental Panel on Climate Change (IPCC) states that the availability and distribution of freshwater resources will be greatly affected by climate change and that the vulnerability to water scarcity that populations currently experience could increase (IPCC, 2007). Studies relating climate change and hydrology are becoming prevalent (Leavesley, 1994; Xu, 1999), but few published studies focus on changes in Sri Lanka streamflow and population dependent upon it. There is need of evaluating the impacts of climate change on streamflow in Sri Lanka.

There is ample evidence to suggest that the climate of South Asian region has already changed(IPCC, 2007; Wijeratne et al., 2009; Premalal, 2009; Eriyagama et al., 2010). According to the research report published by International Water Management Institute, Sri Lanka, (Eriyagama et al., 2010) stated “During 1961-1990, the country’s mean air temperature increased by 0.016 °C per year, and mean annual precipitation decreased by 144 millimeters (mm) (7%) compared to that of 1931-1960. However, the bigger question of national importance is what Sri Lanka’s climate will look like in 50 or 100 years and how prepared the country is to face such changes. Few studies attempted to project future climate scenarios for Sri Lanka and to identify climate change impacts on agriculture, water resources, the sea level, the plantation sector, the economy and health.”

As climate change continues, there is a need to develop tools that empower water resource managers to use the predictions to better understand and manage water sources. It must be emphasized that complex models which generate outputs on continental scales are of little use for decision makers who are trying to allocate resources to alleviate local water scarcity amidst data scarce situation. Decision makers require tools that can reliably forecast hydrologic changes, corresponding to the anticipated climate change. In this context, if the decision makers possess watershed models which can estimate streamflow for given inputs of rainfall, evaporation etc., then such models would equip them with the capability to evaluate climate change impacts on stream water.

Identification of the relationship between rainfall and streamflow is of great importance to address a range of hydrological problems for water resources planning and management. Water balance models are widely used for this purpose(Alley, 1984; Vandewiele et al., 1992; Xu & Singh, 1998; Xu, 1999). A water balance model is the mathematical representation of the response of a catchment system to hydrologic events for a given time period considering the principle of continuity.

Modelling to represent catchments is a very familiar practice where climate and catchment characteristics are used as inputs for streamflow simulations with the use of continuity equation and flow routing (Alley, 1984; Xu, 1997 and 1999).

Water balance models were first developed in the 1940s by Thornthwaite (1948) and later revised by Thornthwaite & Mather (1957). Since then, water balance techniques have been adopted, modified, and applied to a diversity of hydrological problems (Alley,1984; Xu, 1992; Vandewiele & Elias, 1995; Vandewiele & Ni-Lar-Win, 1998), they have proved to be both flexible and understandable and have been developed and computed at various time scales (Alley, 1984) and to varying degrees of complexity (Xu & Singh, 1998).

Monthly water balance models are valuable tools in water resources management, reservoir simulation, drought assessment or long-term drought forecasting (Mouelhi et al., 2006). They are often called monthly models because the time resolution of inputs and output is a month (Wang et al., 2011). Generally, monthly water balance models are mainly applied in three fields, i.e. reconstruction of the hydrology of catchments, assessment of climatic change impacts, and evaluation of seasonal and geographical patterns of water supply and irrigation demand (Xu & Singh, 1998; Hughes & Metzler, 1998; Mouelhi et al., 2006).

Since 1980s, many monthly water balance models had been developed to study the impact of climate change on the hydrological balance and for general water resources planning and management (Gleick, 1986 and 1987; Mimikou et al.,1991; Vandewiele et al.,1992; Guo, 1995; Yin & Guo, 1997; Panagoulia & Dimou, 1997; Xu & Singh, 1998; Xiong & Guo, 1999; Guo et al., 2002; Nan et al., 2011).

Xiong & Guo (1999) have developed the two-parameter monthly water balance model in which a parameters c is used take account of the effect of the change of time scale and the field capacity of the catchment is represented by parameter SC. The results reported in this work shows an average value of Nash–Sutcliffe efficiency on the 70 sub-catchments as 88.60% for calibration while the same is 90.98% for verification. They carried out a comparative study of their two parameter model and the five-parameter water balance model used by Guo (1992 and 1995) and it was found that both models performed runoff simulation with 90% Nash–Sutcliffe efficiency. They concluded that the two-parameter monthly water balance model can easily and efficiently be incorporated in the water resources planning program and the climate impact studies to simulate monthly runoff conditions in the humid and semi-humid regions owing to its simplicity and high efficiency of performance.

Xu & Singh (1998) tracing the development, refinement, and application of monthly models, recognized that in humid regions three to five parameters may be sufficient to reproduce most of the hydrologic information on a monthly time scale.

In Sri Lanka there are only a very limited peer reviewed publications on mathematical modeling for water resources management. Among the recent publications are the following.

Dharmasena et al. (1992) carried out studies mathematical models for streamflow simulations in Sri Lankan Rivers, in which the Kalu Ganga and Kelani Ganga had been considered. Wijesekera (2000) had carried out a study to estimate parameters for a Watershed Model. Mathematical modeling of Karasnagala watershed runoff coefficient had been carried out by Wanniarachchi (2013). Wijesekera & Rajapakse, (2014) modelled the Attanagalu Oya watershed as a flood management cascade formed by road crossings. Wijesekera (2010) publication on Sri Lanka water resources mention that only 58% out of the reviewed were on water resources modeling.

The two parameter model of Xiong & Guo (1999) estimates the watershed runoff considering rainfall, evaporation and initial soil moisture level as inputs. Hence this model helps a modeler to evaluate the moisture level of a watershed, enabling water resource management realistically. Due to the reduced number of parameters, this model is considered simple, and has been classified as computational friendly. There are many applications of this model in various parts of the world. Many advantages have been cited. However in Sri Lanka there are only very limited works on hydrological model applications for watershed management. In Sri Lanka monthly hydrologic data are easily accessible and affordable (http://www.meteo.gov.lk/ and the Hydrological Annuals). Monthly time scale is also the planning temporal resolution in the water sector.

Since there is a strong need for Sri Lanka to identify a suitable mathematical model to estimate watershed response, the present work is on the application of a two parameter monthly watershed model for Sri Lanka basins.

In order to compare the results and then to check the possibility of extending the application to other watersheds, the present work targeted model application in two watersheds. The data availability is one major consideration for the selection of watersheds. Accordingly, the two basins, 1) Gin Ganga at Tawalama and 2) Kelani Ganga at Deraniyagala were chosen as the watersheds to be modeled with the two parameter monthly water balance model of Xiong & Guo (1999).

1.2 Problem Statement

Climate change or its increased variability is expected to alter the timing and magnitude of runoff. As a result it has important implications for existing water resources systems as well as for future water resources planning and management (IPCC, 1993). For example in recent years under the climate change situation, the imbalance between water supply and water demands had been increasing, and had given rise to a great attention from both the authorities and the general public when managing water resources programs. Hence, there is an urgent need to effect actions to understand and solve potential water resources problems for both human and environmental sustainability. Hence reliable streamflow estimation in monthly temporal scale is an important component for the management of water resources in Sri Lanka.

1.3 Objectives

The overall objective of the present work is to develop, calibrate and verify a hydrologic model well suited for the evaluation of climate change impacts on water resources in two Sri Lankan watersheds. The Gin Ganga at Tawalama and Kelani Ganga at Deraniyagala were chosen as study watershed.

1.4 Specific Objective(s)

1. Evaluate and identify a suitable watershed model with soil moisture accounting capability for use in data scarce regions.
2. Develop, calibrate and verify the model for the selected basins.
3. Identify climate change scenario and demonstrate the capability to evaluate water resources.
4. Provide recommendations on the model applicability.

2 LITERATURE REVIEW

2.1 Modelling concept and classification

A model is a simplified representation of reality. A hydrological model is the mathematical representation of the response of a catchment system to hydrologic events during the time period under consideration. Generally, Hydrological models are classified based on the process description, based on spatial representation and based on the aspect of randomness (Moreda, 1999).

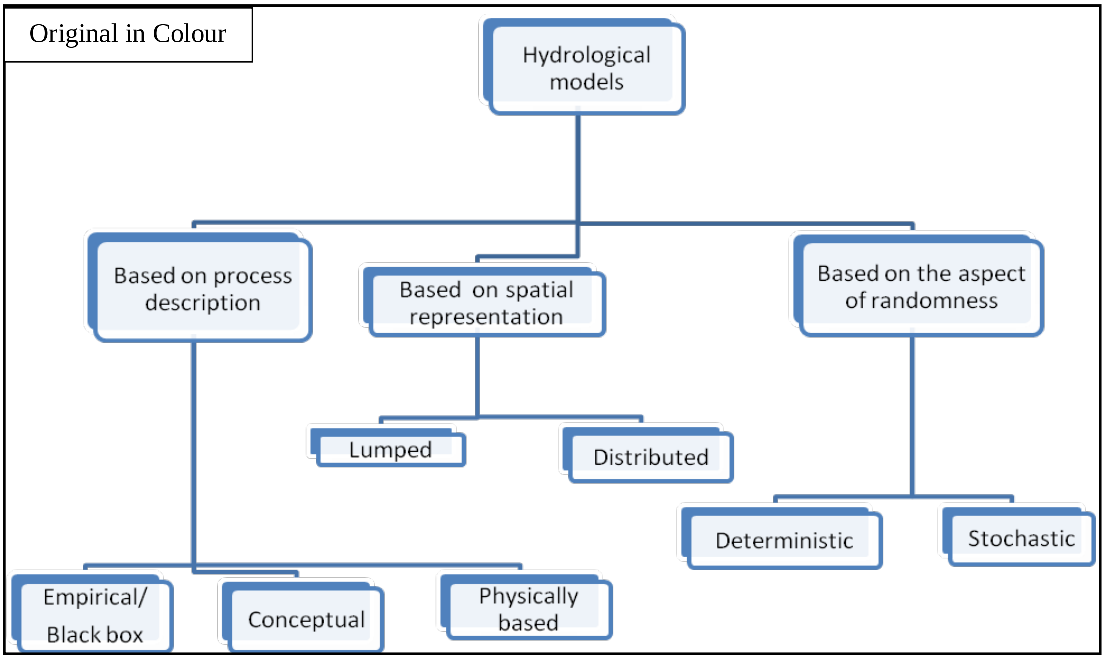


Figure 2-1: Classification of Hydrological Models (Moreda, 1999).

Based on the assumptions and concepts formulating the structure of transformation (Operator) the resulting models may have different forms. According to Clarke, 1973 mathematical models may be classified into four main groups as Stochastic, Deterministic, Conceptual and Empirical.

Hydrologic models sometimes classified into three types as the empirical models (also called black box models in literature), the conceptual models (grey box models) and theoretical models (sometimes called white box models) (e.g. Singh, 1989; 1995). The black box models relate outputs to inputs through a structure which does not aid in physical understanding. Conceptual models are in the form of model equations considering the physical processes in a highly simplified form; the theoretical models have a logical structure closer to reality (Xu & Singh, 1998). The theoretical models are also called physically based models. In recent years there had been an increasing trend towards the development of physically based models (Beven, 1989). However, it is apparent that there are problems associated with the application of physically based models (e.g. Hughes, 1989). For physically based model, goodness of fit is much harder to measure and the physical identification of parameters is important because it is the basis for transferring models from their original test area to others (Clark et al., 1987). The disadvantage of the physically based models includes 1) the computational demand, and 2) the high input data demand on a gridded basis. The needed detailed information on spatial distribution of soils, vegetation and land surface properties are often not available, particularly in areas of weak infrastructure (Kunstmann et al., 2006).

2.2 Types of Monthly Water Balance Model

2.2.1 Model Composition

Monthly water balance models use the month as the temporal resolution and the principle of continuity on water flow through the watershed up to the outlet as the rationale. The following outlines the types of monthly water balance models based on the model input. There are various water balance models such as: 1) models using monthly precipitation (rainfall) as input (Snyder, 1963), 2) monthly models using rainfall and temperature as input, 3) models using monthly rainfall and potential evapotranspiration as input, 4) monthly output models using daily input data.

Xu & Singh (1998) in their work on a review on monthly water balance models had indicated that models using precipitation (rainfall) as input cannot be recommended when other meteorological data besides precipitation are available.

Monthly models using rainfall and temperature as input cited in literature are Palmer's (1965) P-model; Thomas's(1981) abcd-model; Alley (1984); Alley's (1984) T-model; Alley's (1984) P-model; Vandewiele et al. (1992). They can be used to reproduce annual and seasonal flows when only precipitation and temperature are available. As mentioned by Alley (1984) in a work of several regional water balance models and confirmed later by Vandewiele et al. (1992) in their work on methodology and comparative study of monthly water balance models indicated that the variable simulated by these models may be unrealistic.

2.2.2 Comparison of the types

Monthly water balance models have many advantages. Among them are, 1) only monthly data are required, 2) requires low computational costs, 3) enables reasonable and quick answers and 4) lesser number of parameters (Mouelhi et al., 2006; Wang et al., 2011).

Xu & Singh (1998) reviewed four different types of monthly water balance models and stated that the models using rainfall and potential evaporation as input(Pitman, 1973, 1978; Roberts, 1978 and 1979; Krzysztofowicz & Diskin, 1978; Hughes, 1982; Salas et al.,1986; Vandewiele et al., 1992; Xu, 1992; Makhlouf & Michel, 1994 and Xiong & Guo, 1999) and models using daily input data (Haan, 1972; Boughton, 1973; Langford et. al., 1978; Kuczera, 1982) provided more reliable and better estimates of water balance components. They also expressed the ease of applying the monthly water balance models to ungauged watershed.

2.3 Application Potential of Monthly Water Balance Models

In case of water balance models, the primary factor to be considered is the purpose. There are many applications for which monthly water balance models are developed.

Guo (1995) developed a regional hydrological conceptual model to simulate monthly runoff mainly for assessing the effects of climate change or its variability in the Dongjiang Basin in China. In this work evaluation of floods, hydropower generation etc., had been carried out.

Xiong & Guo (1999 and Chen et al. (2007) mentioned that the two-parameter monthly water balance model can easily and efficiently be incorporated in the water resources planning program and the climate impact studies to simulate monthly runoff conditions in the humid and semi-humid regions.

Guo et al. (2001) in their work on the climate change effects on water had identified that these models are capable of producing both the magnitude and timing of runoff and soil moisture conditions, for modelling sustainable water resources development. It had been identified that the annual runoff will decrease by 15-22% in the northeast of China and increase by 10-16% in the northwest.

Wang et al. (2011) compared the monthly and daily water balance models and stated that using daily inputs over monthly inputs for monthly output generation does not make significant impacts on the results.

Chen et al. (2007) applied a distributed monthly water balance model while Karpouzos et.al. (2011) carried out a hydrologic investigation using a lumped model.

McCabe (2007) examined various components of the hydrologic cycle while Vandewiele et al. (1992) applied monthly water balance models for filling missing data and prediction of streamflow in ungauged basins.

In general monthly water balance models are applied for reconstruction of the hydrology of catchments, assessment of climatic impact changes, and evaluation of the seasonal and geographical patterns of water supply and irrigation demands (Xu & Singh, 1998; Hughes & Metzler, 1998; Mouelhi et al., 2006).

2.4 Selected Water Balance Model

Two Parameter Monthly Water Balance Model (TPMWB) selection was made based on an understanding of the objectives and the system being modelled. The model for the present work was selected based on the factors and criteria as being relevant and mentioned in WMO, (2008 & 2009).

Considering the ease of input data collection, capability to reflect the soil moisture status and the simplicity of the equations incorporated in the model, the present work selected the two parameter monthly water balance model proposed by Xiong & Guo (1999).

Following are details corresponding to the selected model inputs and its structure. There are four major components as, Precipitation (Rainfall), Evapotranspiration, Streamflow and Soil Moisture Content.

The conceptual representation of the model is represented in Figure 2-2.

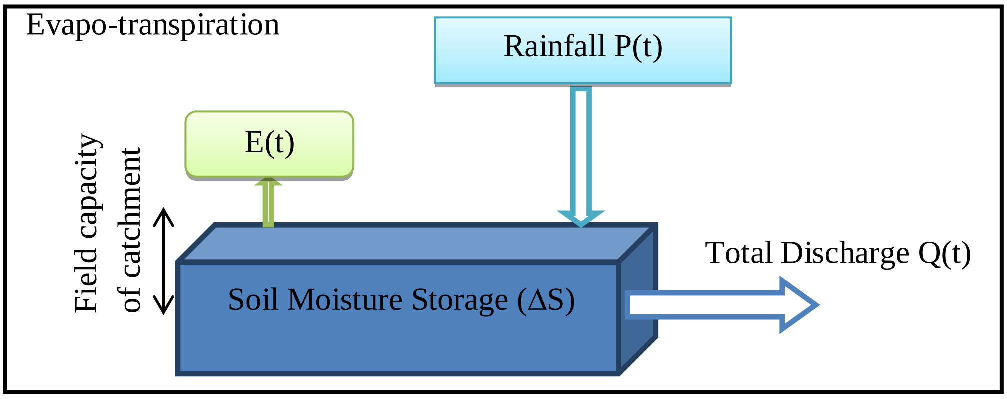


Figure 2-2: Conceptual representation of Two Parameter Monthly Water Balance Model

2.4.1 Precipitations

Precipitation is one of the main inputs to the system. The amount of precipitation is defined as an accumulated total volume for any selected period. Systematic averaging methods such as Thiessen polygon, isohyet and reciprocal distance methods can be used to account for variations in space. However, Singh & Chowdhury (1986) after comparing 13 different methods for calculating areal averages concluded that all methods give comparable results, especially when the time period is long.

2.4.2 Monthly evapotranspiration

Evapotranspiration from land surface comprises evaporation directly from the soil and vegetation surface and transpiration through plant leaves, in which water is abstracted from the sub soil. The other factor is the supply of moisture at the evaporative surface, which brings about the definition of potential and actual evaporation. Evaporation involves a highly complex set of processes, which is influenced by factors dependent on the local conditions such as land use, vegetation cover, and meteorological variables. Monthly areal precipitation and potential evapotranspiration had been used as the sole inputs to most monthly rainfall runoff models mainly to simulate and forecast the monthly runoff in catchments (Vandewiele et al., 1992;Guo, 1995; Hughes & Metzler, 1998; Vandewiele & Ni-Lar-Win, 1998; Xiong & Guo, 1999; Wang et al., 2011) and many formulae are available for the calculation of the actual evapotranspiration of a catchment. Mostly the potential evaporation is obtained either by using some simple empirical formula such as Thornthwaite (1948) or Penman formula (Penman, 1948).

Xiong & Guo (1999) suggested the Equ. (1) to calculate the monthly evapotranspiration after many numerical experiments.

$$E(t) = c * EP(t) * \tanh[P(t) / EP(t)] \quad (1)$$

Where, E(t) represents the monthly evapotranspiration, EP(t) is the monthly pan evaporation value, P(t) is the monthly rainfall and c is the new coefficient which is the first model parameter. This parameter c is used to take an account of the effect of the change of time scale, i.e. from year to month and is linked to evapotranspiration.

2.4.3 Streamflow

The monthly runoff Q is closely related to the soil water content. Xiong & Guo (1999) cited after Shaw (1994) that in the conceptual hydrological models, the regulating effect of a catchment on rainfall is assumed to operate as a linear or non-linear reservoir. The runoff Q is also assumed as a hyperbolic tangent function of the soil water content S, which is given by equation 2.

$$Q(t) = S(t) * \mathrm{Tanh}[S(t) / SC] \quad (2)$$

Where, Q (t) is the monthly runoff and $S(t)$ is the water content in soil, and SC is to represent field capacity of catchments. SC is the second model parameter used in the model which has the unit of millimeter.

The quantity of the remaining water in the soil will be [S(t-1) + P(t) - E(t)], after the abstraction of evapotranspiration E(t). S(t-1) is the water content at the end of the $(t-1)^{th}$ month and at the beginning of the t^{th} month.

Eq. (2) is then used to calculate the t^{th} monthly runoff Q(t) as

$$Q(t) = S(t-1)+P(t)-E(t)*\tanh \{[S(t-1)+P(t)-E(t)]/SC\} \quad (3)$$

Then applying catchment water balance, St at the end of the month is computed. This becomes the initial soil moisture level of the watershed for the next time step.

$$S(t) = S(t-1)+P(t)-E(t)-Q(t) \quad (4)$$

By assuming an initial soil moisture level for the watershed, and values for the two parameters, it is now possible to find out the temporal distribution of monthly runoff, monthly evaporation and monthly soil moisture levels.

The two parameter monthly water balance models perform better and application results show that the model efficiencies are high in both the calibration (88.60%) and verification (90.98%) periods. 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 (Alley, 1984). They give not only better estimates of monthly flow, but also more reliable estimates of other water balance components, such as, actual evapotranspiration, surface and soil moisture content, etc. Moreover, application of such models to ungauged catchments by relating model parameters with physical characteristics of catchments is possible (Xu & Singh, 1998).

The Two Parameter Monthly Water Balance Model was chosen for the present research because this model has been tested in 100 small and medium size basins in China and compared for advantages with other water balance models, including Belgium model (Vandewiele et al., 1992) and the Xinanjiang monthly model (Zhao, 1992). The two-parameter monthly water balance model proved to be quite efficient in simulating the monthly runoff with the simple structure for estimations of surface runoff using only precipitation and evaporation data. It was also shown that the two-parameter water balance model is comparable to other relatively complex water balance models (Yin & Guo, 1997; Xiong & Guo, 999). Due to its simplicity and high efficiency of performance, the two-parameter monthly water balance model can be easily and efficiently incorporated in water resources planning programs and also for the study of climate change impacts. The current research aimed to study the model applicability & capability in case of Sri Lanka where climatic region is different from China. Moreover, to calibrate and validate for two catchments in Sri Lanka in order to evaluate the climate change impacts on the streamflow.

2.4.4 Determination of initial soil water content

The accuracy of the initial value of the soil water content S(0) normally has some effect on the model performance, especially in the case when the used data series is not long enough (Xiong & Guo, 1999; Moreda, 1999). They considered the value of S(0) should not be very different from the soil water content of the month having same rank within a year, such as S(12), S(24) because an year can be regarded as a reasonable cycle period. Therefore, this study had concluded that it is reasonable to choose S(0) as the mean value of the soil water content S over all months having the same rank within a year, i.e.

$$S(0) = \sum_{j=1}^{m} S(j * 12)/m \qquad (5)$$

where m is the number of years of the calibration data series, i.e. m =Nc/12. They suggested that the preliminary run of the proposed two-parameter model can generally take S(0) value of 150–200 mm, for more than 100s of tested catchments in China.

2.5 Model Testing and Parameter Optimization

Several levels of evaluation are necessary before a model can be applied to estimate the output from a catchment and these are: (i) rational examination of the model structure, (ii) estimation of parameter values, (iii) testing the fitted model to verify its accuracy, and (iv) estimation of its range of applicability(Pilgrim & Cordery, 1975).
The most common indicators used in the literature to evaluate outflow hydrograph are Nash and Sutcliffe (1970), MRAE, RMSE, RE, criterion R^2 and correlation

coefficient (Guo, 1995; C. Xu, 1997; Xu & Singh, 1998; Xiong & Guo, 1999; Wijesekera, 2000; Mouelhi et al., 2006; Chen et al., 2007; Wang et al., 2011; Karpouzos et al., 2011). These are shown in Table 2.1. Estimating the model performance by comparing the simulation results with observed data is accomplished by defining different statistical indicator objective functions (OF) to calculate the model efficiency, i.e. how model simulation fits observed data (Mata-Lima, 2011). The objective function (OF) is a function associated with an optimization problem which determines how good a solution is. It is the actual function which needs to be minimized for an optimal choice or a solution to be selected from the many alternatives offered.

2.5.1 Nash-Sutcliffe efficiency E

The efficiency E proposed by Nash and Sutcliffe (1970) is defined as one minus the sum of the absolute squared differences between the predicted and observed values normalized by the variance of the observed values during the period under investigation. It is calculated as:

$$E = \frac{Fo - F}{Fo} * 100\ (\%) \tag{6}$$

$$Fo = \sum (Qi - Qc)^2 \tag{7}$$

$$F = \sum (Qi - Qi')^2 \tag{8}$$

$$Qc = \left(\sum_{i=1}^{Nc} Qi\right) / Nc \tag{9}$$

Where Fo is the sum of squared deviations of the observed runoff Qi from the mean value Qc of the observed runoff series in the calibration period, and F is the sum of squared discrepancies of the simulated runoff Qi' from the observed runoff Qi. Nc is the calibration period. The value of E is always expected to approach unity for a good simulation of the observed runoff series. A negative modelling efficiency means that the model prediction is worse than simply using the mean of the observed flows. This measure is highly affected by a few extreme errors and can be biased if a wide range of flow events is experienced (Krause et al., 2005).

Many modelers had used Nash-Sutcliffe coefficient as the objective function during the parameter optimization (Xiong & Guo, 1999; Guo et al., 2002; Zhang & Savenije, 2005; Chen et al., 2007 and Fish, 2011). It has been mentioned that the Nash-Sutcliffe coefficient can be used for evaluating model performance to arrive at a best parameter set for a given watershed (Zhang & Savenije, 2005).

The largest disadvantage of the Nash-Sutcliffe efficiency is the fact that the differences between the observed and predicted values are calculated as squared values. As a result, larger values in a time series are strongly emphasized whereas lower values are neglected (Legates & McCabe Jr, 1999). For the quantification of runoff predictions this leads to an overestimation of the model performance during peak flows and an underestimation during low flow conditions (Krause et al., 2005).

In Guo, (1995) a reservoir inflow series simulated by the water balance model had model efficiency value reaching 91.64% and 88.64% during the calibration and verification periods respectively.

The two-parameter water balance model proposed by Xiong & Guo, (1999) had been calibrated and verified for 70 sub-catchments using monthly data period of an average of 24 years. The average values of the Nash efficiency criterion E on the 8 sub-catchments from the Dongjiang Basin was 88.60% for calibration and 90.98% for verification. The average values of E on the 21 sub-catchments from the Ganjiang Basin was 90.61% for calibration and 89.11% for verification. The average values of E on the 41 sub-catchments from the Hanjiang Basin was 85.66% for calibration and 84.78% for verification.

2.5.2 Relative Error

The relative error of the volumetric fit between the observed runoff series and the simulated series (Xiong & Guo, 1999) is represented by the Relative Error indicator.

$$\mathrm{RE} = \sum(\mathrm{Qi} - \mathrm{Qi}')/\sum \mathrm{Qi} * 100\% \qquad (10)$$

Where Qi is the observed discharge and Qi' is the simulated discharge.

The value of RE is expected to be close to zero for a good simulation of the total volume of the observed runoff series.

Xiong & Guo (1999) studying seventy sub-catchments in the Dongjiang, Ganjiang and Hanjiang Basins in the south of China report that the RE varies from -0.78 to +0.58 during calibration while the same was -9.0 to +7.22 during validation. Guo et al.(2002) developing a monthly water balance model to predict climate change impacts in China, had experienced RE varies from -0.014 to +1.80 for calibration period and -5.60 to +5.06 for validation period.

2.5.3 Mean Ratio of Absolute Error (MRAE)

Wijesekera (1993) developing conceptual model structures for 15 tropical catchments incorporated the Mean Ratio of Absolute Error (MRAE) as the objective function. This objective function measures the average error in the modelled streamflow by considering the absolute mismatch at each observation point relative to the magnitude of observed streamflow at that particular observation point.

Wanniarachchi (2013) in his work on the mathematical modelling of Attanagalu Oya watershed (52.6 km^2) computed runoff coefficient for reliable estimations in order to meet the future challenges of water resources development in Sri Lanka. The model which was calibrated and verified using 54 events and with Mean Ratio of Absolute Error (MRAE) as the objective function indicated that the error value during calibration was 0.3942 while the same during verification was 0.3567.

Wijesekera (2000) and Wijesekera & Perera (2010) also used the Mean Ratio of Absolute Error (MRAE) for parameter optimization. The MRAE indicates an average relative error of model output with reference to a given observed streamflow.

The MRAE is defined as follows:

$$\text{MRAE} = \frac{1}{n}\left[\sum \frac{|Yobs - Ycal|}{Yobs}\right] \qquad (11)$$

Where, Yobs, Ycal are the observed and calculated streamflow values while n is the number of data in the time series.

This method considers the error on the merit of the specific set of observations being matched. Hence it provides a better representation when contrasting observations are present in the observed data set.

The research carried out by Wijesekera & Rajapakse (2014) on mathematical modelling of watershed wetland crossings for flood mitigation and groundwater enhancement have used MRAE as one of the objective function. The mathematical model was calibrated and verified for the Attanagalu Oya watershed of Gampaha District at Karasnagala and found that the MRAE value varies from 0.62 to 0.84 for calibration and 0.53 to 1.25 for validation. In this work flow duration curves showed a very good matching with a Mean Ratio of Absolute Error of 0.66 for calibration while the same for validation was 0.70.

2.5.4 Ratio of Absolute Error to Mean (RAEM)

World Meteorological Organization(1974) in its publication recommends several objective functions. One of the methods suggested is Ratio of Absolute Error to Mean (RAEM) as given below.

$$\mathrm{RAEM} = \frac{1}{n}\left[\frac{\sum|\mathrm{Yobs} - \mathrm{Ycal}|}{\bar{\mathrm{Y}}\mathrm{obs}}\right] \tag{12}$$

Where, $\bar{Y}$ is the mean of the observed discharge.

This method indicates the ratio between observed and calculated discharge with respect to the mean of observed discharges. The general concept is that the differences between the observed and calculated values are normalized by the observed value and optimum parameters are obtained at the minimum value of MRAE. MRAE provides an average indicator for the matching of each and every point of the two hydrographs relative to the observed value at that particular time point and it has an advantage of reflecting the matching at each and every point based on the order of magnitude at that point.

2.5.5 Objective Function Evaluation

The judgment on the model performance purely based on performance indices (such as RMSE, R2, etc.) may be misleading (i.e. they do not give any information about the homoscedasticity and independence of residuals) and that model performance benefits from being evaluated using a number of evaluation measures (Sudheer et al., 2007).

In the present study various objective functions were identified, discussed and evaluated in Table 2.2, 2,3, 2.4 and 2.5. Objective function evaluation was carried out by extensive literature survey considering the good matching of Low Flow, Intermediate Flow, Peak Flow and Overall Flow. From the literature survey evaluation the behavior of peak flow (Table 2-2), intermediate flow (Table 2-3), low flow (Table 2-4) and overall flow (Table 2-5) reveals that MRAE and Nash Sutcliffe Coefficient (E) are quite good enough to be used as the main objective function. The Mean Ratio of Absolute Error (MRAE) and Nash-Sutcliffe efficiency E were identified as suitable objective functions to match the outputs of model simulations.

By the formulation of the function the MRAE has a bias towards the frequent events. In literature, the Nash-Sutcliffe efficiency behavior is considered for hydrograph matching but this indicator has a bias towards the high flows. Since the monthly water balance models are for long term resources evaluation, the MRAE was selected as the primary objective function.

Table 2-1: Objective function list summary

Indicators	Objective Function	Purpose
Nash Sutcliffe Coeff. (E)	$E = 1 - \frac{\sum_{i=1}^{n}(X_{obs,i} - X_{model})^2}{\sum_{i=1}^{n}(X_{obs,i} - \overline{X}_{obs})^2}$	For the quantification of runoff predictions and model performance.
RE	$\mathrm{RE} = \sum(\mathrm{Qi} - \mathrm{Qi}')/\sum \mathrm{Qi} * 100\%$	Volumetric fit between the observed runoff series and the simulated series
MRAE	$\mathrm{MRAE} = \frac{1}{n}[\sum \frac{\lvert Yobs - Ycal \rvert}{Yobs}]$	Indicates an average relative error of model output with reference to a given observed streamflow.
RAEM	$\mathrm{RAEM} = \frac{1}{n}[\sum \frac{\lvert Yobs - Ycal \rvert}{\hat{Y}obs}]$	Indicates the ratio between observed and calculated discharge with respect to the mean of observed discharges.
MSE	$\mathrm{MSE} = \frac{1}{n}\sum_{i=1}^{n}(\mathrm{Qcal} - \mathrm{Qobs})^2$	Measures the fit of the modeled streamflow to the observed streamflow in order to evaluate the performance of the model.
RMSE	$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(X_{obs,i} - X_{model,i})^2}{n}}$	RMSE serves to aggregate them into a single measure of predictive power.
Pearson correlation Coef. (r)	$r = \frac{\sum_{i=1}^{n}(x_i - \overline{x})\cdot(y_i - \overline{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \overline{x})^2 \cdot \sum_{i=1}^{n}(y_i - \overline{y})^2}}$	Indicates the strength and direction of a linear relationship between two variables

Table 2-2: Peak Flow Evaluation

Objective function	**Peak flow matching**	
	Very Good /Medium /Poor	Reference Literature
Nash	Very Good	Research publication by Xiong & Guo, (1999) and Guo et al., (2002); Chen et al., 2007; Fish, 2011 showed that Nash can be used for Peak flow estimation. But, sometimes overestimation of the model performance during peak flow could occur (Krause et al., 2005).
RAEM	Poor	This method although recommended by WMO, but not commonly used by the Water Balance Modelers.
MRAE	Medium	Study carried out by Perera & Wijesekera, 2010; Wijesekera, 2000 and Wanniarachchi, 2013 shows that Peak flow is not matching perfectly.
RMSE	Medium	Widely used in comparison of daily rainfall runoff models (Moreda, 1999)
BIAS	Poor	BIAS can be used for evaluating model performance to find a best parameter set (Zhang & Savenije, 2005; Szolgay et al., 2003). BIAS also widely used in comparison of daily rainfall runoff models (Moreda, 1999)
RE	Poor	Method adopted by Xiong & Guo, (1999) and Guo et al., (2002)

Table 2-3: Intermediate Flow Evaluation

Objective function	Intermediate flow matching	
	Very Good /Medium /Poor	Reference Literature
Nash	Very Good	Research publication by Xiong & Guo, (1999) and Guo et al., (2002) shows that the intermediate flows are matching perfectly. Nash can be used for evaluating model performance to find a best parameter set (Zhang & Savenije, 2005)
RAEM	Medium	This method although recommended by WMO, but not commonly used by the Water Balance Modelers.
MRAE	Very Good	Study carried out by Perera & Wijesekera, 2010; Wijesekera, 2000 and Wanniarachchi, 2013 shows that the intermediate flow is matching.
RMSE	Medium	Widely used in comparison of daily rainfall runoff models (Moreda, 1999)
BIAS	Very Good	BIAS can be used for evaluating model performance to find a best parameter set (Zhang & Savenije, 2005; Szolgay et al., 2003). BIAS also widely used in comparison of daily rainfall runoff models (Moreda, 1999)
RE	Medium	Method adopted by Xiong & Guo, (1999) and Guo et al., (2002)

Table 2-4: Low Flow Evaluation

Objective function	Low flow matching	
	Very Good /Medium /Poor	Reference Literature
Nash	Medium	Underestimation during low flow conditions (Krause et al., 2005)
RAEM	Medium	This method although recommended by WMO, but not commonly used by the Water Balance Modelers.
MRAE	Medium	Study carried out by Perera & Wijesekera, 2010; Wijesekera, 2000 and Wanniarachchi, 2013 shows that low flow is not matching perfectly.
RMSE	Poor	Widely used in comparison of daily rainfall runoff models (Moreda, 1999)
BIAS	Poor	BIAS can be used for evaluating model performance to find a best parameter set (Zhang & Savenije, 2005; Szolgay et al., 2003). BIAS also widely used in comparison of daily rainfall runoff models (Moreda, 1999)
RE	Medium	Method adopted by Xiong & Guo, (1999) and Guo et al., (2002)

Table 2-5: Overall Flow Evaluation

Objective function	Overall Matching	
	Very Good /Medium /Poor	Reference Literature
Nash	Medium	Research publication by Xiong & Guo, (1999) and Guo et al., (2002) shows that the overall flows are matching.
RAEM	Medium	This method although recommended by WMO, but not commonly used by the Water Balance Modelers. No literature support has been found.
MRAE	Very Good	Study carried out by Perera & Wijesekera, 2010; Wijesekera, 2000 and Wanniarachchi, 2013 shows that the overall flow is matching.
RMSE	Medium	Widely used in comparison of daily rainfall runoff models (Moreda, 1999)
BIAS	Medium	BIAS can be used for evaluating model performance to find a best parameter set (Zhang & Savenije, 2005; Szolgay et al., 2003). BIAS also widely used in comparison of daily rainfall runoff models (Moreda, 1999)
RE	Medium	Method adopted by Xiong & Guo, (1999) and Guo et al., (2002)

2.5.6 Parameter Optimization

Generally parameters are classified into two groups: physical and process parameters(Gupta, & Sorooshian, 1995). A physical parameter represents parameters derived from physically measurable properties of the watershed (e.g. areas of the catchment, fraction of impervious area and surface area of water bodies, surface slope etc). Process parameters represent properties of the watershed which are not directly measurable e.g. monthly evaporation coefficient, c and field capacity catchment, SC (Xiong & Guo, 1999). In fact the division between the two groups depends on the spatial distribution and structure of a model. In the TPMWB model, the parameters are of the second type where the optimum values are obtained by calibrating the model using historical data.

Three different techniques can be applied in order to evaluate the parameter significance and sensitivity; Evaluation of the parameter values during the optimization, Checking the global minimum and Detailed analysis of the variance–covariance matrix (Xu, 1997; Xu & Singh, 1998).

Wijesekera, (2000) have adopted Mean Ratio of Absolute Error (MRAE) as the objective function to indicate the degree of matching of calculated and observed streamflow hydrographs. Using a manual and a semi-automatic optimization and it had been found that the parameter optimization using a manual method was extremely difficult, time consuming and requiring experience for a large number of parameters having a probability of interdependence. Therefore, in this work, parameter optimization had been carried out through an automatic calibration method using a computer program written in FORTRAN77 to carry out the search using the methodology proposed by Powell, 1965. The researcher then carried out an evaluation using a comparison of optimized parameters, annual water balance and duration curves.

Xu & Singh (1998) cited after Pilgrim (1975)contend that automatic optimization using search techniques had been the most common in case of calibration of monthly water balance models. This is partly because most monthly water balance models have a simpler structure and a smaller number of parameters. Automatic optimization techniques are preferred because they are believed to yield a reproducible and unique parameter set.

Xiong & Guo (1999) had also used automatic optimization to get the optimum values of the two parameters model selected for this study. The optimization procedure includes the following two steps. Firstly, optimize the parameter c and SC according to the criterion RE, to achieve a good simulation of the total runoff volume. Secondly, optimize the parameter SC again according to the criterion E, with the value of c obtained in the first step remaining fixed, to further achieve the good fit of shape of runoff hydrograph. It has been told that this two-step optimization procedure can help to reduce effects of the inter-relationship between the two parameters on the model performance.

2.6 Calibration & Validation

Model calibration is one of the most important aspects of hydrologic modelling. Calibration refers to the process of using the first part of data set to find the optimum values of the unknown model parameters by optimization. It is a test of a model with known input and output information that is used to adjust or estimate factors for which reliable data are not available (Xiong & Guo, 1999). Conceptually realistic models can produce erroneous results if they are not properly calibrated (Moreda, 1999). Parameter estimation is not an easy task; it requires the skill, experience and knowledge of the hydrologic model which plays an important role. This is particularly true when manual calibration is employed. It is recommended that a combination of manual and automatic procedure be adopted for the model calibration (Gan, 1988). Manual calibration alone is very tedious, time consuming, and requires the experience of the hydrologist. Because of the time-consuming nature of the manual model calibration, there have been a number of research towards development of automated calibration methods. Automatic calibration on the other hand relies heavily on a specified objective function. However, in the present study both manual and goal seek function technique was adopted to identify the response surface in order to determine the global minimum and local minimum during parameter optimization. Verification refers to the process of using the second part of data set to justify the persistence of the model performance operating with the parameter values obtained in the calibration period. Only when the performance of the model is satisfactory, both in the calibration and in the verification the model can be used with confidence in practice (Xiong & Guo, 1999).

2.7 Climate Change in Sri Lanka

This section briefly discusses the observed changes in climate and future climate projections of Sri Lanka. It is worthwhile to have concise idea about climate change in the context of the present study. Rainfall extremes have adverse impacts on the society and environment of Sri Lanka. Different regions of the country have witnessed either flooding or drought in quick succession in recent years.

2.7.1 Observed Changes in Climate

The rate of increase in temperature from 1961 to 1990 is 0.016 ^{0}C per year (Chandrapala, 1996) which is higher than the global average rate of 0.013 ^{0}C per year for the period 1956 to 2005 (IPCC, 2007). This study also says that Sri Lanka's 100 year warming trend from 1896 to 1996 was 0.003 ^{0}C per year, while it had been 0.025 ^{0}C per year for the 10-year period of 1987-1996, indicating faster warming in more recent years. Scientists attribute this warming trend, seen throughout the country, to both the enhanced greenhouse effect as well as the 'local heat island effect' caused by rapid urbanization (Basnayake et al., 2003; Basnayake, 2008). There has not been a significant trend in Sri Lanka's mean annual rainfall (MAR) during the past century, nevertheless, a higher variability is evident (Jayatillake et al.,, 2005). However, more recent data records reveal a decreasing trend: MAR during 1961-1990 has decreased by 144 mm (7%) compared to that during 1931-1960 (Chandrapala, 1996a; Jayatillake et al. 2005). A few authors have made observations on rainfall in the central region: for example, an analysis of inter-annual as well as intra-annual rainfall trends of the central region from 1964-1993, suggests that there is a decrease in MAR, with the Inter Monsoon 1 (IM1) showing the highest decrease (Herath & Ratnayake, 2004; Shantha & Jayasundara, 2005)and also observed a 39.12 % decrease in MAR in the Mahaweli upper watershed from 1880 to 1974. Bandara & Wickramagamage, 2004 reveal that rainfall on the western slopes of the central highlands has declined significantly from 1900 to 2002 due to reduced south west monsoon (SWM) rainfall. In the country as a whole, the number of consecutive dry days has increased while the number of consecutive wet days has reduced (Herath & Ratnayake, 2004; Premalal, 2009).

2.7.2 Future Climate Projections

IPCC regional projections based on AR4 Atmospheric Ocean General Circulation Models (AOGCMs) suggest a significant acceleration of warming in Asia over that observed in the twentieth century; warming will be stronger than the global mean in South Asia while higher warming is projected during the North-East Monsoon (NEM) than during the South-West Monsoon (SWM) (Cruz et al., 2007). Temperature increases of 5.44 ^{0}C and 2.93 ^{0}C are projected over South Asia in the summer of 2070-2099 (compared to 1961-1990) for the two IPCC emission scenarios: A1F1 (highest future emissions) and B1 (lowest future emissions) (Cruz et al., 2007; IPCC, 2002). Other regional climate models for South Asia also project widespread warming in the region, including in Sri Lanka (rise in annual mean temperature in the range 2.5–4 ^{0}C for IPCC scenario A2 and 2–3 ^{0}C for B2), towards the end of the twenty-first century (see Kumar et al., 2006; (Islam & Rehman, 2004). Both, Kumar et al. 2006 and Islam and Rehman (2004) confirm IPCC's projections of higher warming during the NEM and lower warming during the SWM. Wijesekera (2007) had identified from the literature survey that the 2 degree increase of temperature would affect an increase of 8% in evaporation.

Rainfall projections for Sri Lanka within the century appear to be confusing and sometimes contradictory. While the majority of studies project higher values for MAR, a few had projected lower values. De Silva (2006) and Basnayake & Vithanage (2004) project an increase in SWM rainfall (the season when rainfall is confined mainly to the wet zone) and a decrease in NEM rainfall (the season when the majority of the dry zone receives rainfall). De Silva (2006) envisages a 26-34 % decrease in the NEM rainfall and a 16-38 % increase in the SWM rainfall compared to 1961-1990 for scenarios B2-A2. A 2 % increase in rainfall is projected in the intermediate zone by 2050 (De Silva, 2006). The two regional climate models (Kumar et al. 2006; and Islam and Rehman, 2004), and downscaled projections by Basnayake & Vithanage (2004b) suggest increases in both SWM and NEM rainfall, with Basnayake and Vithanage (2004b) suggesting higher increases in SWM than in NEM. In contrast, downscaled CGCM model projections (Basnayake et al. 2004) indicate decreases in both SWM and NEM.

3 METHODOLOGY

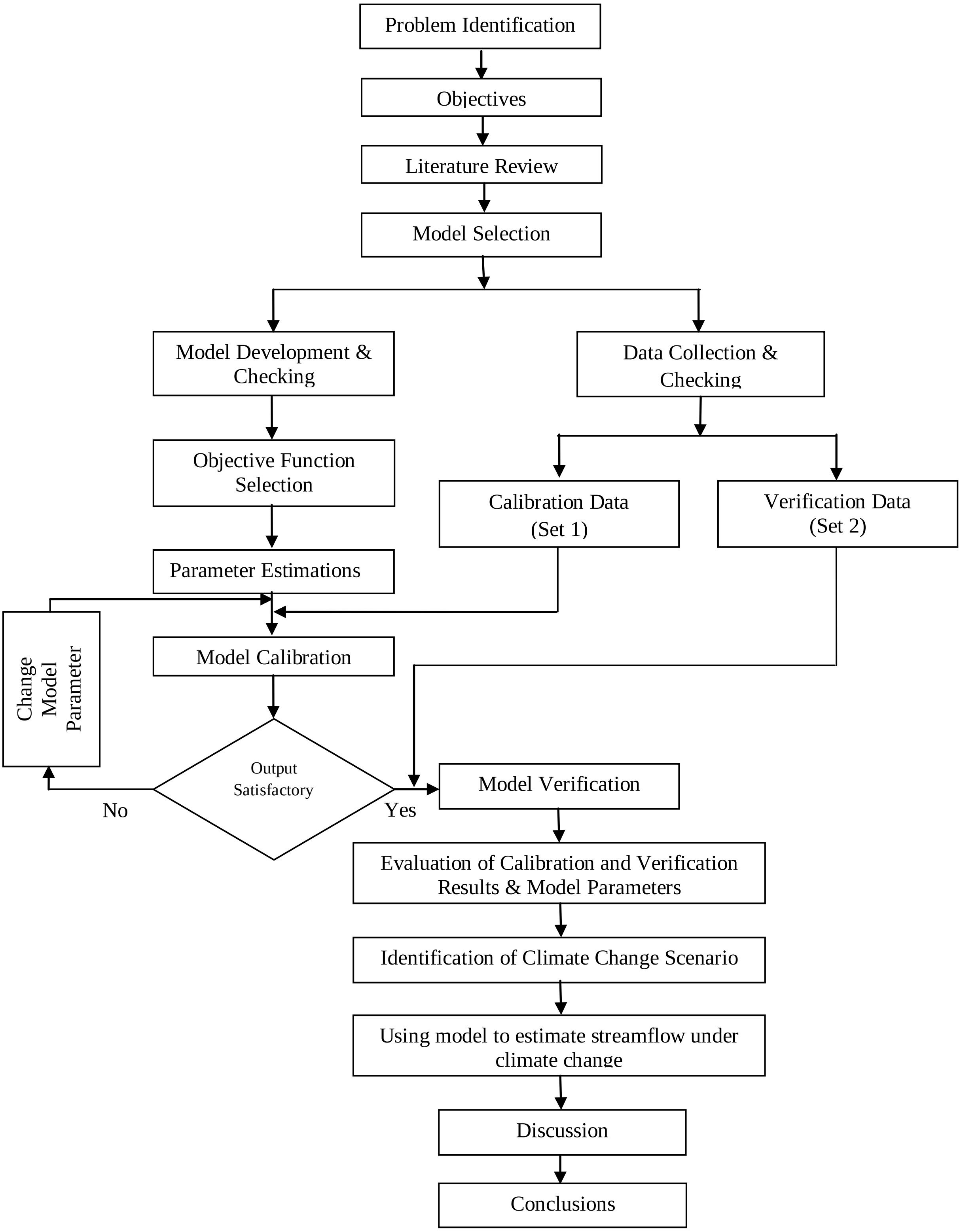


Figure 3-1: Methodology Flow Chart

3.1 General Descriptions

This thesis is divided into 8 chapters including introduction, literature review, methodology, data and data checking, analysis, results, discussions, conclusions and recommendations. The methodology used for the present research is shown in the Figure 3-1. Identification of problems and objectives of the study are included under the Introduction. An extensive literature survey was carried out and reviewed to identify available and commonly used monthly water balance models required for the present study which is presented under the Literature Review.

In order to prepare the study area map and determine the spatial distribution, watershed demarcation was carried out using terrain data available in 1:50,000 topographic maps published by the Department of Survey, Sri Lanka. Main watershed was delineated for the Kelani Ganga Basin at Deraniyagala gauging station and Gin Ganga Basin at Tawalama gauging station. Stream network was also identified using 1:10,000 scale maps. Total of 8 sheets of 1:10,000 scale map were used to demarcate streams and also to verify the watershed boundary.

3.2 Calibration & Validation

The calibration and validation data period and number of years for Kelani Ganga Basin and Gin Ganga Basin are indicated Table 3-1 and Table 3-2 respectively.
Calibration and Validation data selection was made based on the data length, data duration and data time interval. Data used for model calibration and validation is very important because we assume that a better representation of the population would result in a better performance of the rainfall-runoff model. A good information quality of the data set is equivalent to the development of a good model. Both graphical comparisons and statistical tests are required for calibration and validation data sets.
Data period for Kelani Ganga is 48 years from 1966/67 to 2013/2014 and Gin Ganga is 40 years data from 1972/73 to 2011/2012. The data period selected satisfied the data period requirements for climatology studies as recommended by WMO, (1974) which is minimum of 30 years of data period.

Table 3-1: Calibration & Validation Data Summary of Deraniyagala in Kelani Ganga Basin

Purpose	**Data Period**	**No. of Years**
Calibration	1966/67 - 1989/90	24
Validation	1990/91 - 2013/14	24

Table 3-2: Calibration & Validation Data Summary of Tawalama in Gin Ganga Basin

Purpose	**Data Period**	**No. of Years**
Calibration	1972/73 - 1991/92	20
Validation	1992/93 - 2011/12	20

4 DATA & DATA CHECKING

4.1 Kelani Ganga Watershed at Deraniyagala

The Deraniyagala watershed is a sub watershed of Kelani Ganga Basin in Kegalle district (Figure 4-1). It lies between the Kalu Ganga basin (South), Mahaweli Ganga basin (East), Attanagala Oya and Maha Oya basins (North). Drainage area of the Deraniyagala watershed is 182.54 km^2. In the selected study area there is one stream gauging station at Deraniyagala and four rain gauging stations located in and around the catchment area. The nearest Evaporation station at Colombo Meteorology was selected for evaporation data. The details are indicated in the Table 4-1 and Table 4-2.

It was observed that about 36.97 % of the watershed area is under rubber cultivation, 32.76% forest, 10.15% under Homesteads and coverage of other area are as shown in the Table 4-3 and Figure 4-5. The soil type found in the catchments is Red-Yellow Podzolic soils, steeply dissected, hilly and rolling plain.

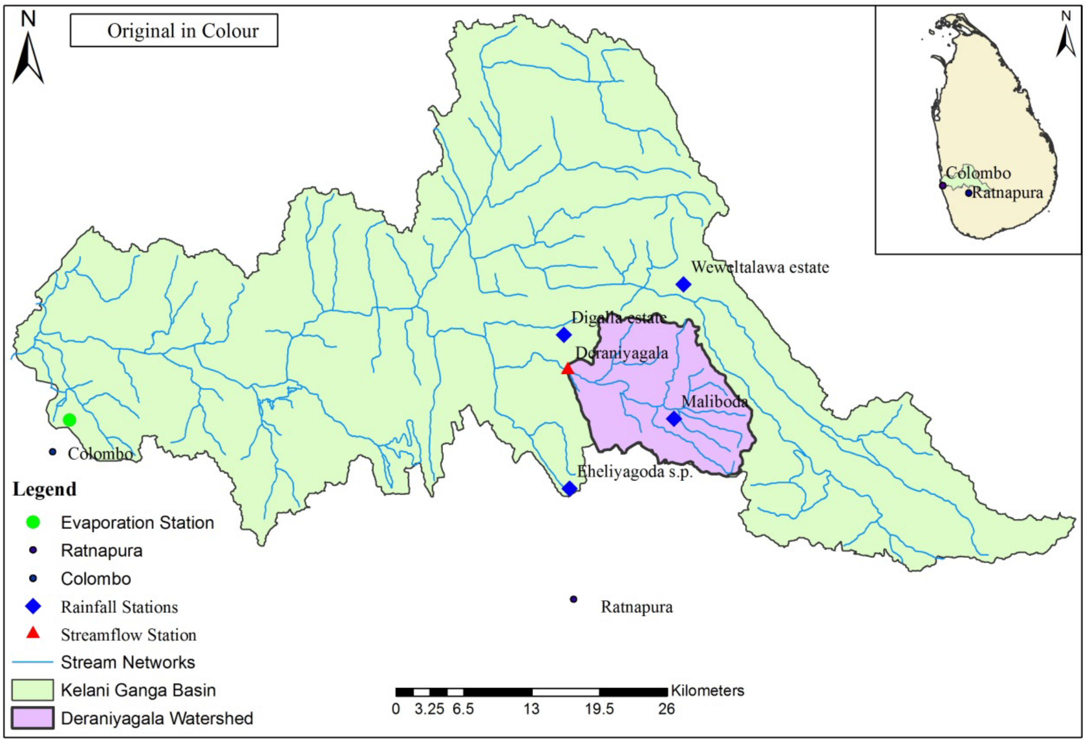


Figure 4-1: Kelani Ganga Watershed at Deraniyagala

Table 4-1: Summary of Deraniyagala watershed

Kelani Ganga River Basin (km²)	2315.00
Watershed at Deraniyagala (km²)	183.00
Divisional Secretary Divisions (DSD)	Deraniyagala
District	Kegalle
Province	Sabaragamuwa (SG)
Maximum Stream Length (km)	19.00

Table 4-2: Rainfall, Streamflow and Evaporation Gauging Station at Deraniyagala

Stations	**Location**			**District**
	Latitude	**Longitude**	**Elevation (m)**	
Rainfall Station				
Maliboda	06-53-27N	80-25-26E	274.40	Kegalle
Digalla Estate	06-57-31N	80-17-46E	122.00	Kegalle
Weweltalawa Estate	07-03-14N	80-22-57E	116.00	Kegalle
Eheliyagoda S.P	06-51-12N	80-16-35E	225.60	Ratnapura
Streamflow Station				
Deraniyagala	06-55-30N	80-20-15E	82.00	Ratnapura
Evaporation Station				
Colombo Meteorology	06-54-00N	79-52-47E	7.00	Colombo

Table 4-3: Landuse details of Deraniyagala watershed

#	Landuse Type	Area (A) km²	Area (%)
1	Forest- Unclassified	59.81	32.76
2	Homesteads/Garden	18.52	10.15
3	Minor Streams	2.40	1.31
4	Other Cultivations	2.79	1.53
5	Paddy	1.96	1.07
6	Rock	6.28	3.44
7	Rubber	67.48	36.97
8	Scrub land	10.79	5.91
9	Tea	12.51	6.86

4.2 Gin Ganga Watershed at Tawalama

The Tawalama watershed is a sub watershed of Gin Ganga Basin in Galle district (Figure 4-2). It lies between the Nilwala Ganga basin (South), Walawe Ganga basin (East), Kalu Ganga and Bentota basins (North). Drainage area of the Tawalama watershed is 368.75 km^2. In the selected study area there is one stream gauging station at Tawalama and four rain gauging stations within the proximity to the catchment area. The nearest Evaporation station at Ratnapura has been selected for evaporation data. The details are as shown in the Table 4-4 and Table 4-5.

Land use distribution of the study area is indicated in Table 4-6 and Figure 4-6. It was observed that about 29.33 % of the watershed area is under forest, 10.23% under other cultivations, 7.92% of Homesteads/garden, 7.85% of Chena and the soil type found in the catchments is Red-Yellow Podzolic soils, steeply dissected, hilly and rolling plain.

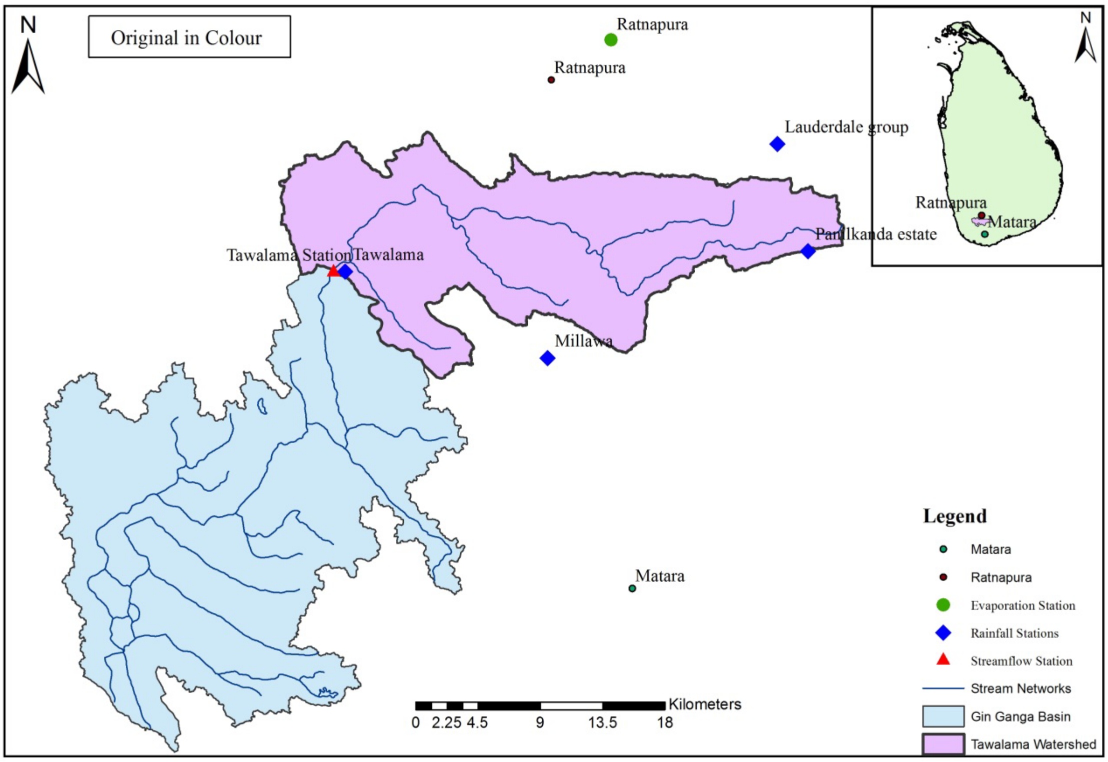


Figure 4-2: Gin Ganga Watershed at Tawalama

Table 4-4: Summary of Tawalama watershed

Gin Ganga River Basin (km²)	943.00
Watershed at Tawalama (km²)	369.00
Divisional Secretary Divisions (DSD)	Neluwa
District	Galle
Province	Southern Province (SP)
Maximum Stream Length (km)	36.00

Table 4-5: Rainfall, Streamflow and Evaporation Gauging Station at Tawalama

Stations	**Location**			**District**
	Latitude	**Longitude**	**Elevation (m)**	
Rainfall Station				
Lauderdale Group	06-25-08N	80-36-23E	18.00	Ratnapura
Tawalama	06-20-28N	80-21-22E	30.00	Galle
Millawa	06-17-35N	80-27-41E	76.00	Matara
Panilkande Estate	06-21-33N	80-37-38E	579.00	Ratnapura
Streamflow Station				
Tawalama	06-20-28N	80-21-22E	30.00	Galle
Evaporation Station				
Ratnapura	06-40-00N	80-25-00E	34.00	Ratnapura

Table 4-6: Landuse details of Tawalama watershed

#	Landuse Type	Area (A) km²	Area (%)
1	Chena	28.94	7.85
2	Coconut	0.16	0.04
3	Forest - Unclassified	108.15	29.33
4	Grassland	0.50	0.14
5	Homesteads/Garden	29.21	7.92
6	Marsh	0.06	0.02
7	Minor Streams	3.92	1.06
8	Paddy	15.00	4.07
9	Other Cultivations	37.82	10.26
10	Rock	1.60	0.43
11	Rubber	18.54	5.03
12	Scrub land	40.30	10.93
13	Tea	84.54	22.93

4.3 Thiessen Average Rainfall

Thiessen polygons for Kelani Ganga at Deraniyagala using four rain gauging stations shown in Figure 4-3 were used to calculate the Thiessen Average Rainfall. In the Kelani Ganga at Deraniyagala one rain gauging station lies inside the boundary and the others located outside the boundary. The calculated Thiessen area and weights are shown in Table 4-7.

Similarly, four rain gauging stations at Gin Ganga (Figure 4-4) were used to calculate the Thiessen Average Rainfall. One rain gauging station is located inside the boundary, one is at the boundary and the others are located outside the boundary. The Thiessen weights are shown in Table 4-8.

Table 4-7: Thiessen weights for Kelani Ganga at Deraniyagala

Station Name	Thiessen Area (km^2)	Weight
Maliboda	126.8	0.695
Digalla Estate	32.27	0.177
Weweltalawa Estate	17.83	0.097
Eheliyagoda S.P	5.64	0.030

Table 4-8: Thiessen weights for Gin Ganga at Tawalama

Station Name	Thiessen Area (km^2)	Weight
Lauderdale Group	39.37	0.107
Tawalama	146.05	0.396
Millawa	135.4	0.367
Panilkande Estate	47.93	0.130

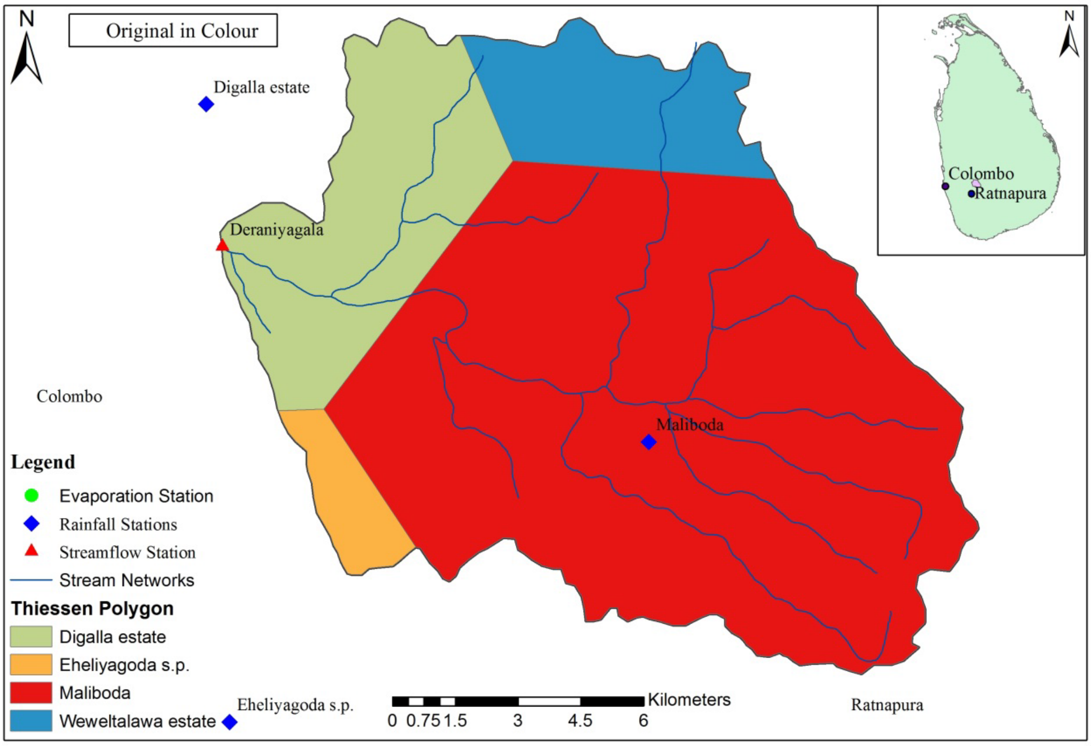


Figure 4-3: Thiessen Polygons and Rainfall Stations at Deraniyagala

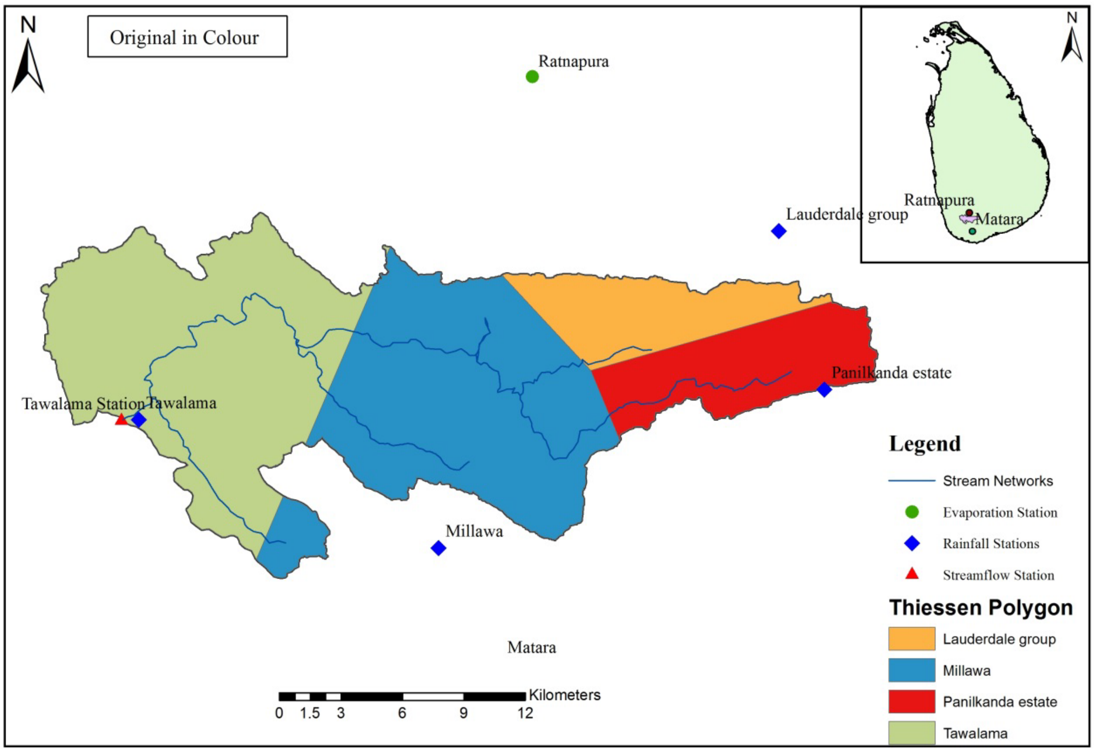


Figure 4-4: Thiessen Polygons and Rainfall Stations at Tawalama

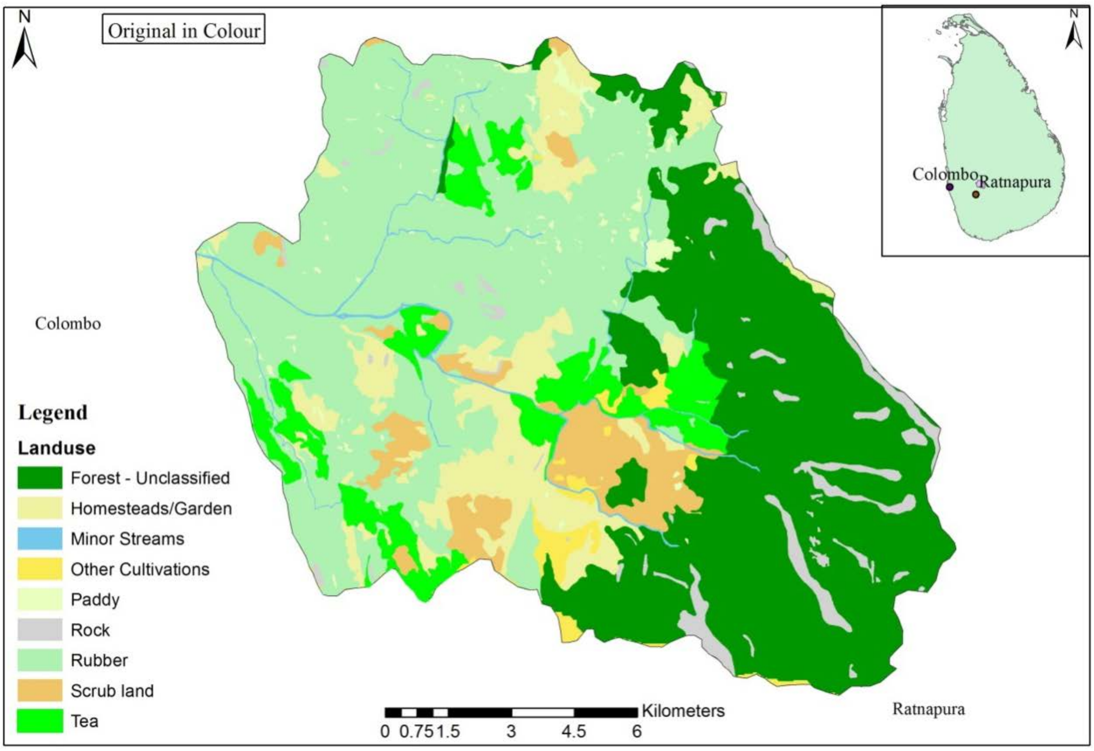


Figure 4-5: Land-use of Deraniyagala

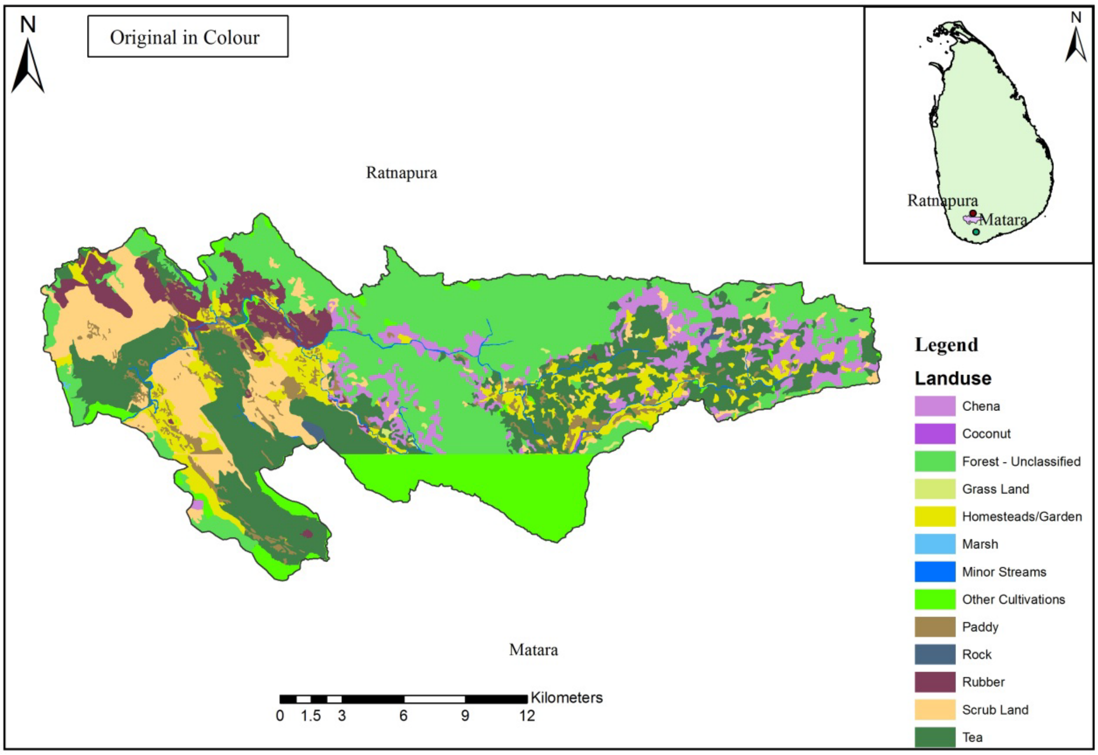


Figure 4-6: Land-use of Tawalama

4.4 Data and Data Checking

4.4.1 Data

In Sri Lanka the Department of Irrigation and Department of Meteorology are the agencies responsible to maintain most of gauging stations (rainfall, evaporation and streamflow). As per Hydrological Annual (2010-2011), Irrigation Department maintained 31 stream gauges. The data sources and resolutions are indicated in the Table 4-9 and Table 4-10. The data used in the present study are rainfall, streamflow, evaporation, land-use and topographic data. The data record period before 1985 were taken from the Electricity Master Plan, 1987.

4.4.2 Data Errors

Hydrological data must be cleaned from random and systematic error for erroneous data leads to either non-verifiable rejection of a model or wrong calibration that affects the usefulness of a model.

4.4.3 Data Checking Methods

The data checking method adopted in the present study include both Graphical Checking (Visual Checking) and Statistical Checking.

Data obtained were screened for outliers, and missing values were estimated using a linear interpolation method (Schatzman, 2002) after carrying out Single Mass Curve (S-Curve) analysis. The consistency of the precipitation data has been checked by the Double Mass curve technique (Subramanya, 1994). Outlier testing was carried out for the entire data set. Double mass plots indicated the homogeneity of annual rainfall and streamflow data. Initially time series plots were used to identify the data duration that showed a significant compatibility between the rainfall and streamflow. The S-Curve and D-Mass Curve for Kelani Ganga and Gin Ganga are presented in the Appendix-A and Appendix-B respectively.

The distribution of Gauging Stations for both watersheds were compared with the standards of the World Meteorological Organization (Table 4-11) and (Table 4-12) and were found to be within the acceptable range.

Table 4-9: Data Sources and Resolutions of Kelani Ganga at Deraniyagala

Data Types	Temporal Resolution	Spatial Resolution(km²/station)	Data Period	Source
Rainfall	Monthly	45.64	1966-2014	Dept. of Meteorology
Evaporation	Monthly	182.54	1966-2014	Dept. of Meteorology
Streamflow	Monthly	182.54	1966-2014	Dept. of Irrigation
Topo Map	-	1:50,000	Updated 2003	Dept. of Survey
Land-use	-	1:50,000	Updated 2006	Dept. of Survey

Table 4-10: Data Sources and Resolutions of Gin Ganga at Tawalama

Data Types	Temporal Resolution	Spatial Resolution(km²/station)	Data Period	Source
Rainfall	Monthly	92.19	1972-2012	Dept. of Meteorology
Evaporation	Monthly	368.75	1972-2012	Dept. of Meteorology
Streamflow	Monthly	368.75	1972-2012	Dept. of Irrigation
Topo Map	-	1:50,000	Updated 2003	Dept. of Survey
Land-use	-	1:50,000	Updated 2006	Dept. of Survey

Table 4-11: Distribution of Gauging Stations of Kelani Ganga at Deraniyagala

Gauging Station	Number of Stations	Station Density (km²/station)	WMO Standards (km²/station)
Rainfall	4	45.64	575
Streamflow	1	182.54	1875
Evaporation	1	182.54	

Table 4-12: Distribution of Gauging Stations of Gin Ganga at Tawalama

Gauging Station	Number of Stations	Station Density (km²/station)	WMO Standards (km²/station)
Rainfall	4	92.19	575
Streamflow	1	368.75	1875
Evaporation	1	368.75	

4.5 Monthly Comparison

4.5.1 Precipitation

Deraniyagala watershed at Kelani Ganga has four rain gauging stations namely Maliboda, Digalla Estate, Weweltalawa Estate and Eheliyagoda S.P. The common period of monthly precipitation record from 1966-2014 is shown in Table 4-9. The spatial resolution of the data is 1 Station per 45.64 km².

Tawalama watershed at Gin Ganga has four rain gauging stations namely Lauderdale Group, Tawalama, Millawa and Panilkande Estate. The common period of monthly precipitation record from 1972-2012 is shown in Table 4-10. The spatial resolution of the data is 1 Station per 92.19 km^2.

Rainfall data were obtained from the Department of Meteorology of Sri Lanka and Electricity Master Plan (1987). Data were tabulated in hydrologic years. In Sri Lanka there are two seasons namely Maha (wet) season which starts from October to March and Yala (dry) season starts from April to September. The island is divided into three principal agro-climatic zones, viz. wet, intermediate and dry zones, which have been demarcated based on hydrology, meteorology, soils and vegetation (Ponrajah, 1984). The Wet Zone covers the south-western region including the central hill country and receives relatively high mean annual rainfall over 2,500 mm without pronounced dry periods. The current study area is situated in wet zone region WL1 where there is heavy rainfall during Yala season due to South West monsoon from the Bay of Bengal. Unlike in the dry zone, the rainfall intensity and streamflow quantity in the study area is stated as higher during the Yala season than the Maha season. Rainfall volumes received by the monsoonal winds at the wind ward slopes increases with altitude. Basically there are four monsoons in Sri Lanka: First-Inter Monsoon (Mar-Apr), South-West Monsoon (May-Sep), Second-Inter Monsoon (Oct-Nov) and North-East Monsoon (Dec-Feb) (http://www.meteo.gov.lk/).

4.5.1.1 Precipitation of Kelani Ganga at Deraniyagala

In Kelani Ganga Basin, Mean rain-year precipitation varies from 149–541 mm. Maximum precipitations varies from 268-999 mm, while the minimum varies from 68-303 mm. The monthly comparison of Thiessen average rainfall for Kelani Ganga is shown in the Figure 4-7 and Rainfall variation at each rain gauging station and a comparison for Kelani Ganga is shown in the Appendix A.

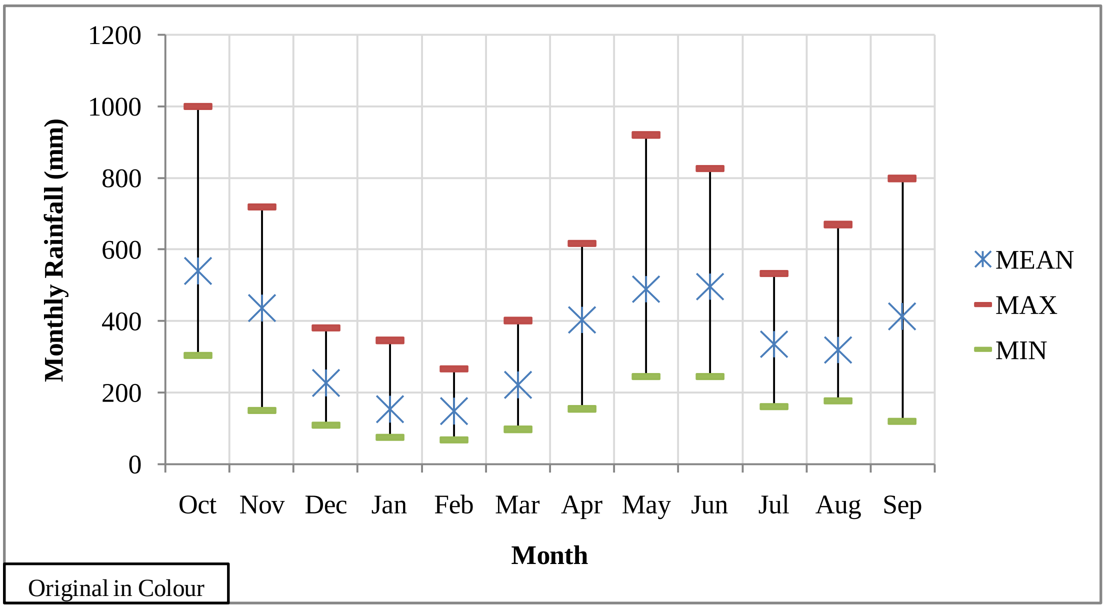


Figure 4-7: Monthly Comparison of Thiessen Average Rainfall at Deraniyagala

4.5.1.2 Precipitation of Gin Ganga at Tawalama

In Gin Ganga Basin, Mean rain-year precipitation varies from 163.9-489.7 mm. Maximum precipitation varies from 343-816 mm, while the minimum varies from 70-282 mm. The monthly comparison of Thiessen average rainfall for Gin Ganga is shown in the Figure 4-8 and Rainfall variation at each rain gauging stations for Gin Ganga is shown in the Appendix A. The highest annual rainfall was recorded 4999.6 mm in the year 1987/88 and highest rainfall in a month was recorded 816.3 mm in October 1993/94. Comparison of monthly rainfall is indicated in the Appendix-B.

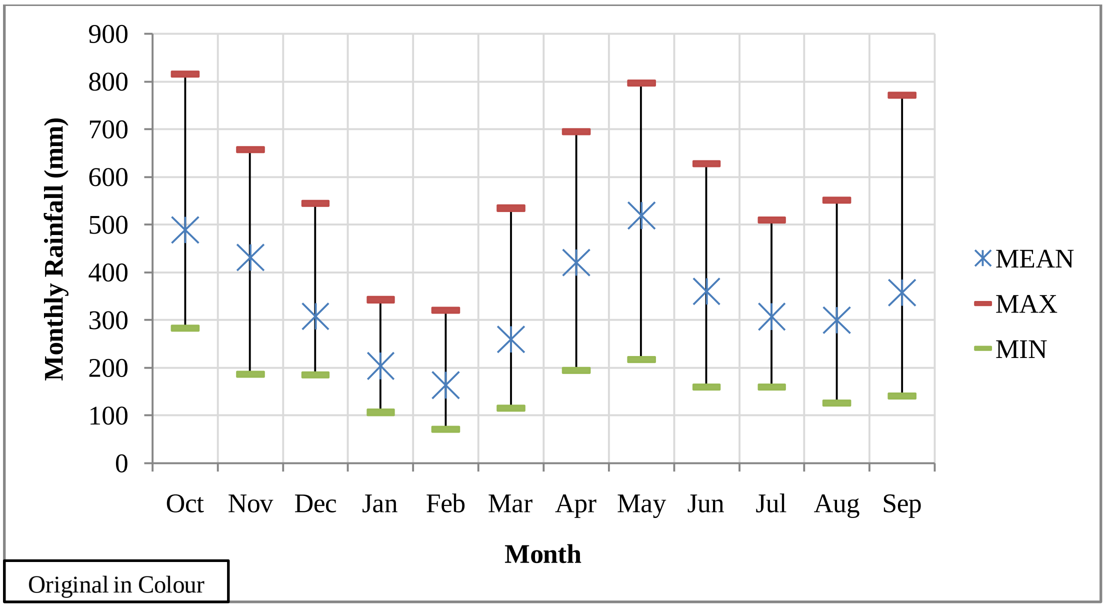


Figure 4-8: Monthly Comparison of Thiessen Average Rainfall at Tawalama

4.5.2 Evaporation of Kelani Ganga at Deraniyagala

In Kelani Ganga Basin, Mean monthly pan evaporation varies from 85-136 mm. Maximum pan evaporation varies from 118-177 mm, while the minimum varies from 46-98 mm. Comparison of monthly pan evaporation is indicated in the Appendix A.

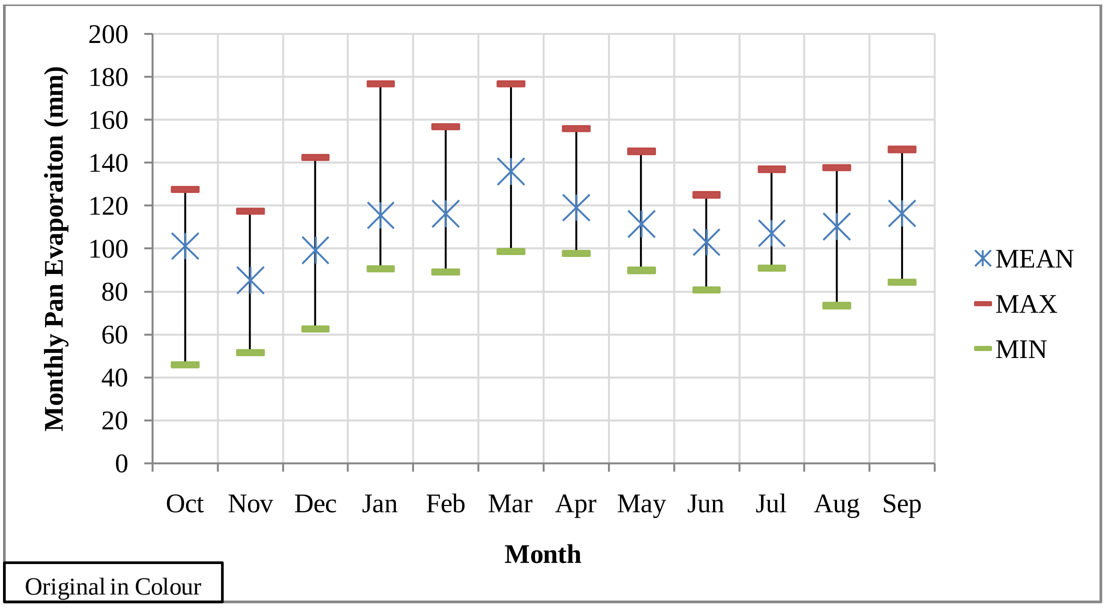


Figure 4-9: Monthly Comparison of Pan Evaporation at Deraniyagala

4.5.3 Evaporation of Gin Ganga at Tawalama

In Gin Ganga Basin, Mean pan evaporation varies from 96-140 mm. Maximum pan evaporation varies from 135-175 mm; while the minimum varies from 54 -99 mm. Comparison of monthly pan evaporation of Gin Ganga is indicated in the Appendix-B.

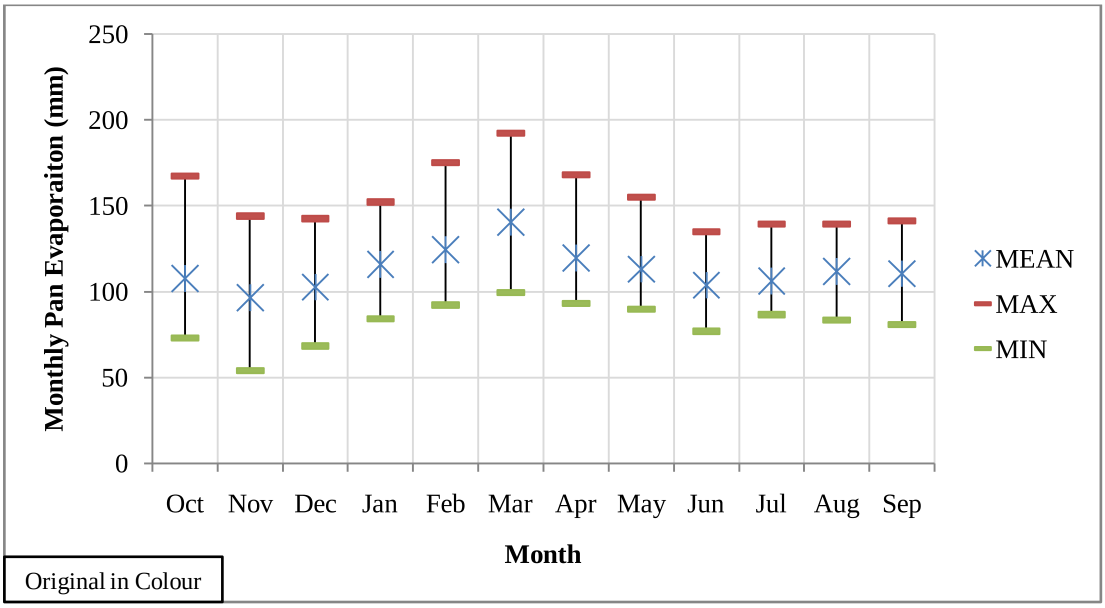


Figure 4-10: Monthly Comparison of Pan Evaporation at Tawalama

4.5.4 Streamflow of Kelani Ganga at Deraniyagala

In Kelani Ganga Basin, Mean streamflow varies from 91-432 mm. Maximum streamflow varies from 177-888 mm, while the minimum varies from 45-220 mm. Comparison of monthly streamflow is indicated in the Appendix A.

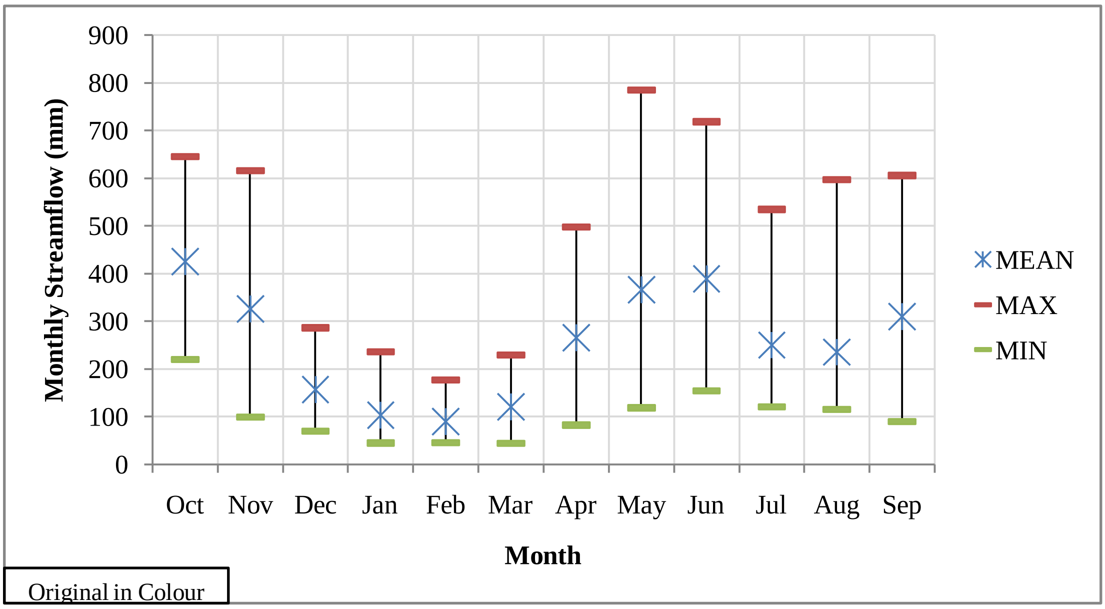


Figure 4-11: Monthly Comparison of Streamflow at Deraniyagala

4.5.5 Streamflow of Gin Ganga at Tawalama

In Gin Ganga Basin, Mean monthly streamflow varies from 112-354 mm. Maximum monthly streamflow varies from 210-650 mm, while the minimum varies from 52-193 mm. Comparison of monthly streamflow is indicated in the Appendix-B.

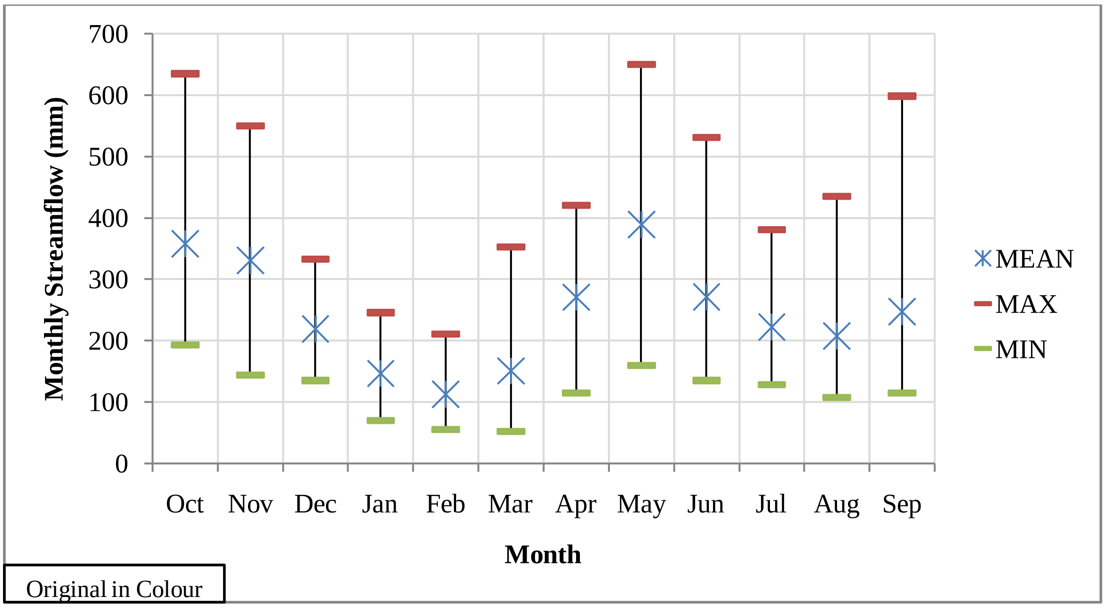


Figure 4-12: Monthly Comparison of Streamflow at Tawalama

4.6 Annual Comparison

4.6.1 Rainfall and Streamflow

Annual Comparison was carried out for Precipitations Vs Discharge, Annual Water Balance Vs Pan Evaporation and Annual Water Balance Vs Actual Evaporation in order to observe the annual variations and patterns.

The annual comparison of rainfall and streamflow for Kelani Ganga is shown in Figure 4-13 and the rainfall and streamflow shows the good matching (Figure 4-14). Annual comparison of Streamflow Corresponding Monthly Rainfall is indicated in Appendix A with 6 years of interval from 1966 to 2014.

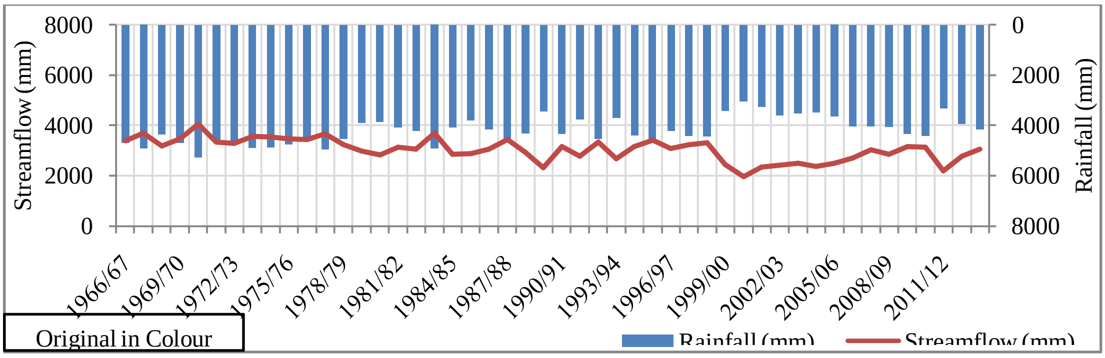


Figure 4-13: Annual Comparison of Rainfall & Streamflow at Deraniyagala

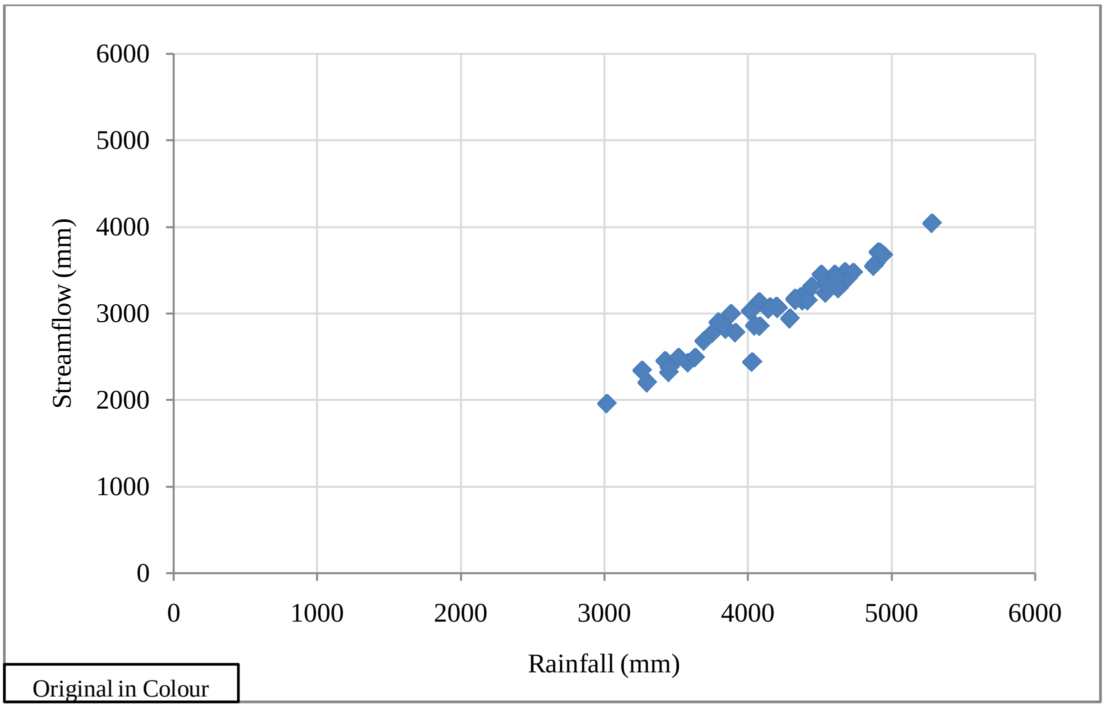


Figure 4-14: Annual Comparison of Rainfall & Streamflow at Tawalama

The annual comparison of rainfall and streamflow for Gin Ganga is shown in Figure 4-15 and the rainfall and streamflow shows a good match (Figure 4-16). Annual comparison of Streamflow Corresponding Monthly Rainfall is indicated in Appendix B with 5 years of interval from 1972 to 2012.

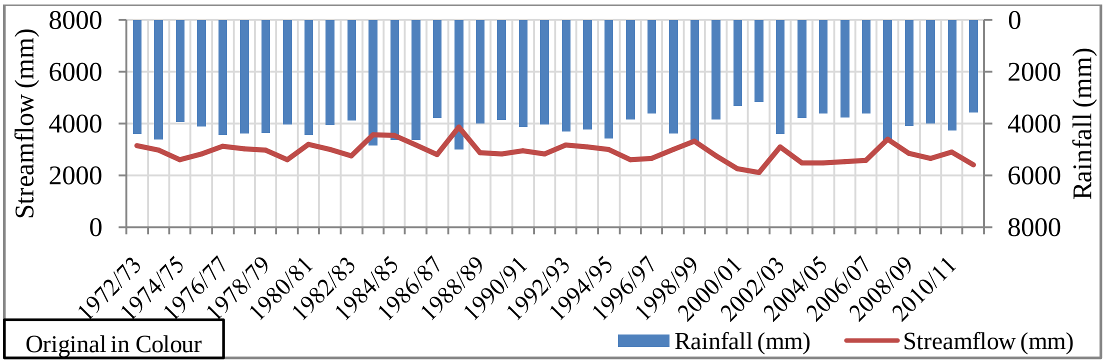


Figure 4-15: Annual Comparison of Rainfall & Streamflow at Deraniyagala

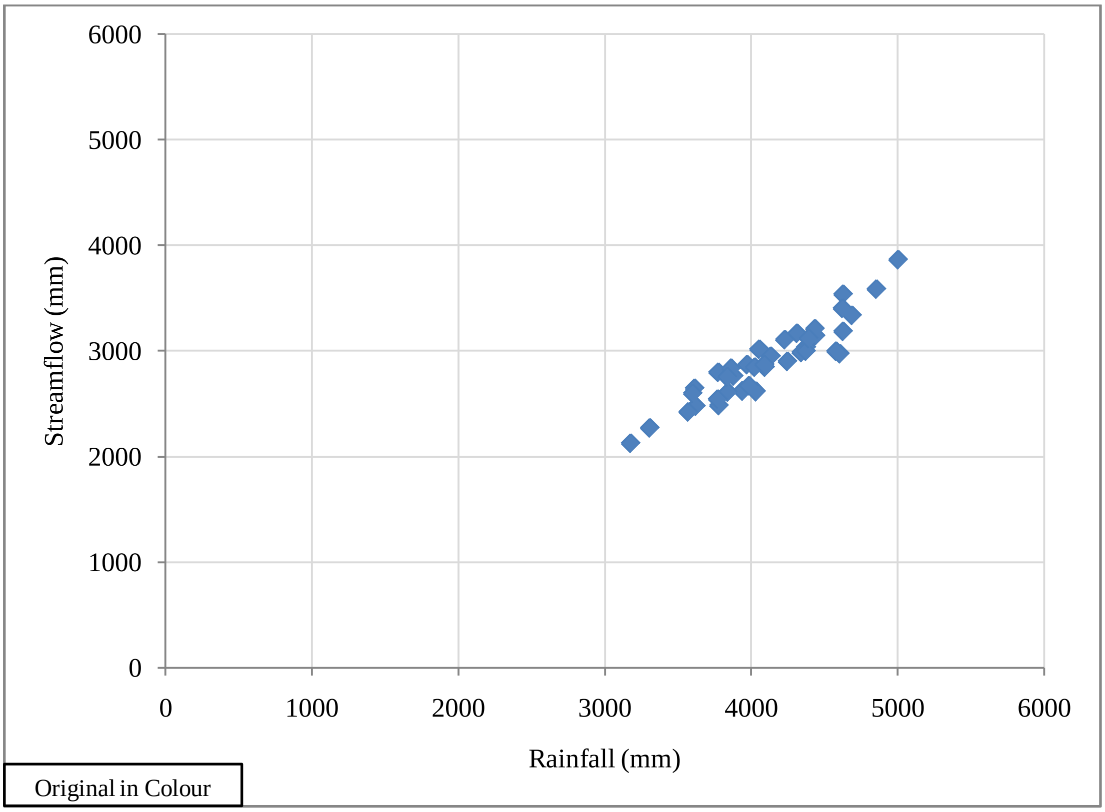


Figure 4-16: Annual Comparison of Rainfall & Streamflow at Tawalama

4.6.2 Water Balance and Pan Evaporation

Annual water balance comparison is very important to check the data input and computation errors. Annual water balance of observed components also reveal gross errors, because in annual cycle seepage loss and change in storage is negligible.

Annual water balance is given by;

$$P(t) - E(t) - Seepage(t) - Q(t) = S_t - S_{t-1} \quad (13)$$

Where; P(t) is Rainfall, E(t) is Evapotranspiration, Q(t) is outflow, S_t-S_{t-1}=ΔS which is change in storage.

For Kelani Ganga, the graph indicated a good match with the annual water balance recorded between 898 and 1359 mm with an average of 1151 mm. The monthly pan evaporation was recorded between 1148 and 1560 mm with an average of 1321 mm as indicated in the Figure 4-17.

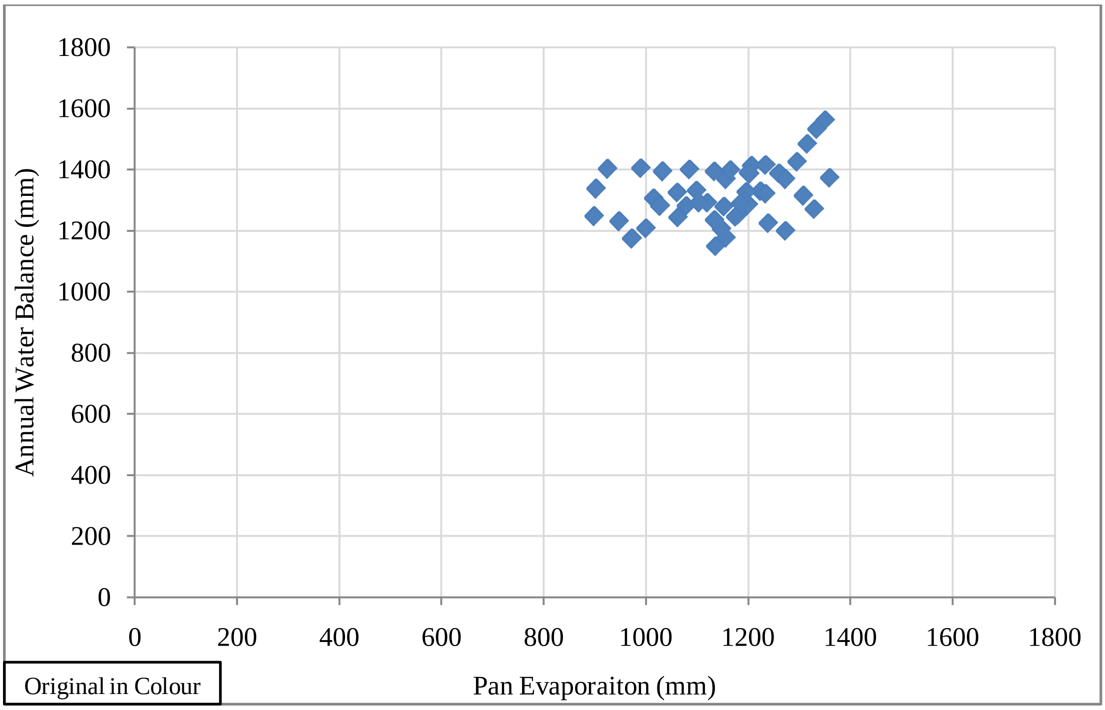


Figure 4-17: Annual Water Balance & Pan Evaporation at Deraniyagala

In Gin Ganga, the graph indicated a good match with annual water balance recorded between 963 and 1612 mm with an average of 1200 mm. The pan evaporation was recorded between 1166 and 1542 mm with an average of 1354 mm as indicated in the Figure 4-18.

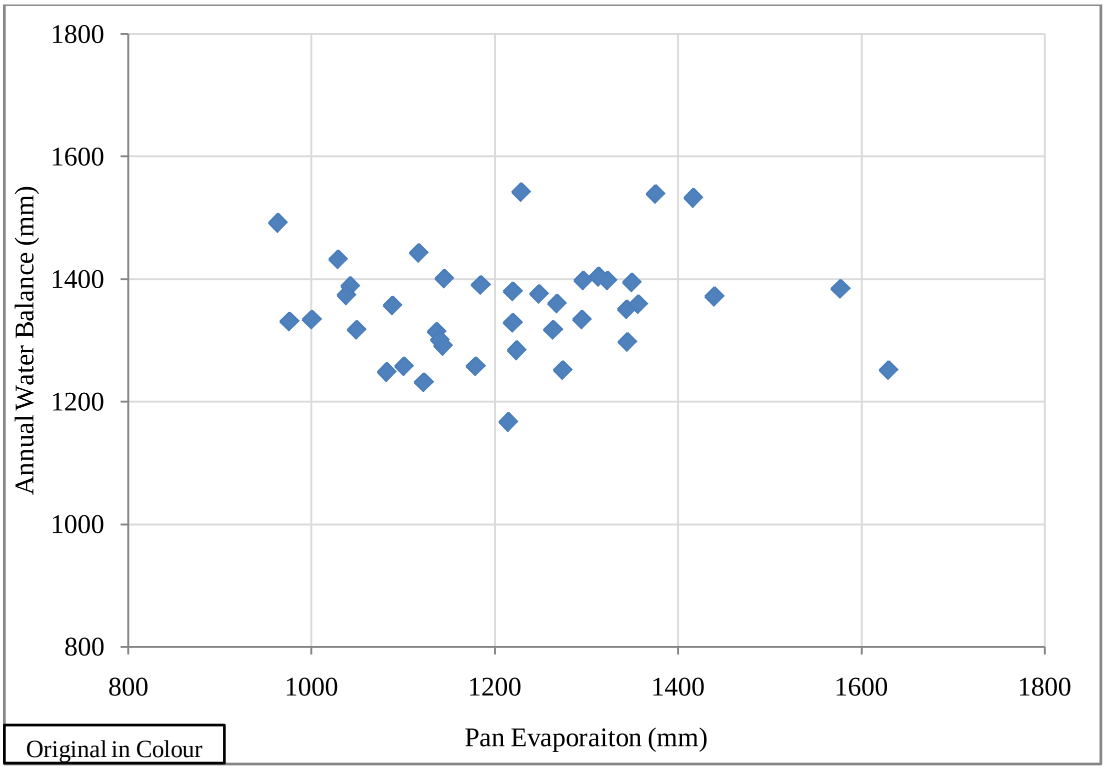


Figure 4-18: Annual Water Balance & Pan Evaporation at Tawalama

4.7 Seasonal Comparison

Seasonal comparison of streamflow Vs rainfall for Yala & Maha Season has been carried out to observe the seasonal variations. Seasonal comparison of streamflow & rainfall for Kelani Ganga is presented in Figure 4-19; it was observed that the rainfall is higher during Yala season than Maha season due to south west monsoon from the Bay of Bengal.

Similarly, seasonal comparison of streamflow & rainfall for Gin Ganga is presented in Figure 4-20. It was observed that the rainfall is higher during Yala season than Maha season due to south west monsoon from the Bay of Bengal.

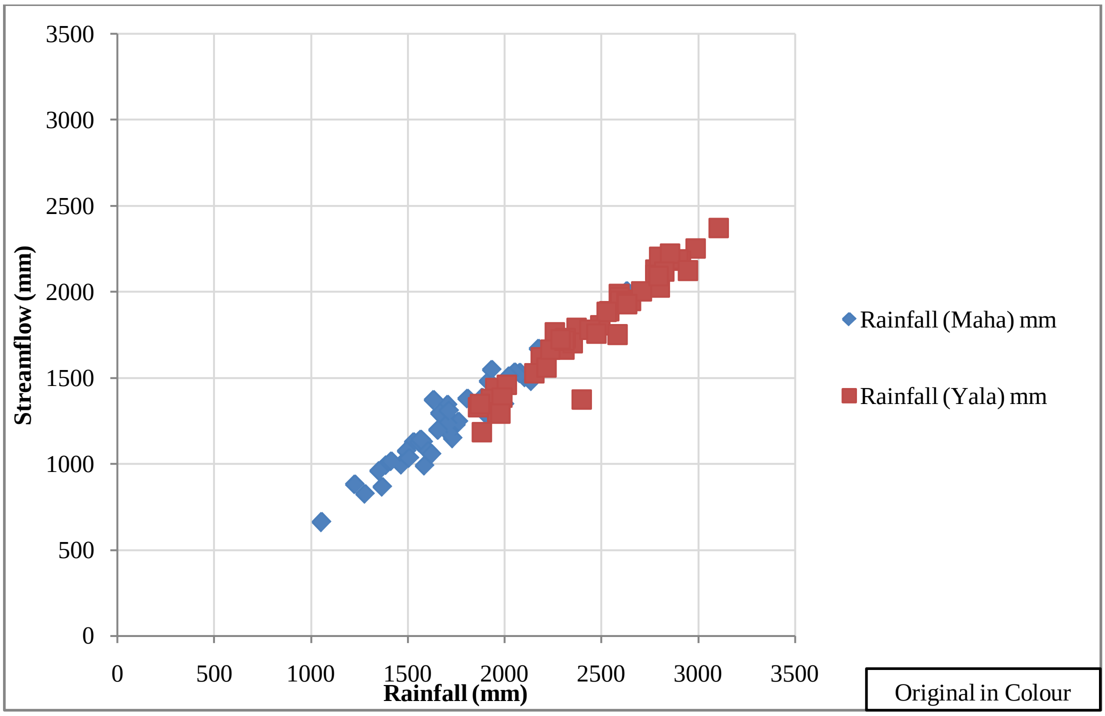


Figure 4-19: Seasonal Comparison of Streamflow & Rainfall at Deraniyagala

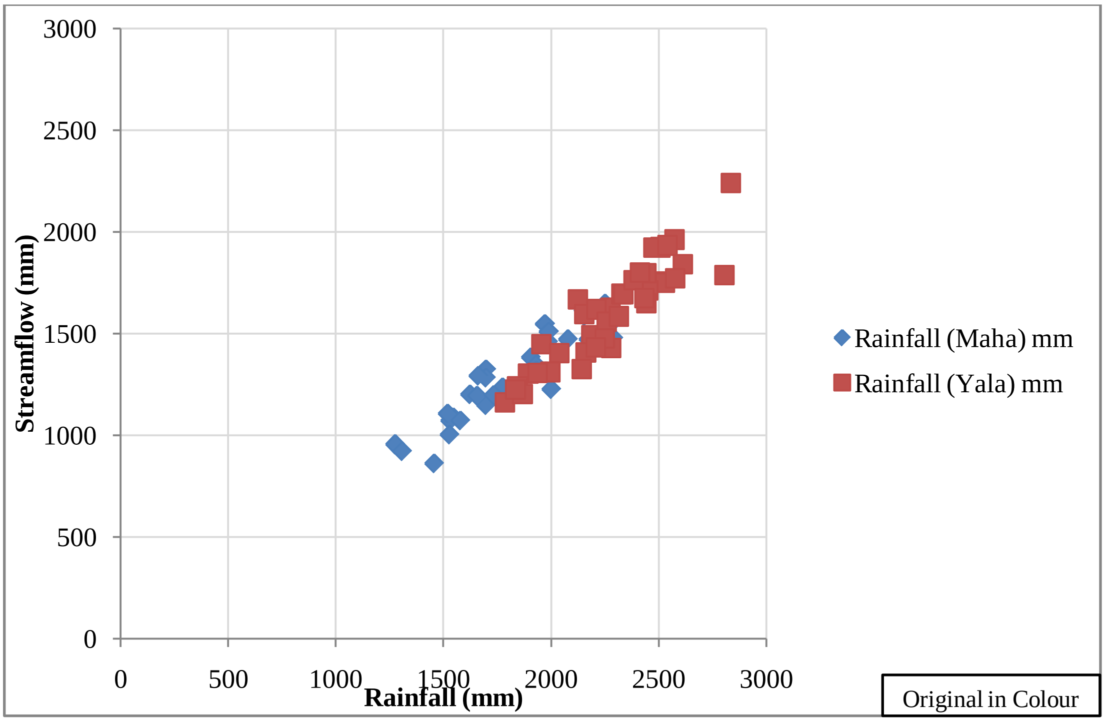


Figure 4-20: Seasonal Comparison of Streamflow & Rainfall at Tawalama

4.8 Runoff Coefficient

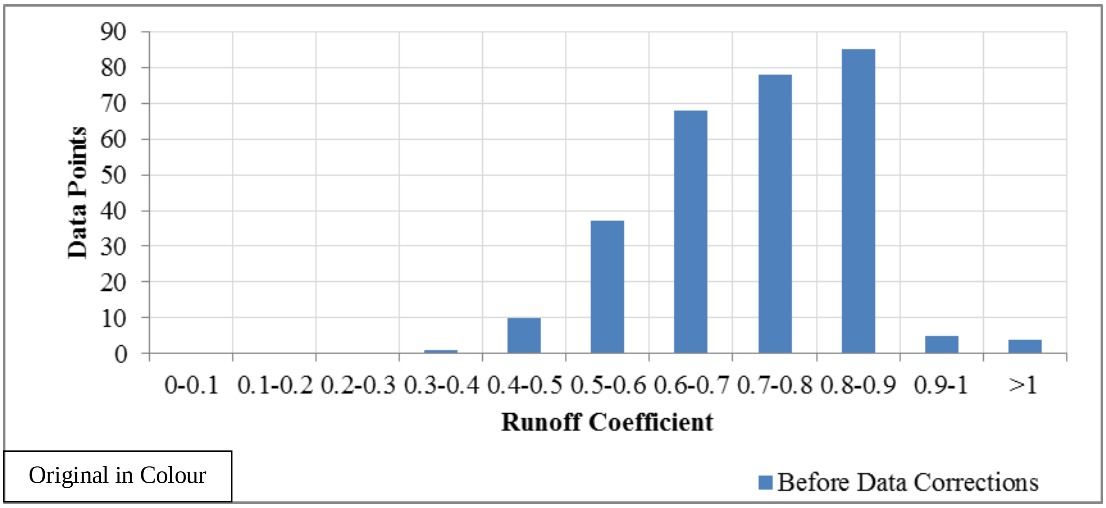
For Kelani Ganga, the monthly, annual and seasonal runoff coefficient comparisons were carried out as presented in the Appendix A. The average runoff coefficient monthly is 0.71, annual is 0.73 and seasonal is 0.72.

For Gin Ganga, the monthly, annual and seasonal runoff coefficient comparisons were carried out as presented in the Appendix-B. The average runoff coefficient monthly is 0.712, annual is 0 0.718 and seasonal 0.704.

It was observed that some data points have runoff coefficient more than 1.0 which are unrealistic data points indicating that there had been more monthly streamflow than the monthly rainfall. These can happen when there had been heavy antecedent rainfall. The unrealistic data points in the observed streamflow were checked with the antecedent rainfall. Frequency analysis was carried out for Kelani Ganga as indicated in the Table 4-13 and Figure 4-21. Data correction was made by removing 15.97% unrealistic data points which did not match well with antecedent rainfall. Similarly, Frequency analysis has been carried out for Gin Ganga as indicated in the Table 4-14 and Figure 4-22. Data correction was made by removing 14.167% unrealistic data points. All Data were well checked before the model computation but outliers were removed only after comparing with model simulation results. This is to make sure that the extreme values are not mistakenly removed.

Table 4-13: Data Points Analysis for Kelani Ganga

Before Data Corrections			After Data Corrections			Data Corrected
Runoff Coefficient	Data Points	Category	Runoff Coefficient	Data Points	Category	
0-0.1	0	Likely	0-0.1	0	Likely	0
0.1-0.2	0	Likely	0.1-0.2	0	Likely	0
0.2-0.3	0	Very Likely	0.2-0.3	0	Very Likely	0
0.3-0.4	1	Very Likely	0.3-0.4	6	Very Likely	5
0.4-0.5	10	Very Likely	0.4-0.5	23	Very Likely	13
0.5-0.6	37	Very Likely	0.5-0.6	42	Very Likely	5
0.6-0.7	68	Likely	0.6-0.7	60	Likely	8
0.7-0.8	78	Likely	0.7-0.8	78	Likely	0
0.8-0.9	85	Likely	0.8-0.9	79	Likely	6
0.9-1	5	Unlikely	0.9-1	0	Unlikely	5
>1	4	Unlikely	>1	0	Unlikely	4
Total	288		Total	288		46
Percentage Correction						15.97%



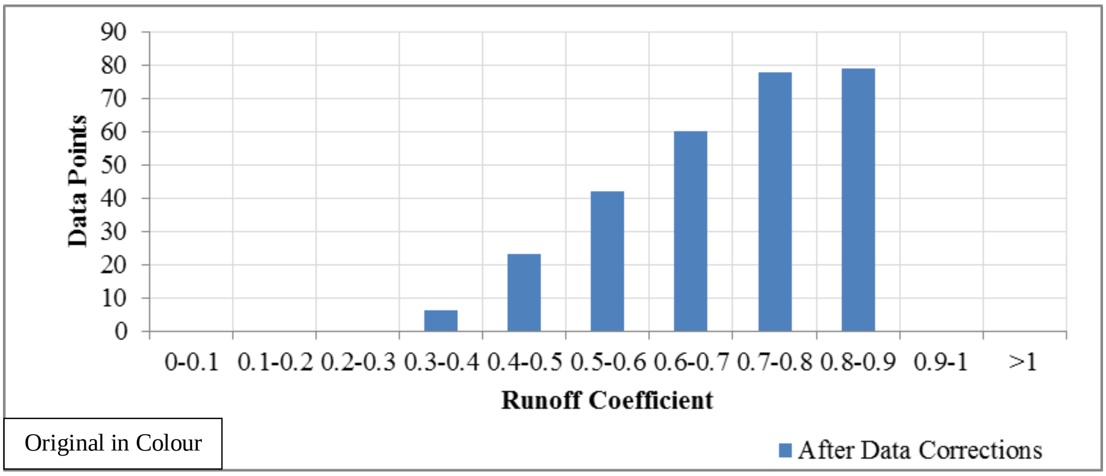
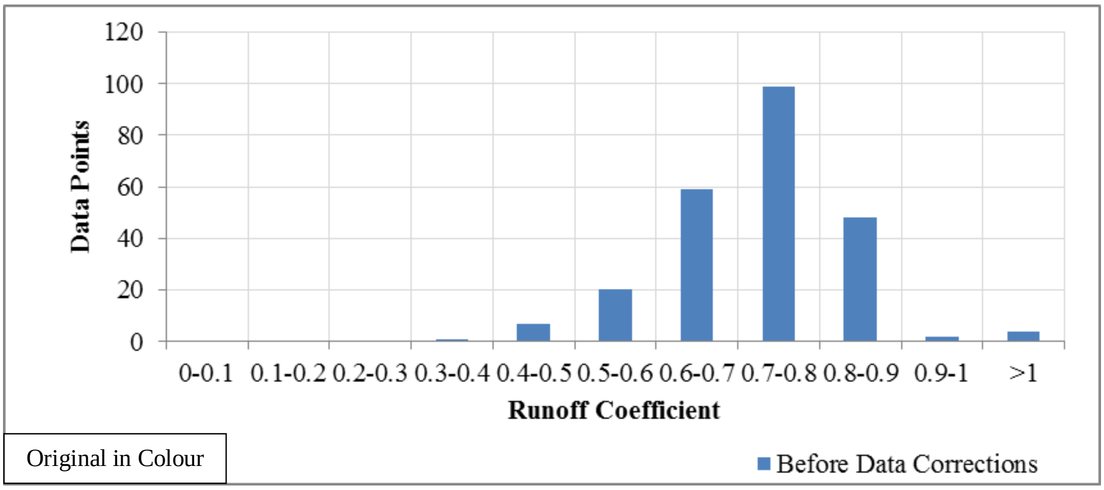


Figure 4-21: Frequency Analysis Before & After Data Corrections (Kelani Ganga)

Table 4-14: Data Points Analysis for Gin Ganga

Before Data Corrections			After Data Corrections			Data Corrected
Runoff Coefficient	Data Points	Category	Runoff Coefficient	Data Points	Category	
0-0.1	0	Likely	0-0.1	0	Likely	0
0.1-0.2	0	Likely	0.1-0.2	0	Likely	0
0.2-0.3	0	Very Likely	0.2-0.3	0	Very Likely	0
0.3-0.4	1	Very Likely	0.3-0.4	1	Very Likely	0
0.4-0.5	7	Very Likely	0.4-0.5	7	Very Likely	0
0.5-0.6	20	Very Likely	0.5-0.6	20	Very Likely	0
0.6-0.7	59	Likely	0.6-0.7	76	Likely	17
0.7-0.8	99	Likely	0.7-0.8	88	Likely	11
0.8-0.9	48	Likely	0.8-0.9	48	Likely	0
0.9-1	2	Unlikely	0.9-1	0	Unlikely	2
>1	4	Unlikely	>1	0	Unlikely	4
Total	240		Total	240		34
Percentage Correction						14.167%



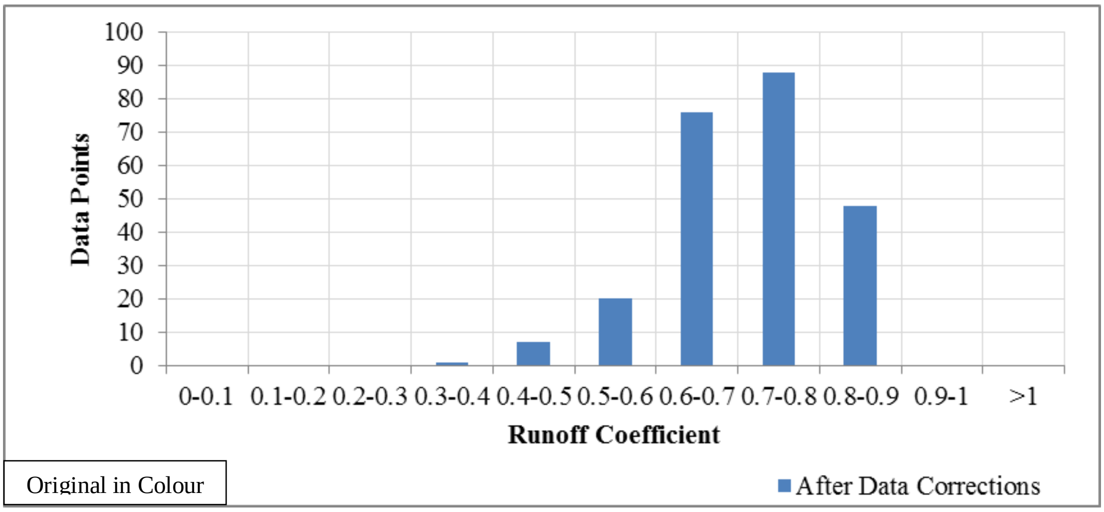


Figure 4-22: Frequency Analysis Before & After Data Corrections (Kelani Ganga)

5 ANALYSIS

5.1 Determination of High, Medium and Low Flows

5.1.1 Kelani Ganga

It was observed that the monthly streamflow fluctuations occurs less than or equal to 30% of time exceedance for High flow and more than or equal to 65% of time exceedance for Low flow. Flow duration curves were plotted for each year as indicated in the Figure 5-1.

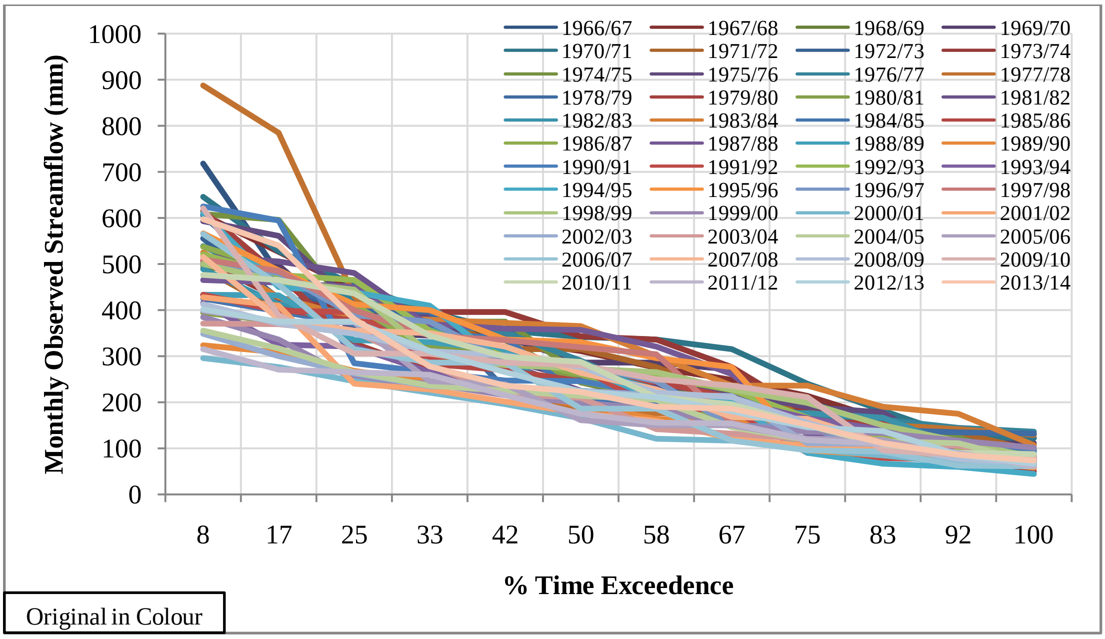


Figure 5-1: Flow duration curves plotted for each year at Kelani Ganga (1966-2014)

5.1.2 Gin Ganga

It was observed that the monthly streamflow fluctuations occurs less than or equal to 35% of time exceedance for High flow and more than or equal to 70% of time exceedance for Low flow. Flow duration curves were plotted for each year as indicated in the Figure 5-2.

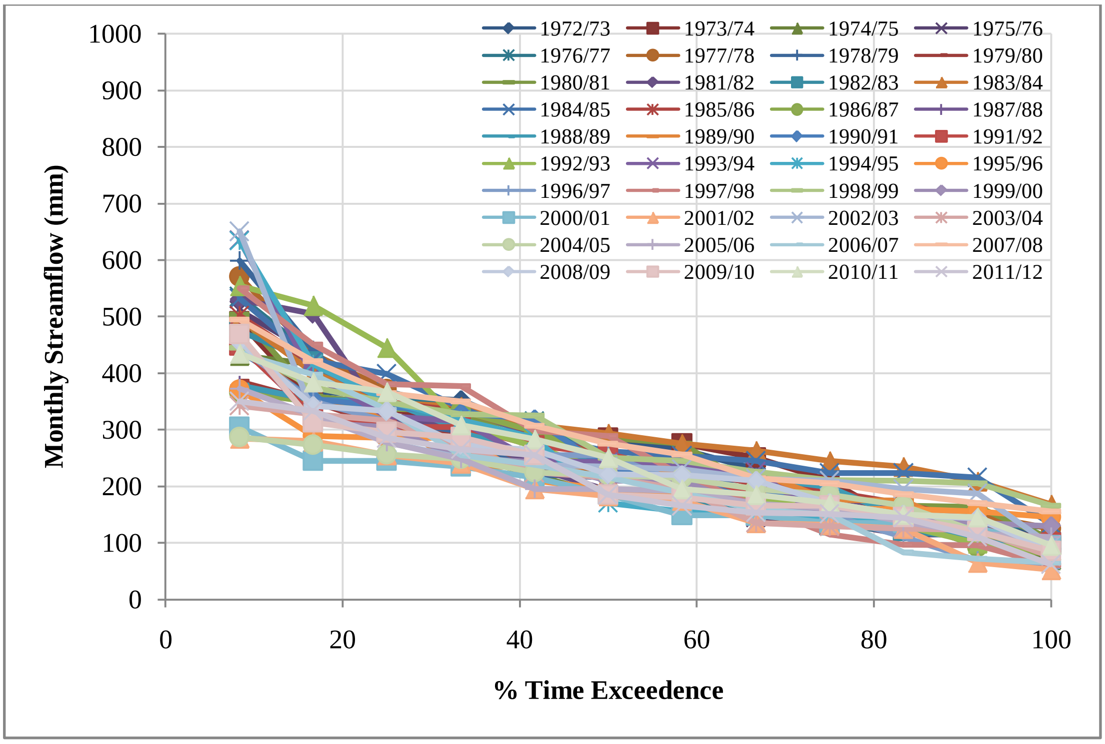


Figure 5-2: Flow duration curves plotted for each year at Gin Ganga (1972-2012)

5.2 Average Flow Duration

5.2.1 Kelani Ganga

Average streamflow duration curves indicated that High flow occurs at almost less than or equal to 30% of time exceedance with four points of datasets and Low flow occurs at almost more than or equal to 65% of time exceedance with four points of datasets. Average flow duration curve for normal plot and logarithmic plot are shown in the Figure 5-3.

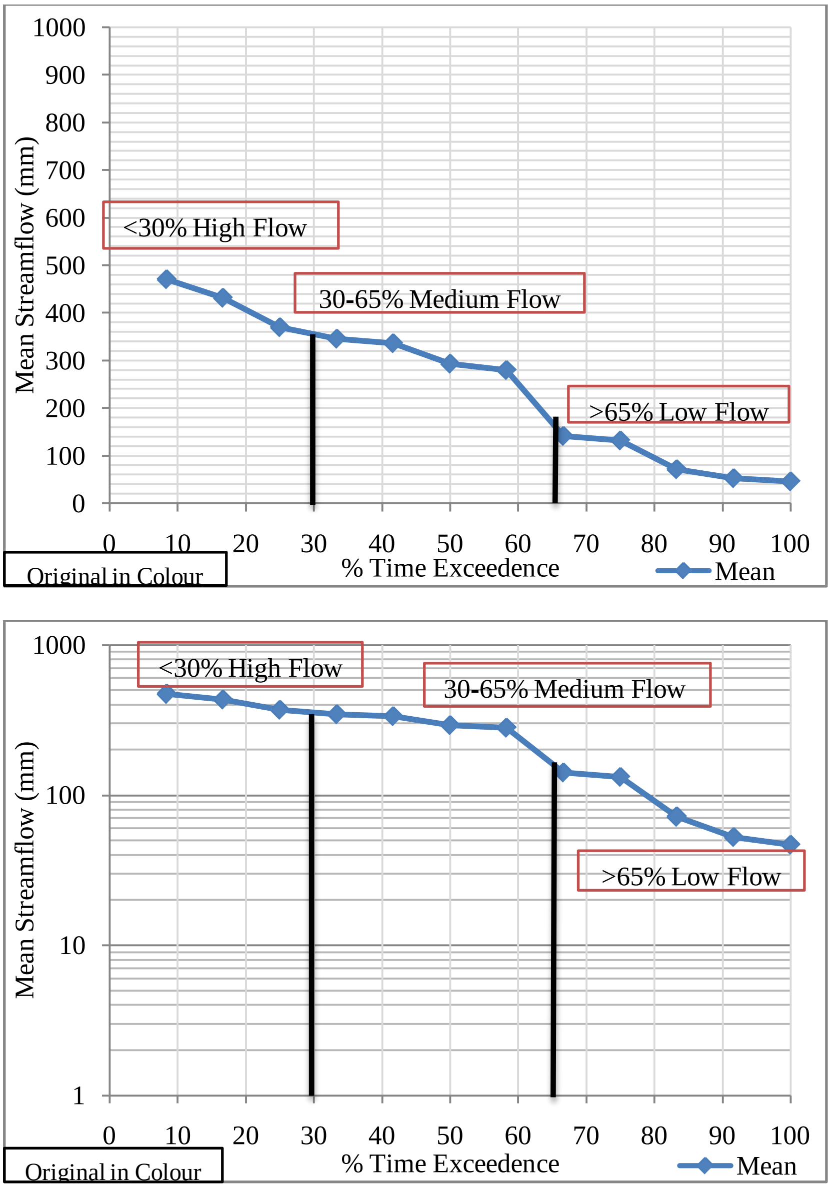


Figure 5-3: Flow Duration Curve of Average Streamflow for Kelani Ganga (Normal and Logarithmic Plot)

5.2.2 Gin Ganga

Average streamflow flow duration indicated that High flow occurs at almost less than or equal to 35% of time exceedance with four monthly points of dataset and Low flow occurs at almost more than or equal to 70% of time exceedance with four monthly points of dataset. Average flow duration curve in normal plot and logarithmic plot are shown in the Figure 5-4.

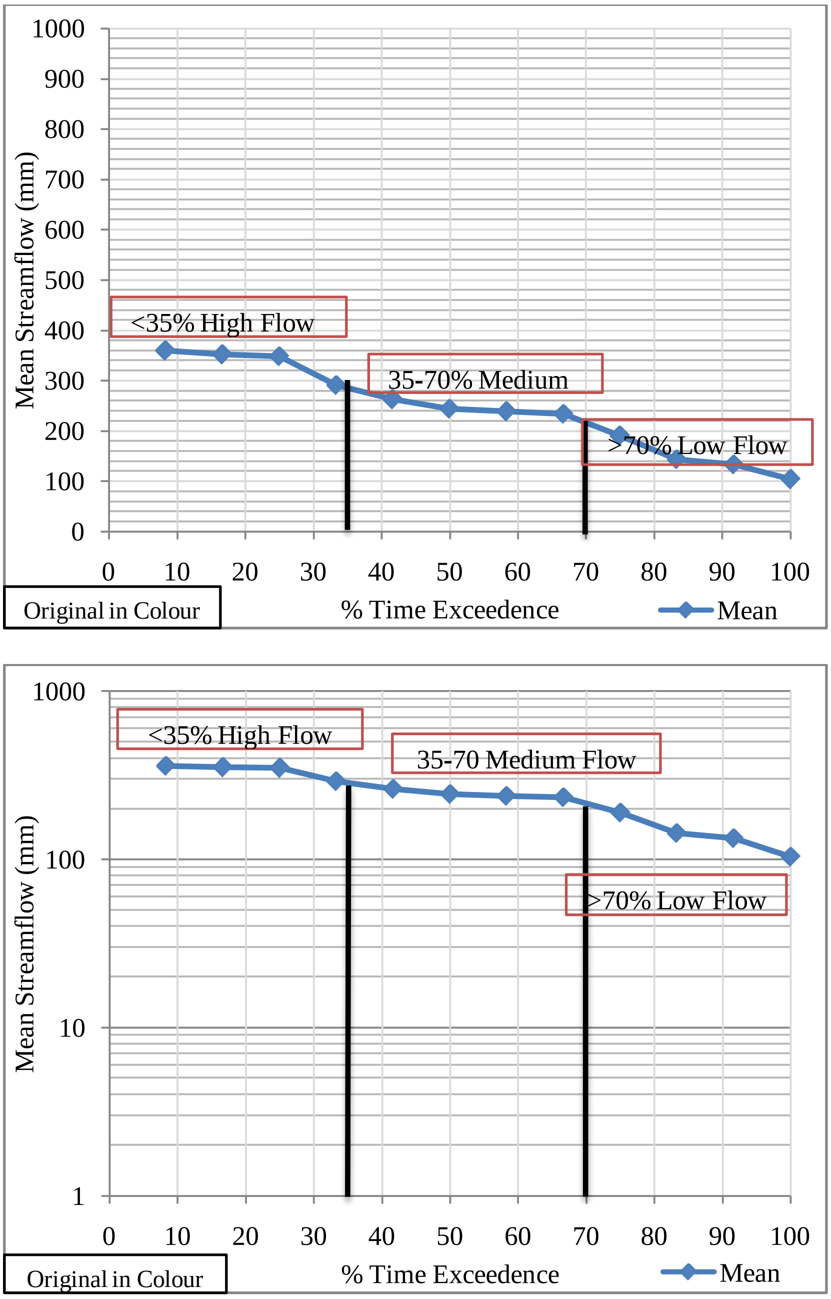
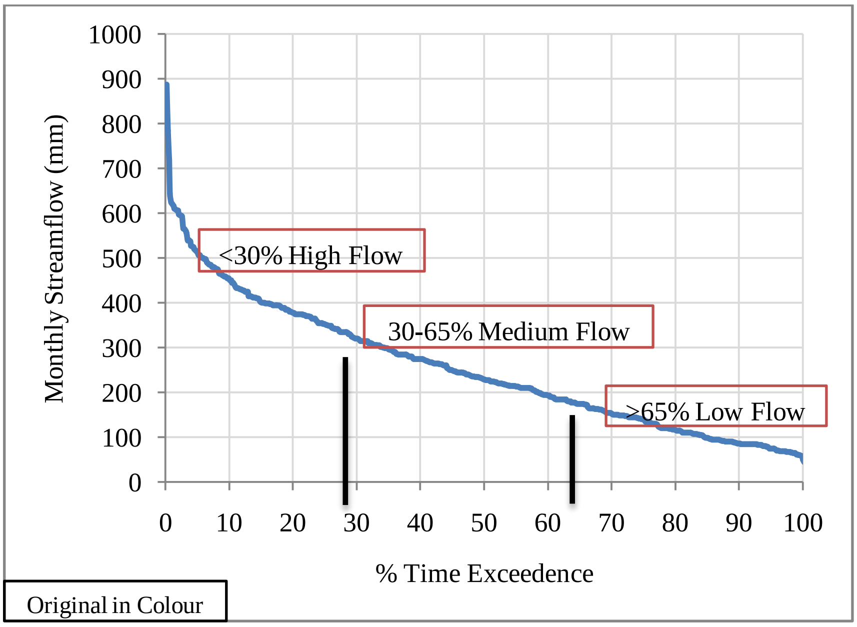


Figure 5-4: Flow Duration Curve of Average Monthly Streamflow for Gin Ganga (Normal and Logarithmic Plot)

5.3 Overall Flow Duration

5.3.1 Kelani Ganga

Overall flow duration indicated that high flow occurs at almost less than or equal to 30% time exceedance and low flow occurs at almost greater than or equal to 65% time exceedance. The normal plot and logarithmic plots are shown in Figure 5-5.



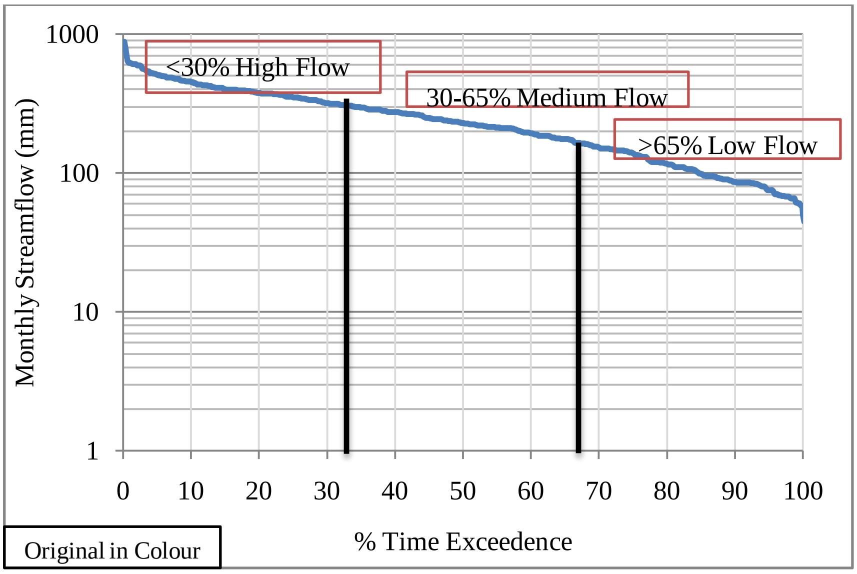
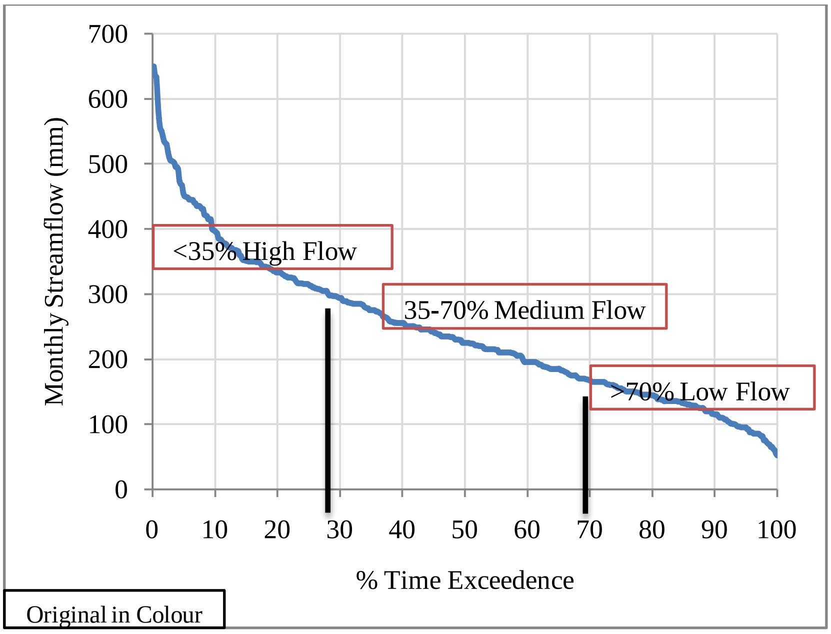


Figure 5-5: Flow Duration Curve of Overall Monthly Streamflow for Kelani Ganga (Normal and Logarithmic Plot)

5.3.2 Gin Ganga

Overall flow duration curve indicated that high flow occurs at almost less than or equal to 35% time exceedance and low flow occurs at almost greater than or equal to 70% time exceedance. The normal plot and logarithmic plots are shown in Figure 5-6.



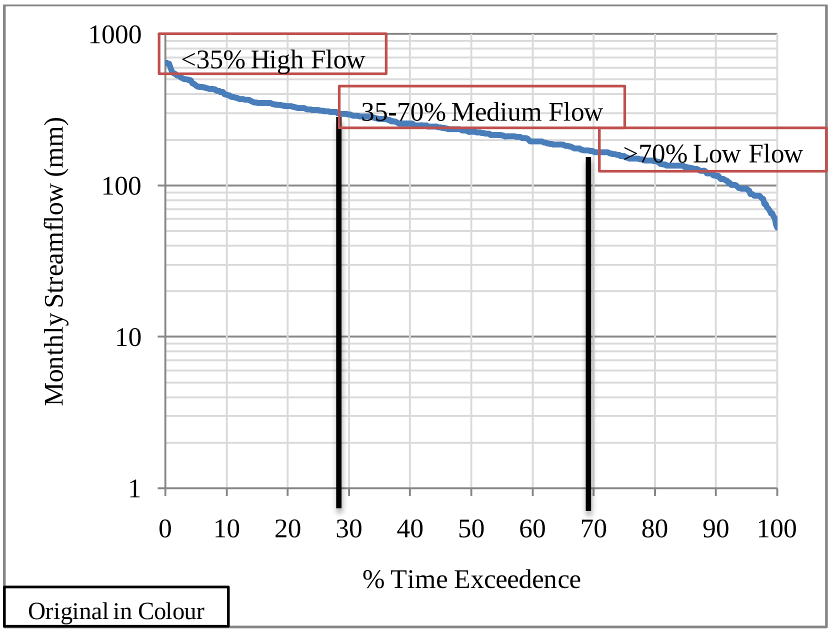


Figure 5-6: Flow Duration Curve of Overall Monthly Streamflow for Gin Ganga (Normal Logarithmic Plot)

5.4 Behavior of Hyperbolic Tangent Function

The inter relationship between the actual evaporation E(t), pan evaporation EP(t) and rainfall P(t) is given by;

$$E(t)/ EP(t) = \tanh [P(t)/ EP(t)] \quad (14)$$

Equation 14 shows an inter-relationship between E(t) and EP(t) and P(t), i.e. the larger the ratio of P(t) to EP(t), the closer the E(t) approaches to EP(t). The Figure 5-7 shows the inter-relationship between E(t) and EP(t) and P(t) and indicating that the function of tanh(x) is contracting reflection of the independent variable x.

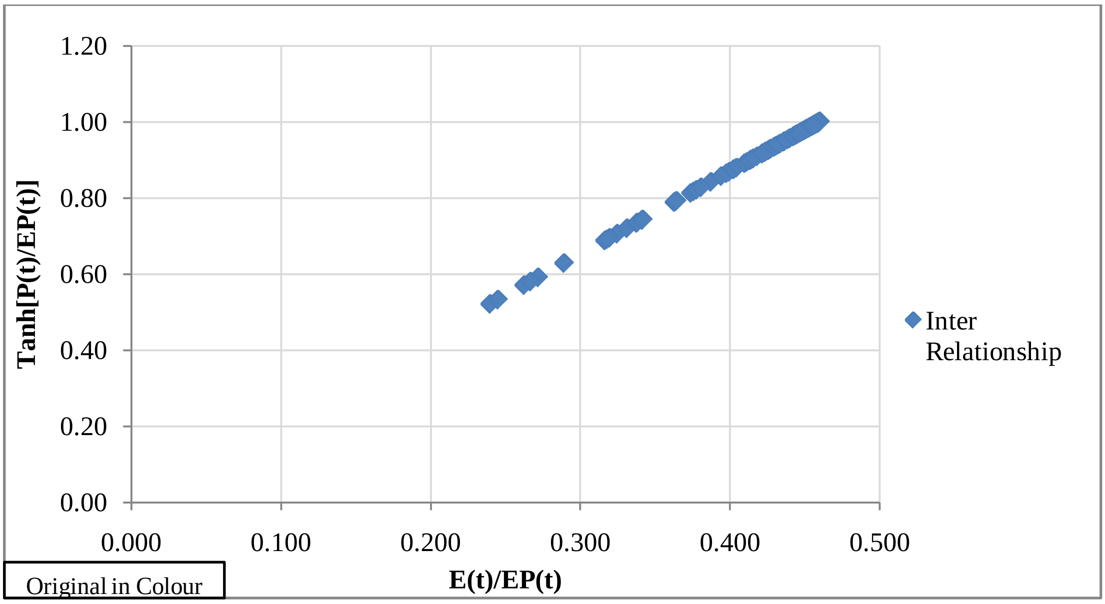


Figure 5-7: Inter-Relationship of Evaporation and Rainfall

5.5 Relationship between E(t) and EP(t)

Relationship between the actual Evaporation E(t) and Pan Evaporation EP(t) for various parameter c ranging from 0.1 to 1.0 for Kelani Ganga and Gin Ganga is indicated in Figure 5-8 and Figure 5-9. It was observed that the E(t) & EP(t) is directly proportional to the parameter c value. Therefore, with increase in parameter c the E(t) and EP(t) is showing the increasing trend.

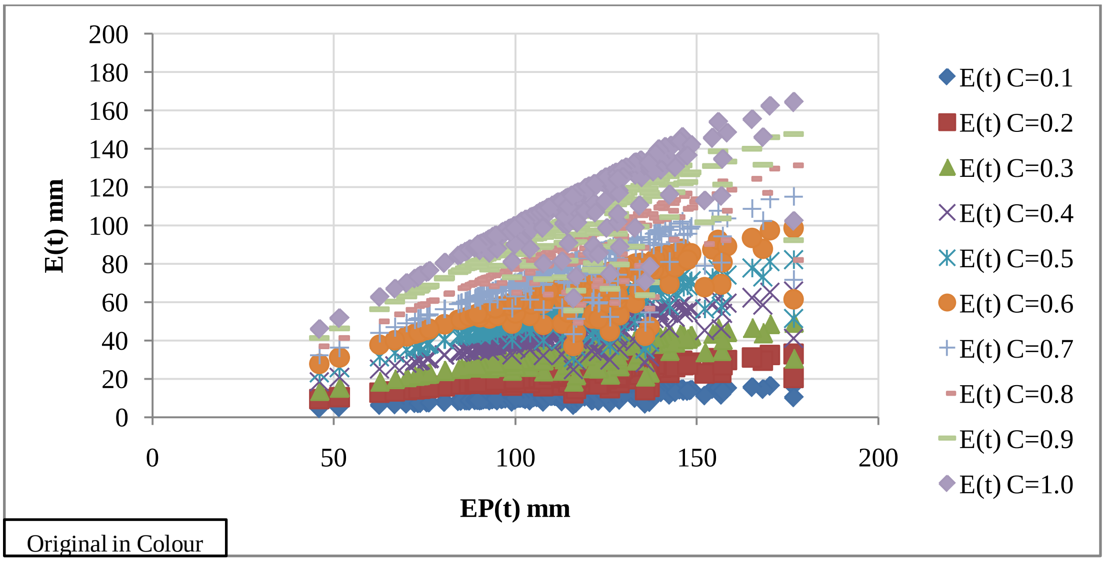


Figure 5-8: E(t) and EP(t) Relationship for parameter c at Kelani Ganga

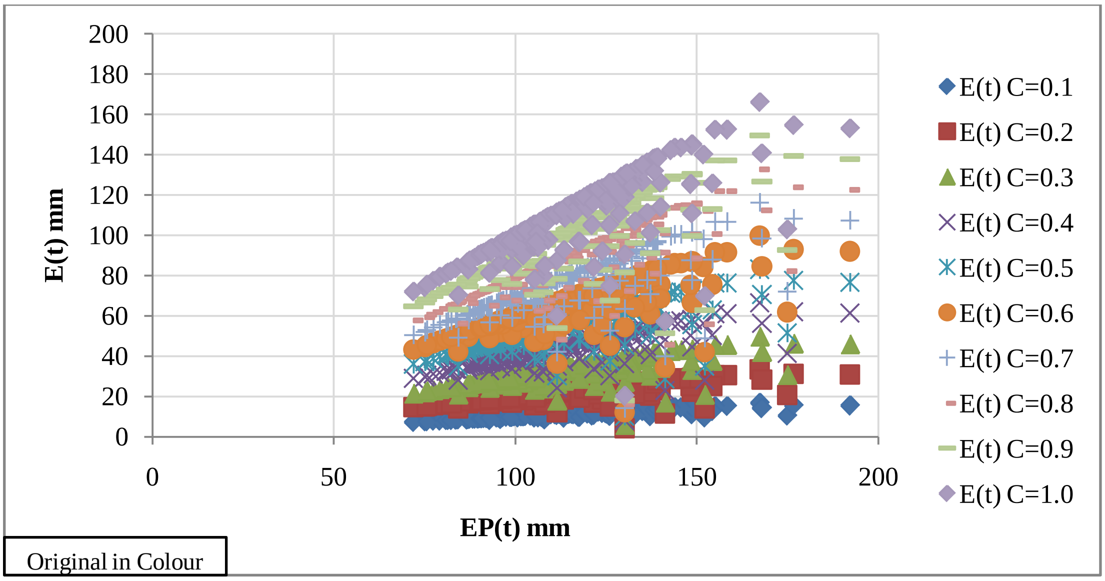


Figure 5-9: E(t) and EP(t) Relationship parameter c at Gin Ganga

5.6 Comparison of Actual Evaporation and Pan Evaporation

Evaporation of water is a major consideration in water budget analysis and important in determining the water balance of watersheds, and in predicting and estimating runoff. Actual evaporation and pan evaporation comparison is indicated in the Figure 5-10 and Figure 5-11 for Kelani Ganga and Gin Ganga respectively. The pan evaporation is more than actual evaporation. But it is not possible for the E(t) become more than EP(t) because the ratio of P(t) to EP(t) is always large.

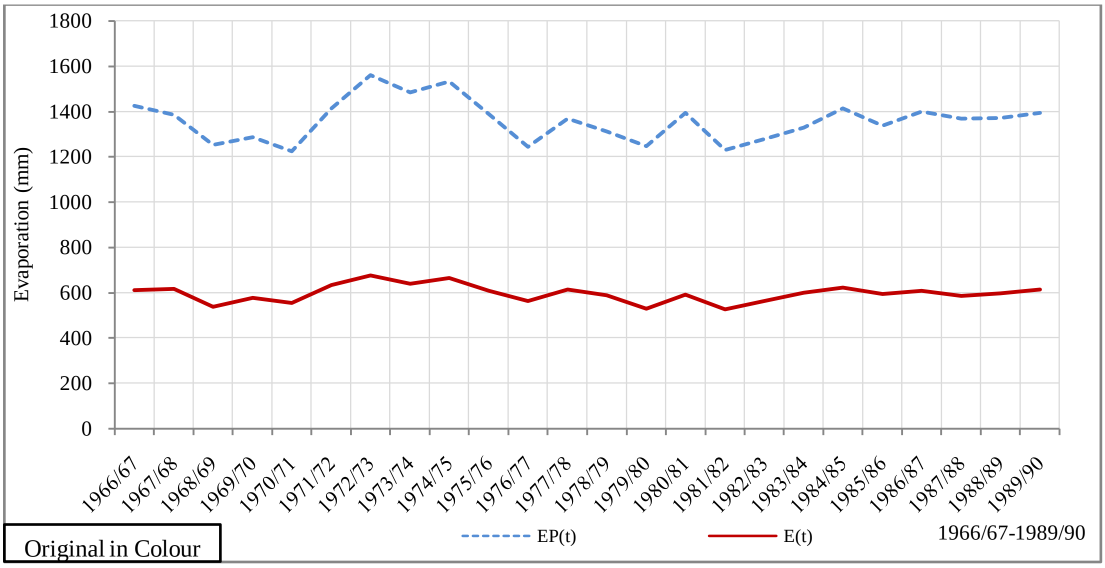


Figure 5-10: Actual Evaporation and Pan Evaporation Comparison at Kelani Ganga

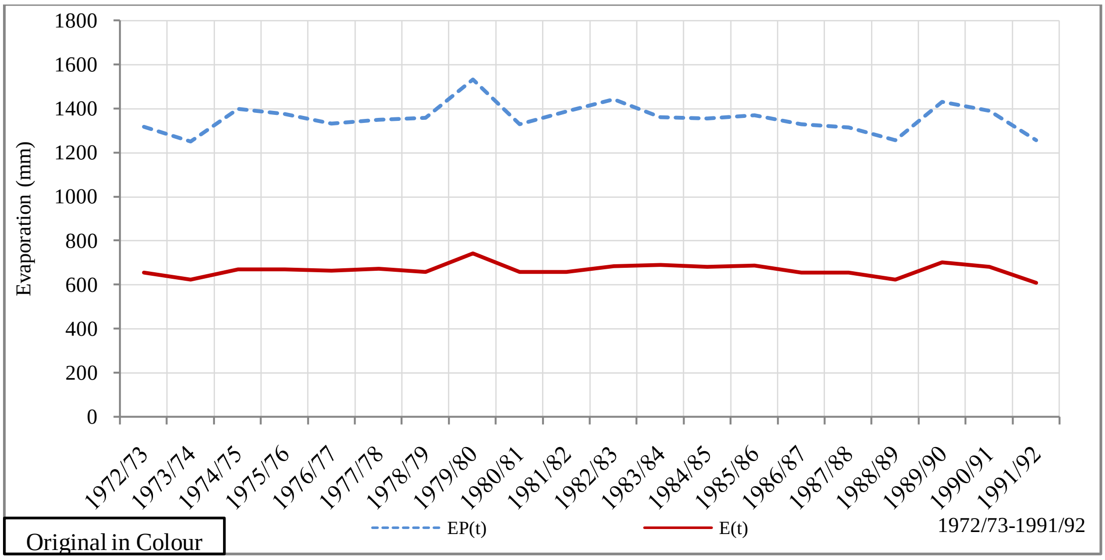


Figure 5-11: Actual Evaporation and Pan Evaporation Comparison at Gin Ganga

5.7 Model Calibration

5.7.1 Initial Soil Moisture Content, c and SC

The model requires an initial soil moisture content and the accuracy of the initial value of the soil moisture content S(0) has some effect on the model performance during the calibration. Literature recommended the use of a warming up period to determine the initial soil moisture content. A cyclic period or a warming up period would be necessary before the calibration period so that the model results would not be influenced by the approximated initial soil moisture content. The length of warming up period should stabilize the storage and minimize the effect of soil moisture content on the model performance. Literature suggests that 3 to 5 years may required as the warming up period in humid catchments.

In Kelani Ganga, the value of initial soil moisture content S(0) obtained was 138 mm after running model for five hydrologic-cycles. The initial parameter c and SC was taken as 0.50 and 989.78 mm respectively.

Similarly, for Gin Ganga the value of initial soil moisture content S(0) obtained was 280 mm after running model for five hydrologic-cycles. The initial parameter c and SC was taken as 0.50 and 1292.27 mm respectively.

5.7.2 Objective function

The primary objective function used was MRAE and the secondary objective function used was Nash-Sutcliffe efficiency. The parameters c and SC were optimized for calibration period by using objective function MRAE while observing the behavior of Nash-Sutcliffe efficiency indicator.

5.7.3 Optimization Methods

Method used for parameter estimation and calibration includes both manual and automatic optimization. Goal Seek technique was used for model parameter optimization. Initially the manual optimization was carried out because the goal seek search technique cannot optimize two parameters at a time. Once the optimum value for parameters found in the manual optimization the results were checked using the automatic optimization method.

5.7.4 Methods/Parameter trial ranges

Parameter trial ranges used to find the minimum are c values varied from 0.10 to 1.00 and SC values varied from 200 to 3500 which are acceptable as recommended in the literature. In order to determine the global minimum, the MRAE at each trial in the parameter ranges was tabulated in a matrix format and then 3-D surface graph was plotted for MRAE corresponding to the parameters c and SC. Global minimum is identified by varying the parameter values over the error surface.

5.7.5 MRAE behavior during calibration period

5.7.5.1 Kelani Ganga

MRAE behavior during calibration period was observed. From Figure 5-12 and Figure 5-13 it was observed that MRAE value decreased from 0.309 to 0.086 at which the optimum parameter c and SC values were obtained.

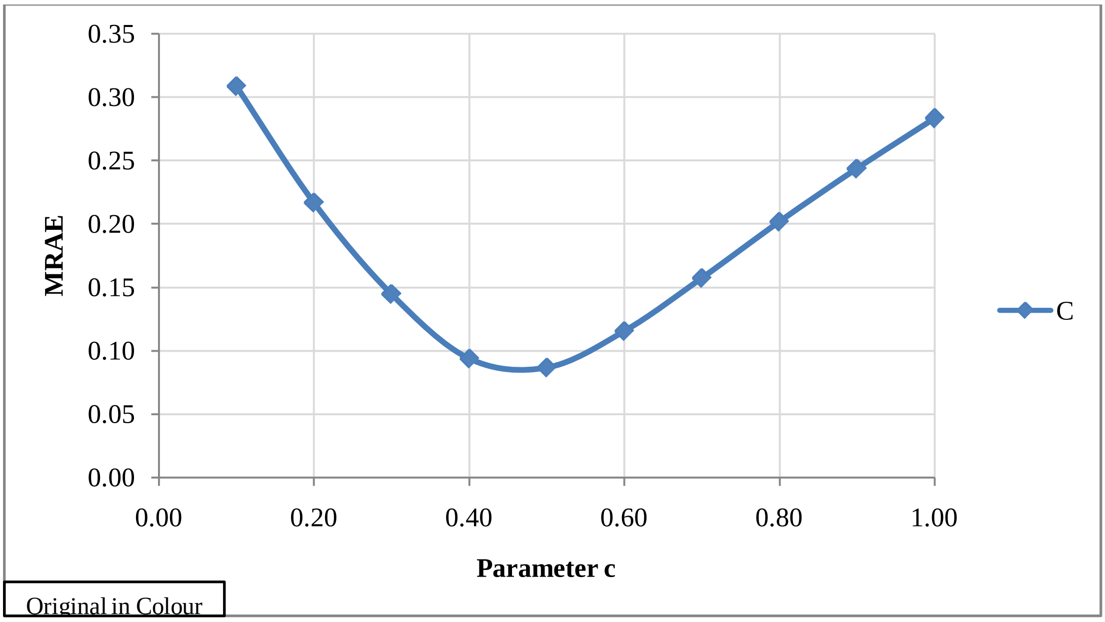


Figure 5-12: MRAE and Parameter c at Kelani Ganga

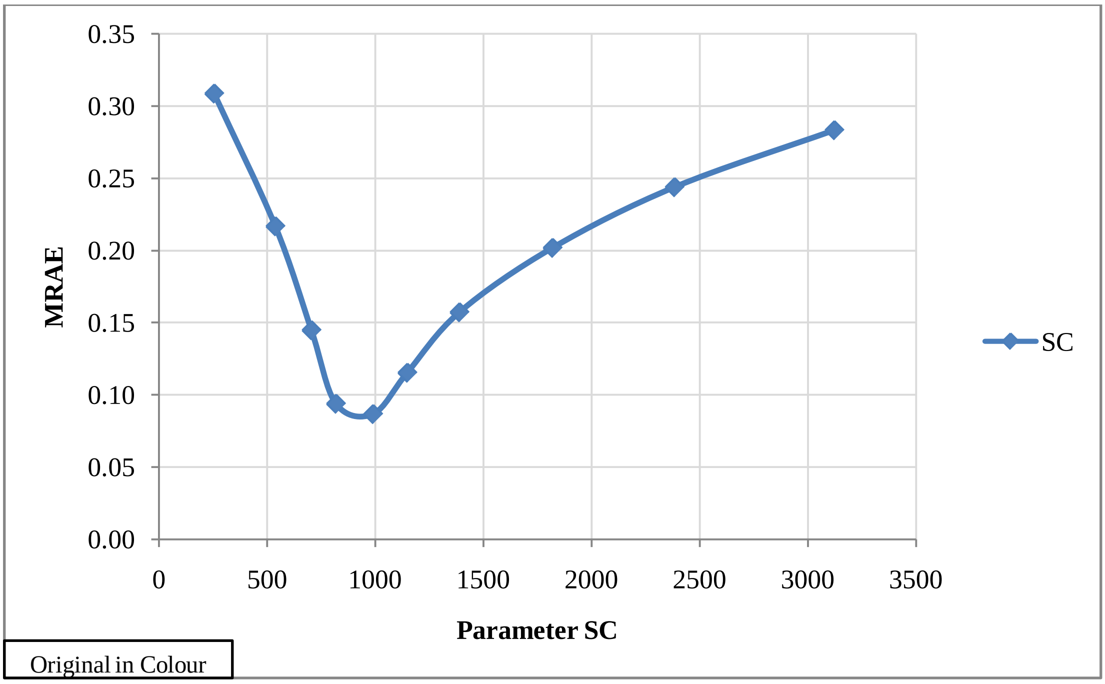


Figure 5-13: MRAE and Parameter SC at Kelani Ganga

5.7.5.2 Gin Ganga

MRAE behavior during calibration period was observed. From Figure 5-14and Figure 5-15 it was observed that MRAE value decreased from 0.332 to 0.097 at which the optimum parameter c and SC values were obtained.

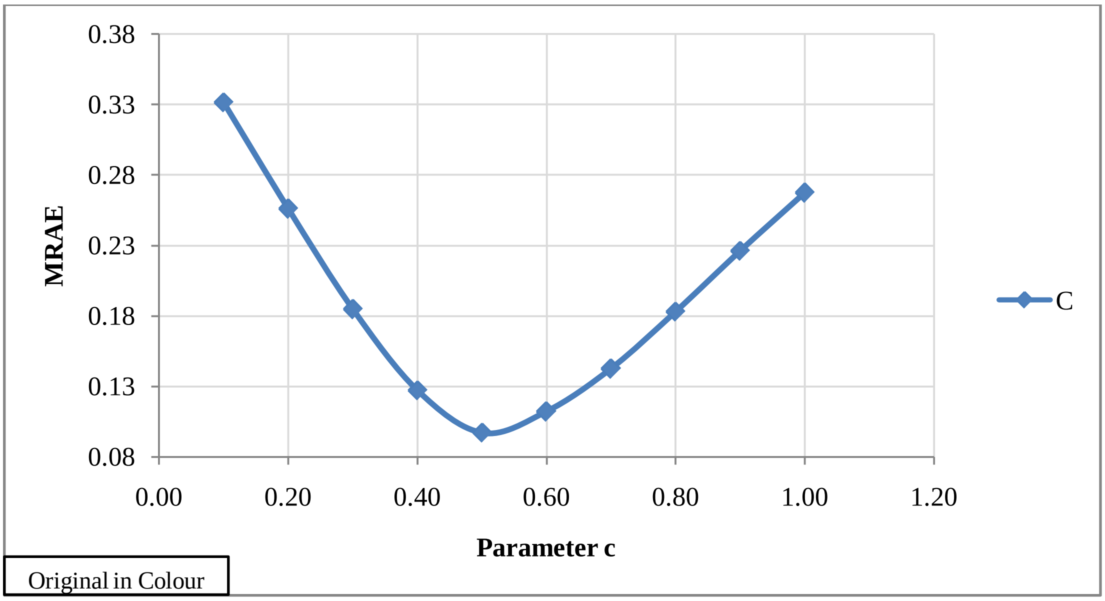


Figure 5-14: MRAE and Parameter c at Gin Ganga

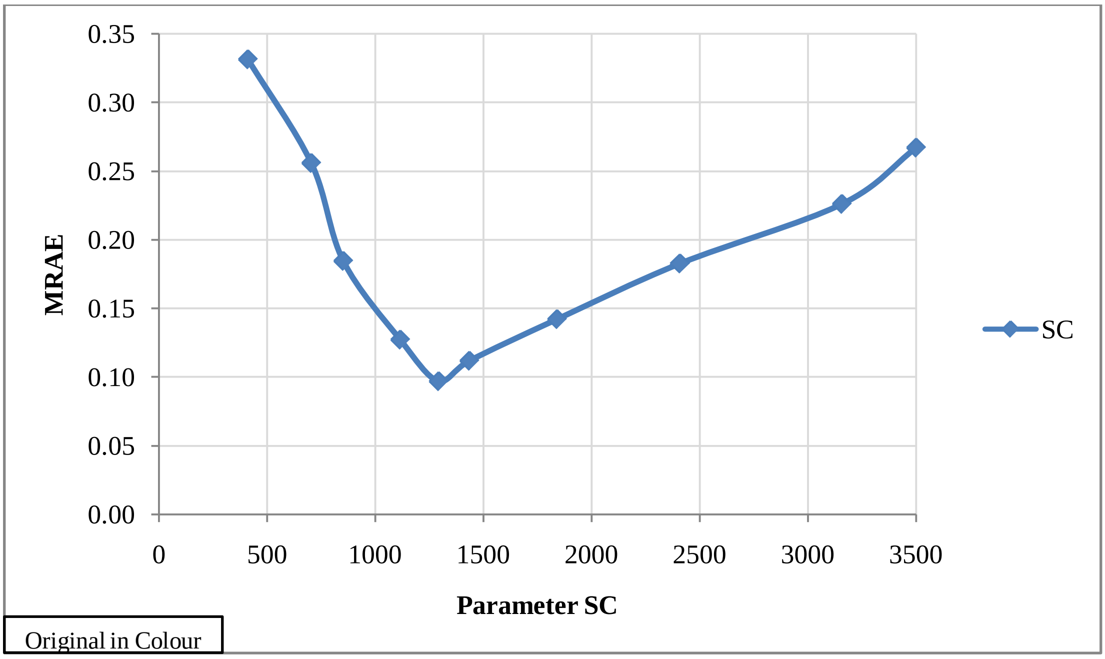


Figure 5-15: MRAE and Parameter SC at Gin Ganga

MRAE comparison for monthly, annual and seasonal is indicated in the Appendix C & D for Kelani Ganga and Gin Ganga respectively.

Minimum MRAE value for Annual Water Balance of Kelani Ganga and Gin Ganga is 0.027 (Figure C-5) and 0.0254 (Figure D-5) respectively. Minimum MRAE for Seasonal matching of estimated and observed flow for Kelani Ganga and Gin Ganga is 0.036 (Figure C-5) and 0.041 (Figure D-5) respectively. Minimum MRAE for Monthly matching of estimated and observed flow for Kelani Ganga and Gin Ganga is 0.088 (Figure C-5) and 0.084 (Figure D-5) respectively.

5.7.6 Nash-Sutcliffe efficiency behavior during calibration period

5.7.6.1 Kelani Ganga

Nash-Sutcliffe Efficiency behavior during calibration period was observed. From Figure 5-16 and Figure 5-17 it was observed that Nash-Sutcliffe Efficiency value increases from 0.671 to 0.972 at which the optimum parameter c and SC value was obtained.

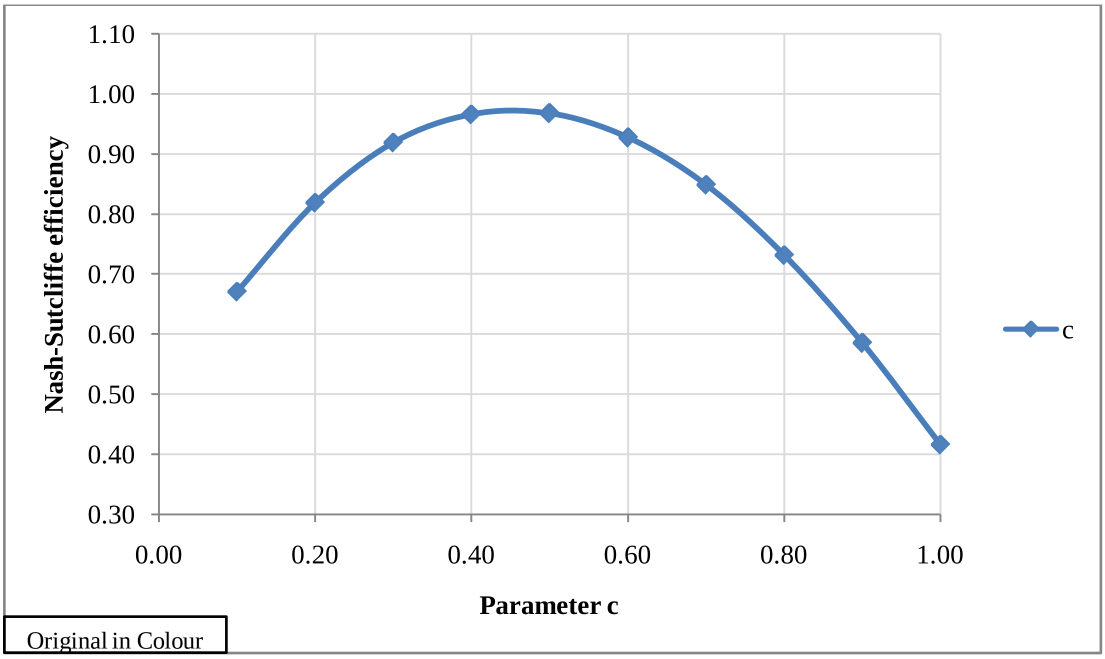


Figure 5-16: Nash-Sutcliffe efficiency and Parameter c at Kelani Ganga

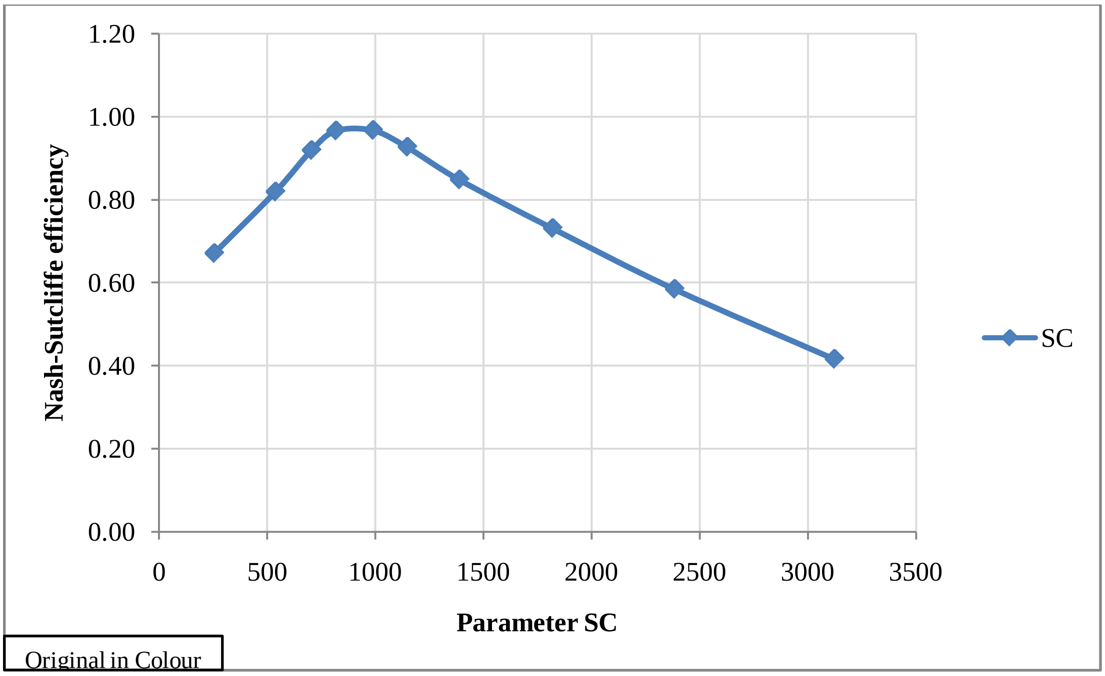


Figure 5-17: Nash-Sutcliffe efficiency and Parameter SC at Kelani Ganga

5.7.6.2 Gin Ganga

Nash-Sutcliffe Efficiency behavior during calibration period was observed. From Figure 5-18 and Figure 5-19 it was observed that Nash-Sutcliffe Efficiency value increases from 0.112 to 0.925 at which the optimum parameter c and SC value was obtained.

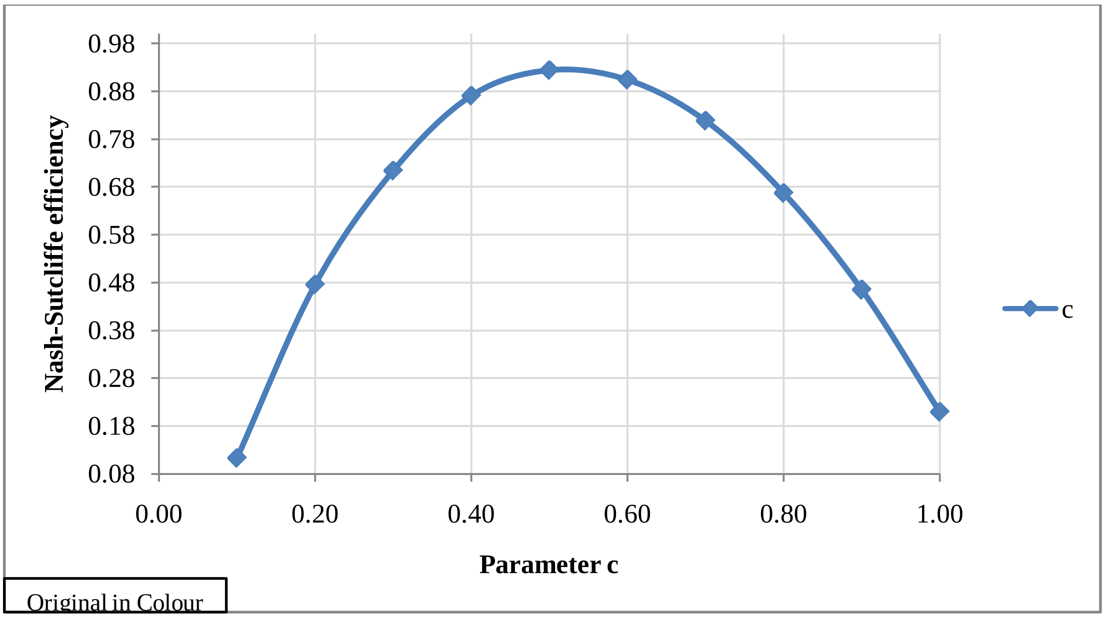


Figure 5-18: Nash-Sutcliffe efficiency and Parameter c at Gin Ganga

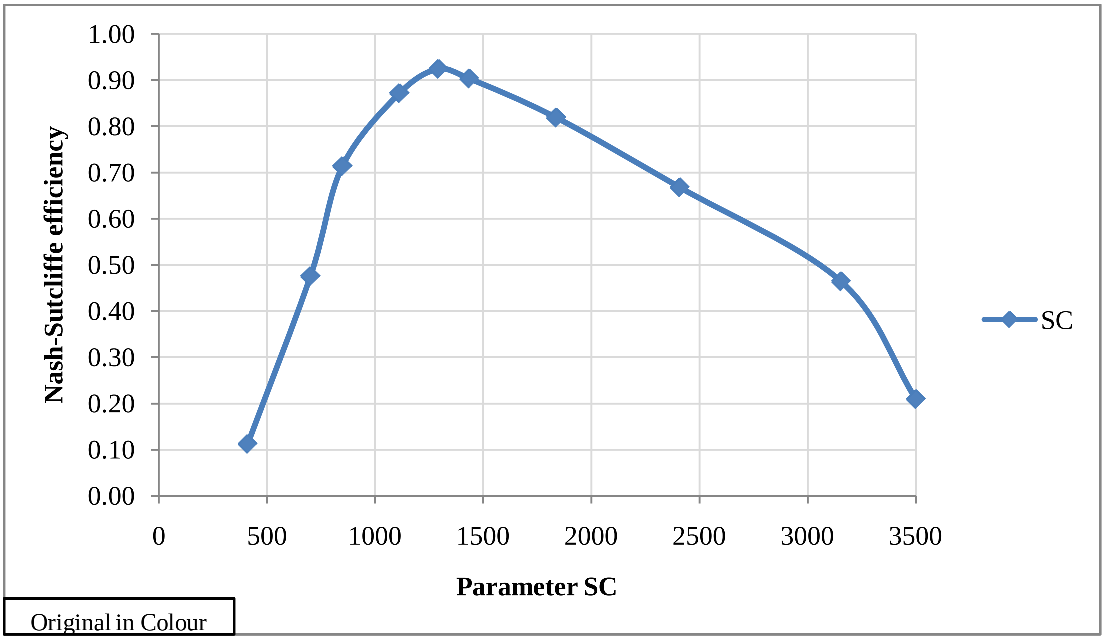


Figure 5-19: Nash-Sutcliffe efficiency and Parameter SC at Gin Ganga

5.7.7 Estimated Streamflow

5.7.7.1 Annual

Annual matching of estimated and observed streamflow indicated the good matching as shown in the Figure 5-20and Figure 5-21 for Kelani Ganga and Gin Ganga respectively. Annual streamflow varies from 2200-4000 mm/year in Kelani Ganga and 2600-3600 mm/year in Gin Ganga.

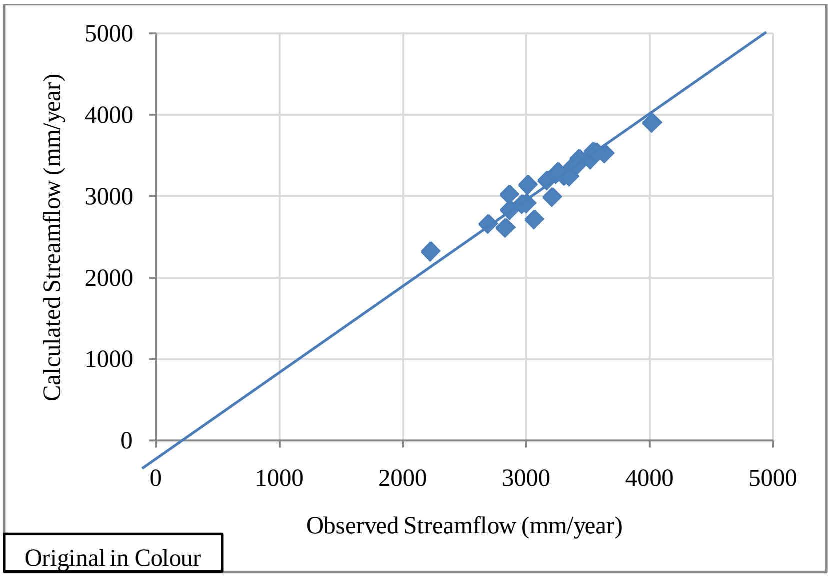


Figure 5-20: Annual Water Balance at Kelani Ganga (1966-1990)

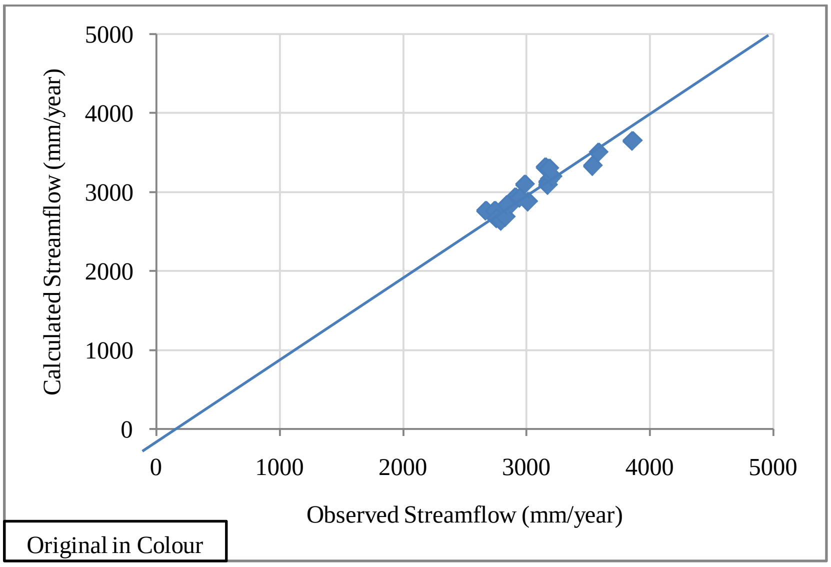


Figure 5-21: Annual Water Balance for Gin Ganga (1972-1992)

5.7.7.2 Seasonal

Seasonal matching of estimated and observed streamflow is mainly for the model checking to observe the seasonal variations. In Kelani Ganga, streamflow comparison for Maha Season and Yala Season indicated the good matching as shown in the Figure 5-22and Figure 5-23 respectively. Seasonal streamflow varies from 900-1600 mm during Maha season and 1300-2300 mm during Yala season.

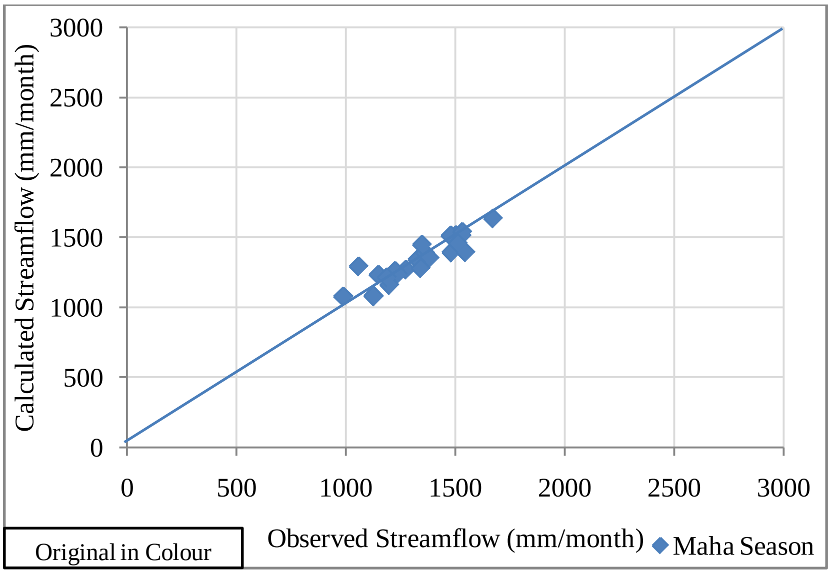


Figure 5-22: Maha Season Streamflow at Kelani Ganga (1966-1990)

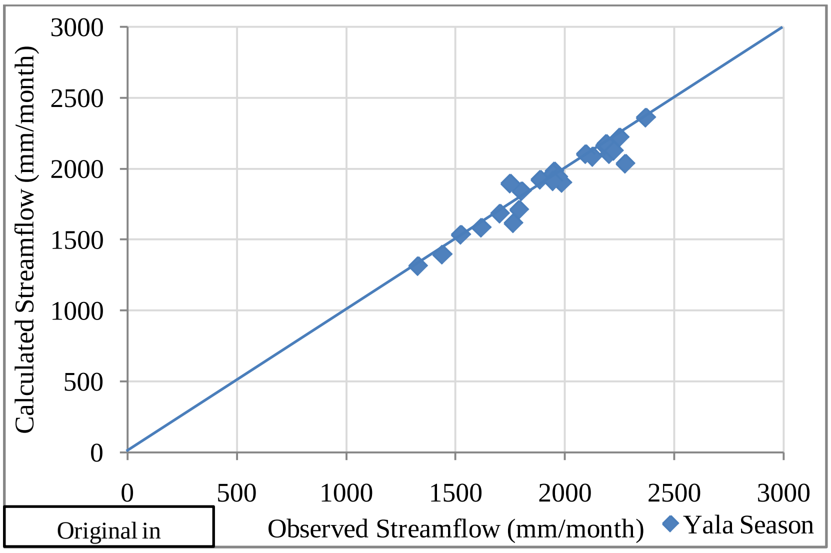


Figure 5-23: Yala Season Streamflow at Kelani Ganga (1966-1990)

Similarly, in Gin Ganga the streamflow comparison for Maha Season and Yala Season indicated the good matching as shown in the Figure 5-24 and Figure 5-25 respectively. Seasonal streamflow varies from 900-1500 mm during Maha season and 1300-2200 mm during Yala season.

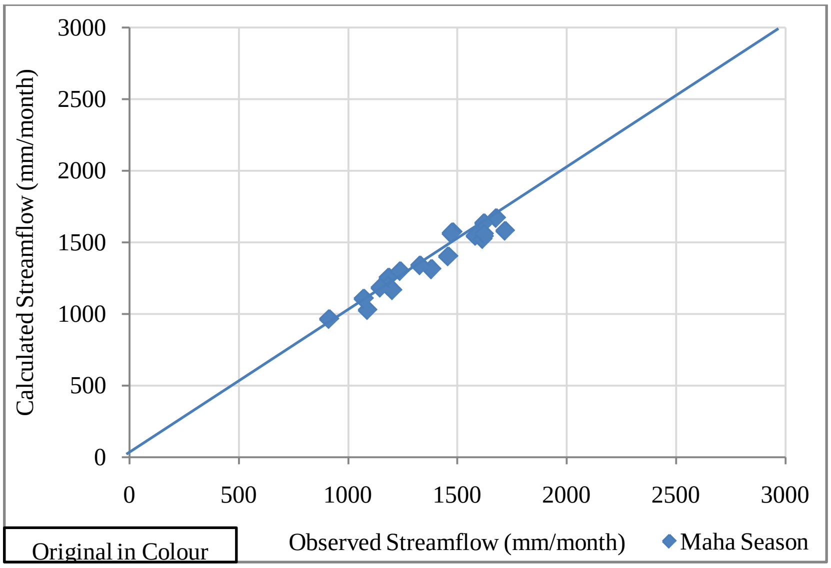


Figure 5-24: Maha Season Streamflow at Gin Ganga (1972-1992)

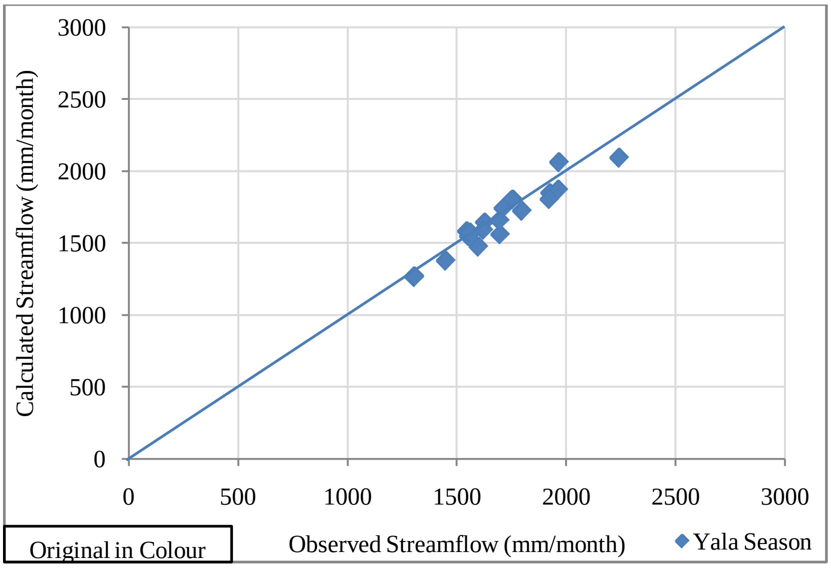


Figure 5-25: Yala Season Streamflow at Gin Ganga (1972-1992)

5.7.7.3 Monthly

The Monthly matching of estimate and observed streamflow is essential especially for regions with strong variation of flow in a year. This test reveals mainly the general performance of the model over flow regimes. Monthly streamflow comparison of Kelani Ganga and Gin Ganga is indicated in Figure 5-26 and Figure 5-27. The comparison indicated good matching with monthly value varying from 50-900 mm in Kelani Ganga and 70-600 mm in Gin Ganga.

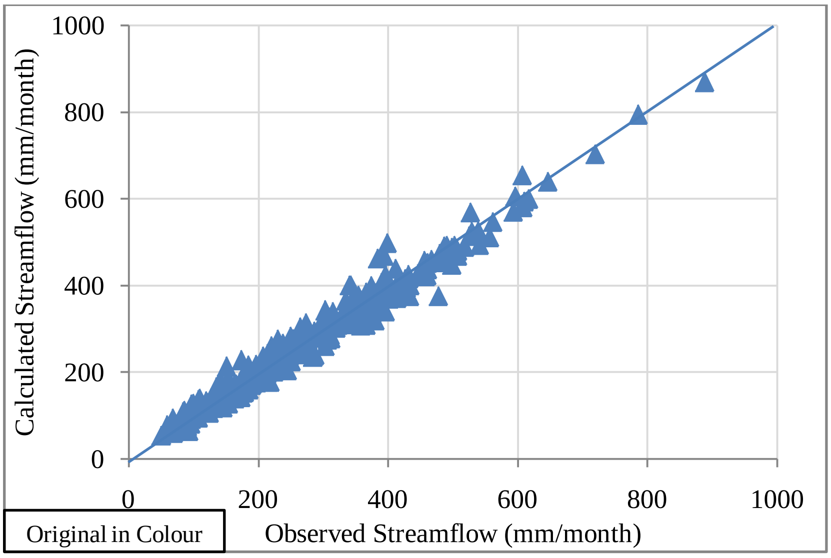


Figure 5-26: Monthly Streamflow at Kelani Ganga (1966-1990)

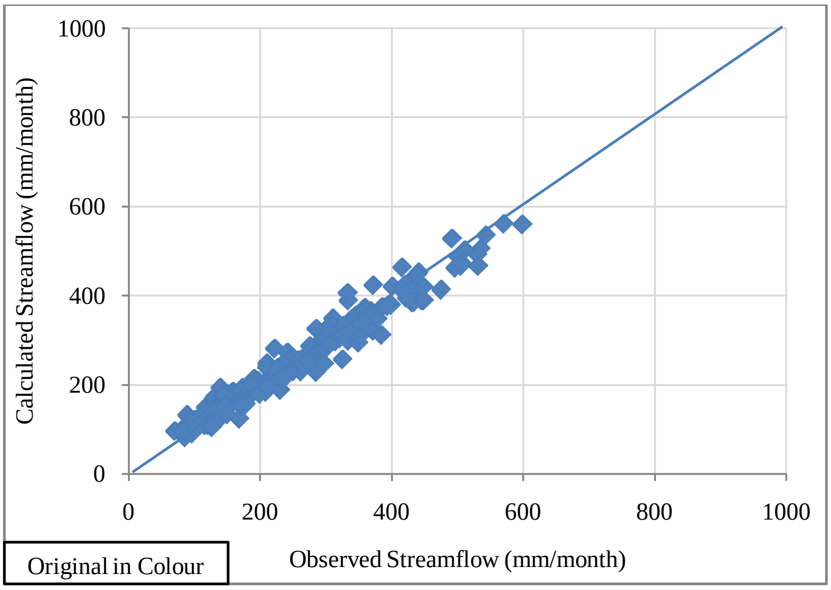


Figure 5-27: Monthly Streamflow at Gin Ganga (1972-1992)

5.7.8 Flow duration curves

Flow duration curve for observed and estimated streamflow of Kelani Ganga is presented in the Figure 6-2 & Figure 6-3 and Gin Ganga in Figure 6-10 & Figure 6-11. Flow duration was analyzed by determining the High, Medium and Low Flow and MRAE was calculated separately for each flow region and total flow.

In Kelani Ganga, MRAE for High, Medium, Low and Total Flow are 0.056, 0.070, 0.107 and 0.084 respectively.

Similarly, in Gin Ganga, MRAE for High, Medium, Low and Total Flow are 0.064, 0.059, 0.130and 0.081 respectively.

5.7.9 Estimated Evaporation (Actual)

5.7.9.1 Kelani Ganga

5.7.9.1.1 Annual Volume

From the Figure 5-28 it was observed that the annual volume varies from minimum of 528 mm/year to maximum of 675 mm/year with an average value of 597 mm/year.

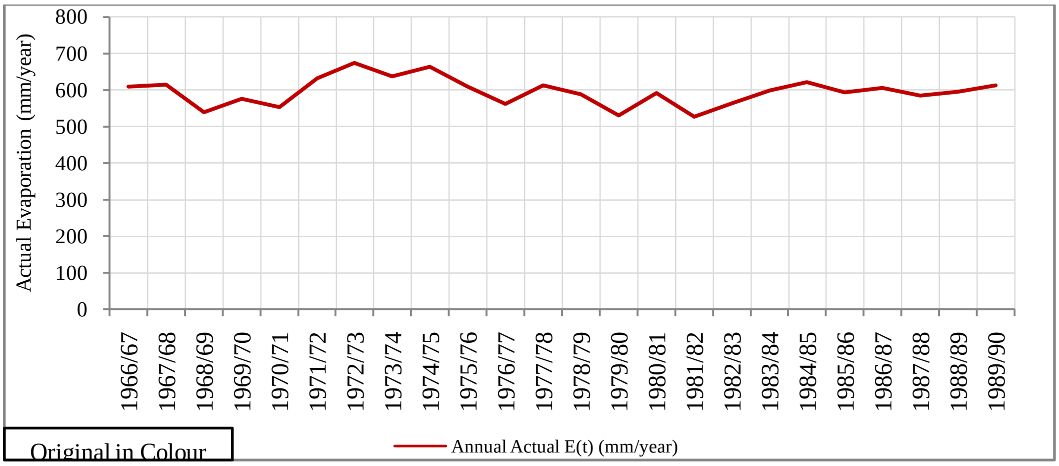


Figure 5-28: Annual Actual E(t) at Kelani Ganga (1966-1990)

5.7.9.1.2 Seasonal Volume

From the Figure 5-29 it was observed that during Maha season the volume varies from minimum of 222 mm/year to maximum of 346 mm/year with an average value of 287 mm/year and during Yala season the volume varies from minimum of 271 mm/year to maximum of 340 mm/year with an average value of 310 mm/year

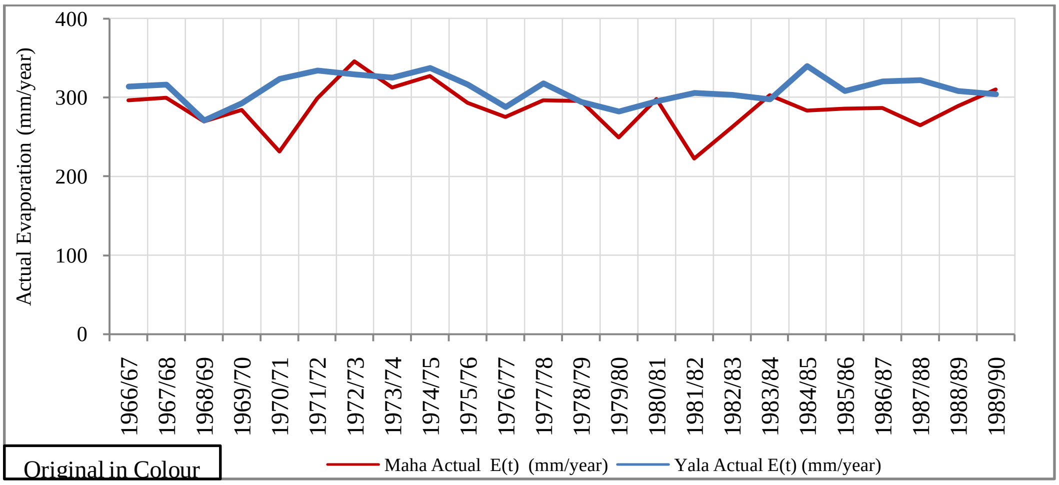


Figure 5-29: Seasonal Actual E(t) at Kelani Ganga (1966-1990)

5.7.9.1.3 Monthly Volume

From the Figure 5-30 it was observed that the monthly volume varies from minimum of 21 mm/month to maximum of 76 mm/month with an average value of 50 mm/month.

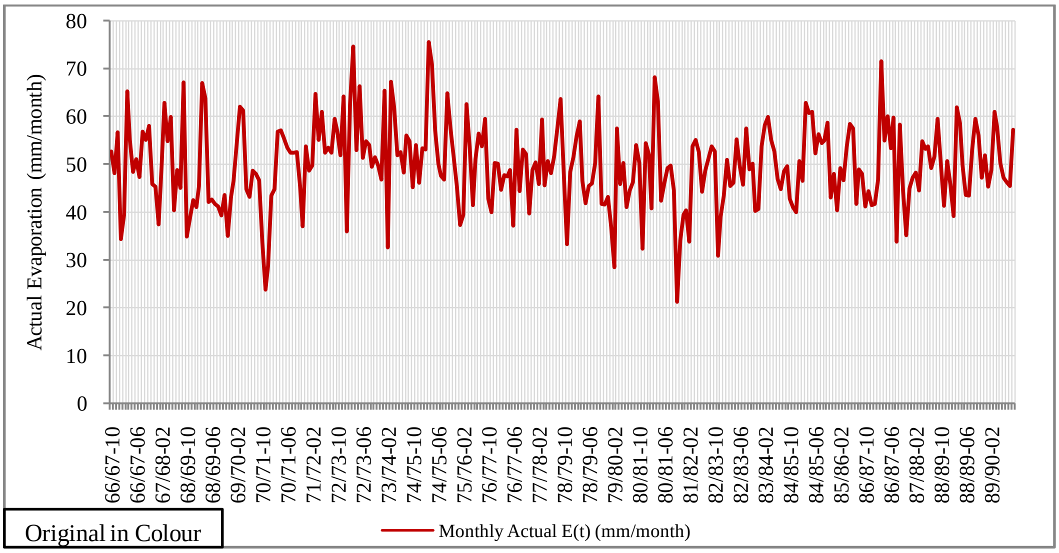


Figure 5-30: Monthly Actual E(t) at Kelani Ganga (1966-1990)

5.7.9.2 Gin Ganga

5.7.9.2.1 Annual Volume

From the Figure 5-31 it was observed that the annual volume varies from minimum of 609 mm/year to maximum of 742 mm/year with an average value of 667 mm/year.

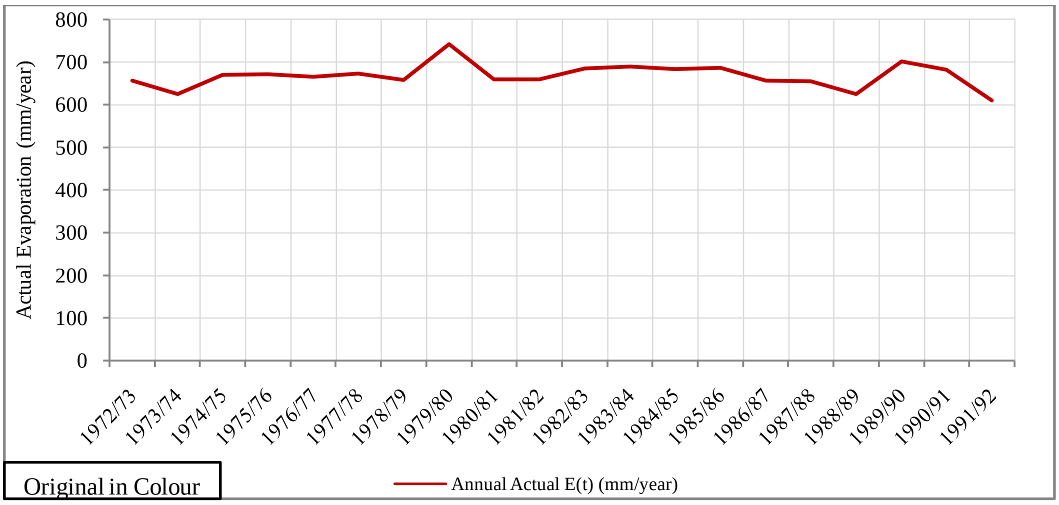


Figure 5-31: Annual Actual E(t) at Gin Ganga (1972-1992)

5.7.9.2.2 Seasonal Volume

From the Figure 5-32 it was observed that during Maha season the volume varies from minimum of 284 mm/year to maximum of 397 mm/year with an average value of 335 mm/year and during Yala season the volume varies from minimum of 300 mm/year to maximum of 362 mm/year with an average value of 332 mm/year.

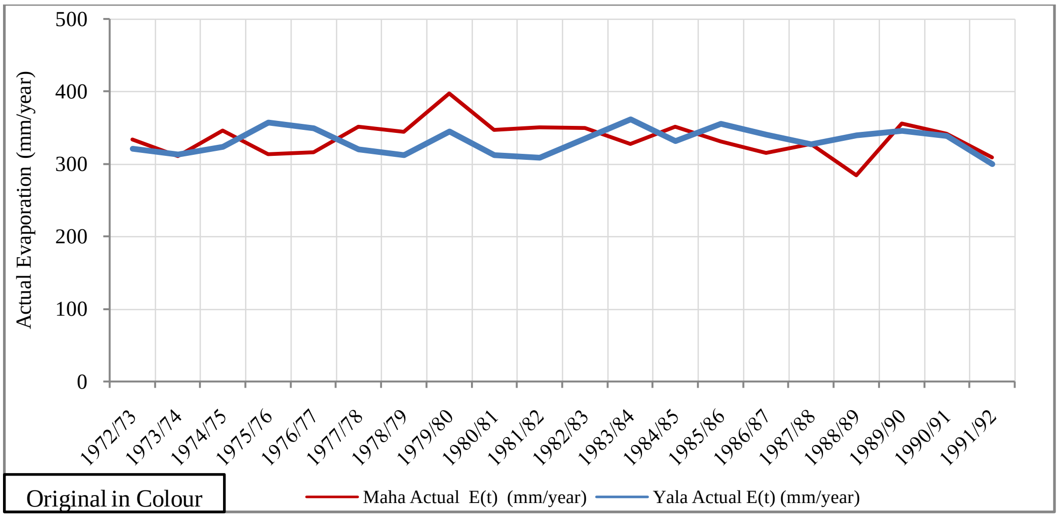


Figure 5-32: Seasonal Actual E(t) at Gin Ganga (1972-1992)

5.7.9.2.3 Monthly Volume

From the Figure 5-33 it was observed that the monthly volume varies from minimum of 37 mm/month to maximum of 85 mm/month with an average value of 56 mm/month.

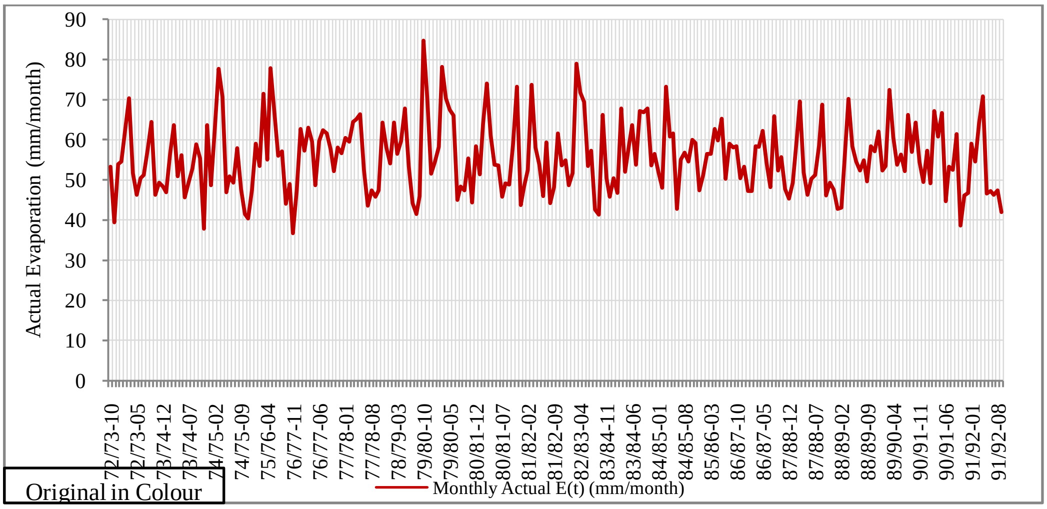


Figure 5-33: Monthly Actual E(t) at Gin Ganga (1972-1992)

5.7.10 Estimated Soil Moisture Content

5.7.10.1 Kelani Ganga

5.7.10.1.1 Annual Volume

From the Figure 5-34 it was observed that the annual volume varies from minimum of 2724 mm/year to maximum of 2903 mm/year with an average value of 2833mm/year.

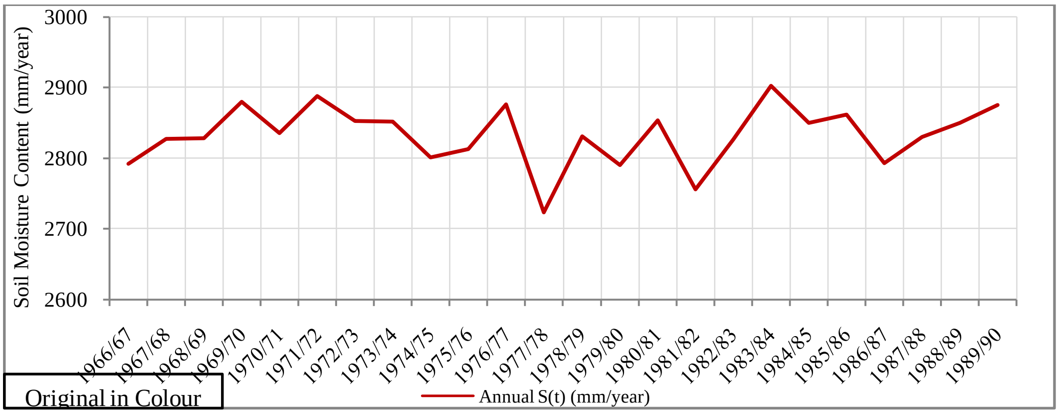


Figure 5-34: Annual Estimated Soil Moisture Content at Kelani Ganga (1966-1990)

5.7.10.1.2 Seasonal Volume

From the Figure 5-35 it was observed that during Maha season the volume varies from minimum of 1287 mm/year to maximum of 1453 mm/year with an average value of 1379 mm/year and during Yala season the volume varies from minimum of 1368 mm/year to maximum of 1487 mm/year with an average value of 1454 mm/year.

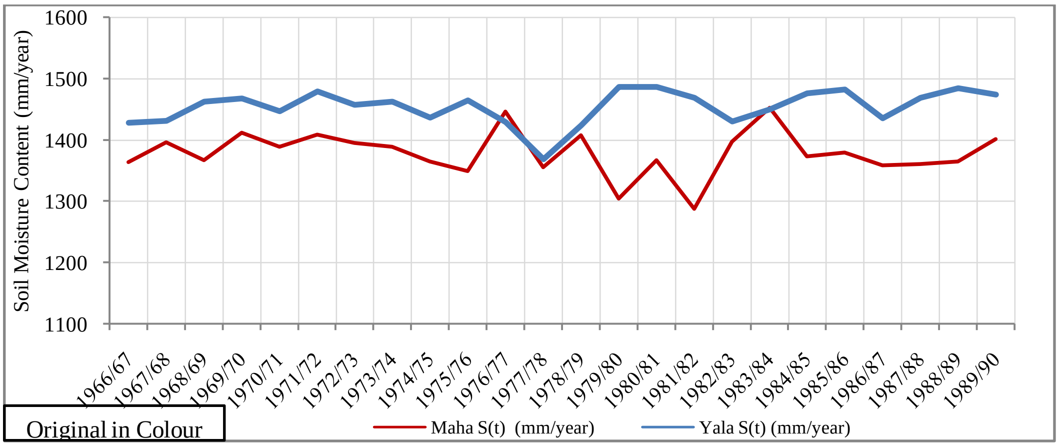


Figure 5-35: Seasonal Estimated Soil Moisture Content at Kelani Ganga (1966-1990)

5.7.10.1.3 Monthly Volume

From the Figure 5-36 it was observed that the monthly volume varies from minimum of 158 mm/month to maximum of 250 mm/month with an average value of 236 mm/month.

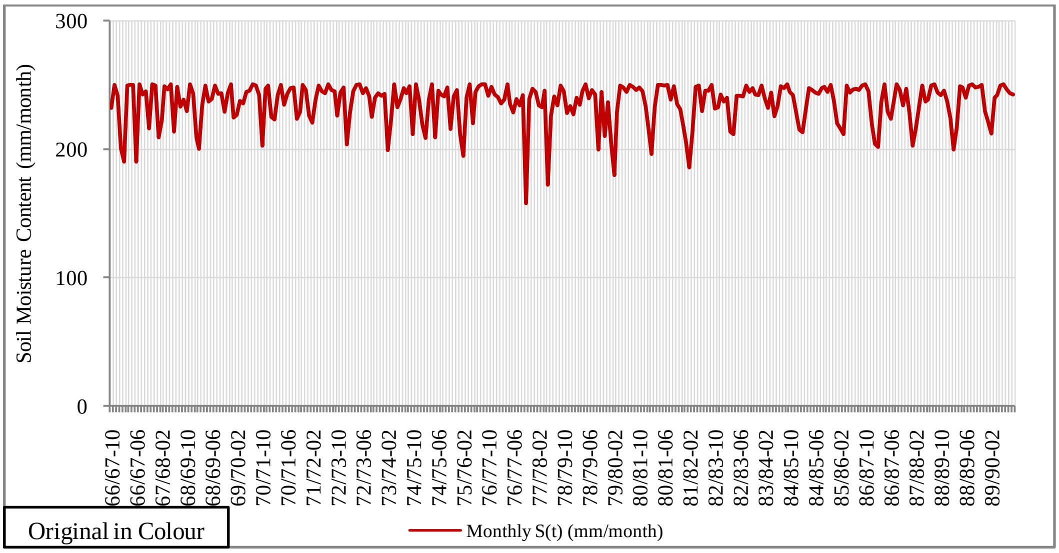


Figure 5-36: Monthly Estimated Soil Moisture Content at Kelani Ganga (1966-1990)

5.7.10.2 Gin Ganga

5.7.10.2.1 Annual Volume

From the Figure 5-37 it was observed that the annual volume varies from minimum of 3994 mm/year to maximum of 4273 mm/year with an average value of 4112 mm/year.

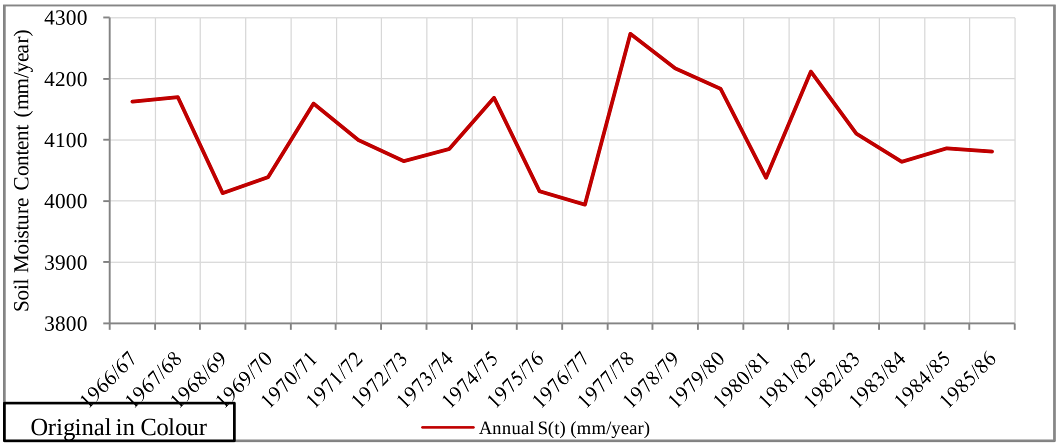


Figure 5-37: Annual Estimated Soil Moisture Content at Gin Ganga (1972-1992)

5.7.10.2.2 Seasonal Volume

From the Figure 5-38 it was observed that during Maha season the volume varies from minimum of 1917 mm/year to maximum of 2133 mm/year with an average value of 2010 mm/year and during Yala season the volume varies from minimum of 2020 mm/year to maximum of 2187 mm/year with an average value of 2102 mm/year.

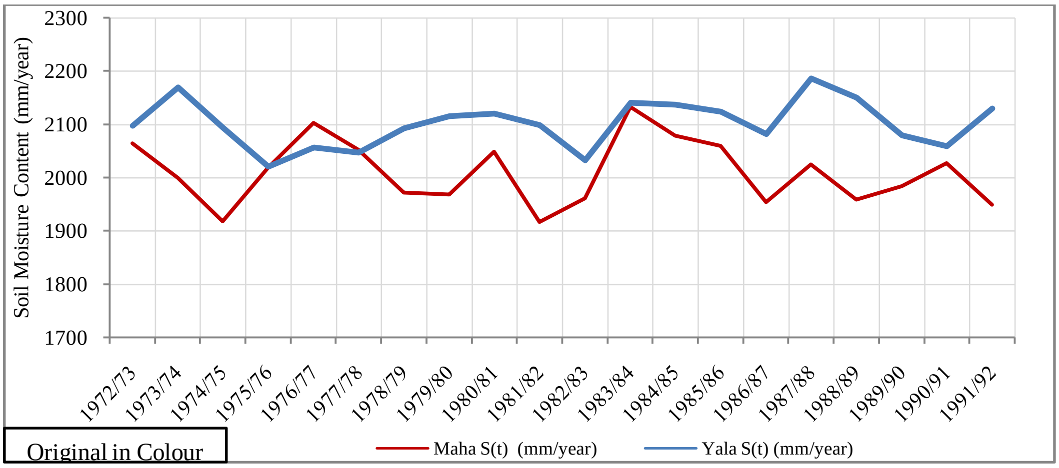


Figure 5-38: Seasonal Estimated Soil Moisture Content at Gin Ganga (1972-1992)

5.7.10.2.3 Monthly Volume

From the Figure 5-39 it was observed that the monthly volume varies from minimum of 266 mm/month to maximum of 368 mm/month with an average value of 343 mm/month.

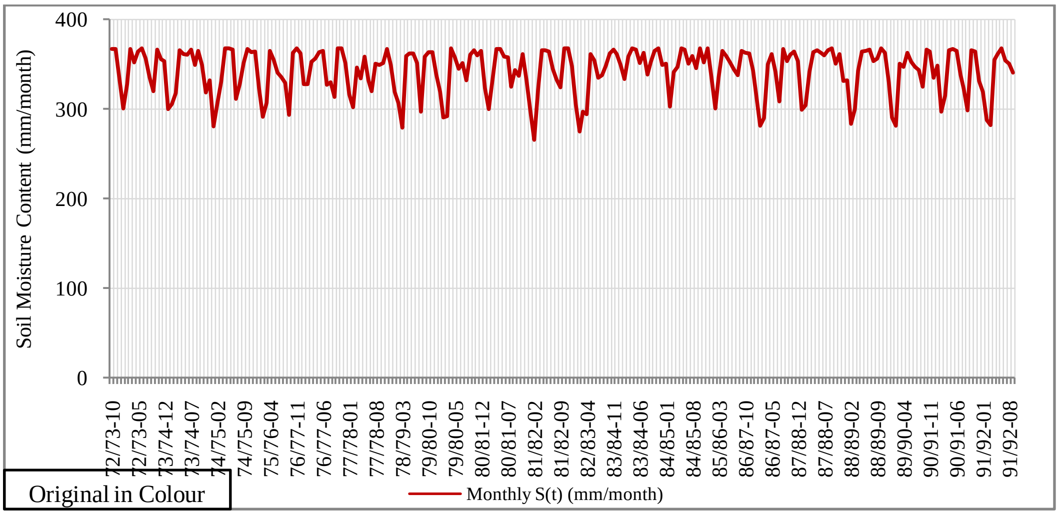


Figure 5-39: Monthly Estimated Soil Moisture Content at Gin Ganga (1972-1992)

5.8 Model Verification

5.8.1 Estimated Streamflow

5.8.1.1 Annual

Annual matching of estimated and observed streamflow indicated the good matching as shown in the Figure 5-40 and Figure 5-41 for Kelani Ganga and Gin Ganga respectively. Annual streamflow varies from 2200-4000 mm/year in Kelani Ganga and 2600-3600 mm/year in Gin Ganga.

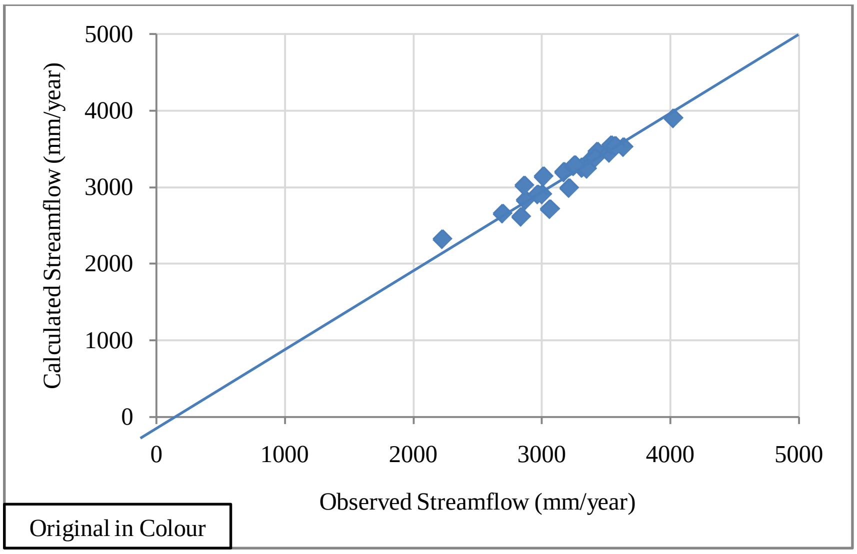


Figure 5-40: Annual Water Balance at Kelani Ganga (1990-2014)

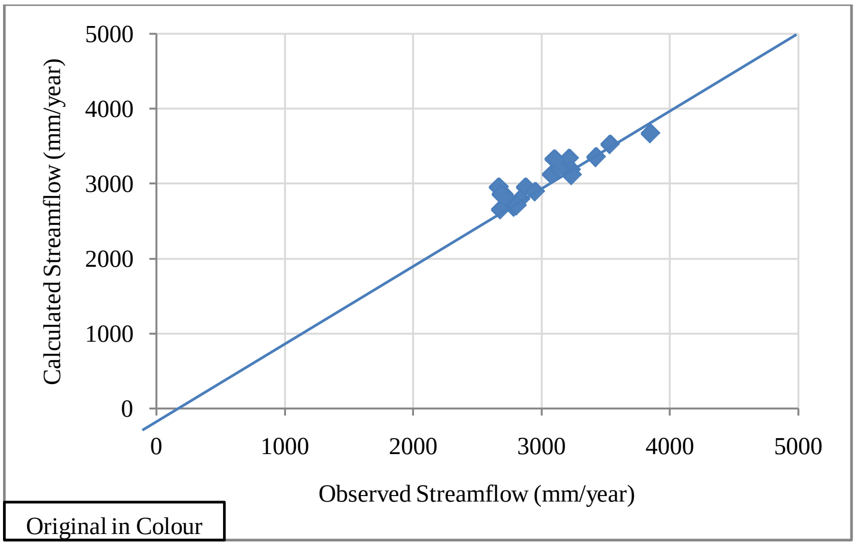


Figure 5-41: Annual Water Balance for Gin Ganga (1992-2012)

5.8.1.2 Seasonal

In Kelani Ganga, streamflow comparison for Maha Season and Yala Season indicated the good matching as shown in the Figure 5-42 and Figure 5-43 respectively. Seasonal streamflow varies from 1000-1600 mm during Maha season and 1400-2400 mm during Yala season.

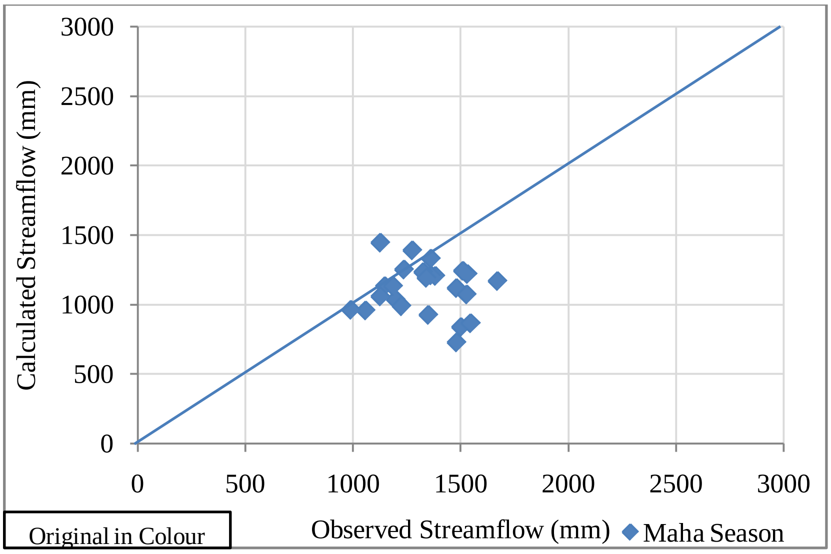


Figure 5-42: Maha Season Streamflow at Kelani Ganga (1990-2014)

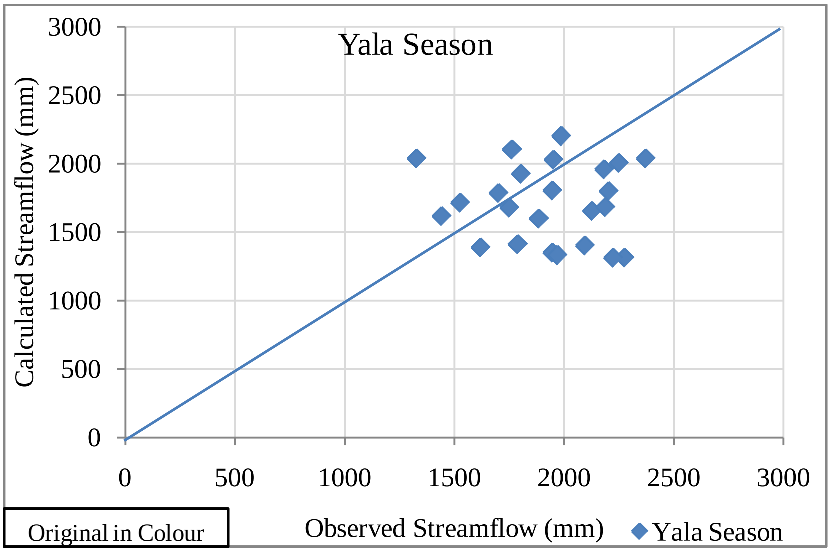


Figure 5-43: Yala Season Streamflow at Kelani Ganga (1990-2014)

Similarly, in Gin Ganga the streamflow comparison for Maha Season and Yala Season indicated the good matching as shown in the Figure 5-24 and Figure 5-25 respectively. Seasonal streamflow varies from 1000-1500 mm during Maha season and 1300-2200 mm during Yala season.

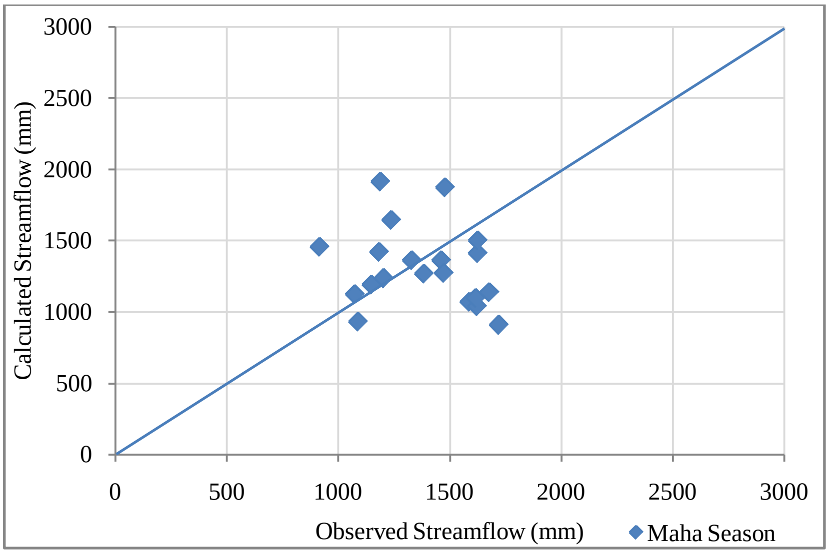


Figure 5-44: Maha Season Streamflow at Gin Ganga (1992-2012)

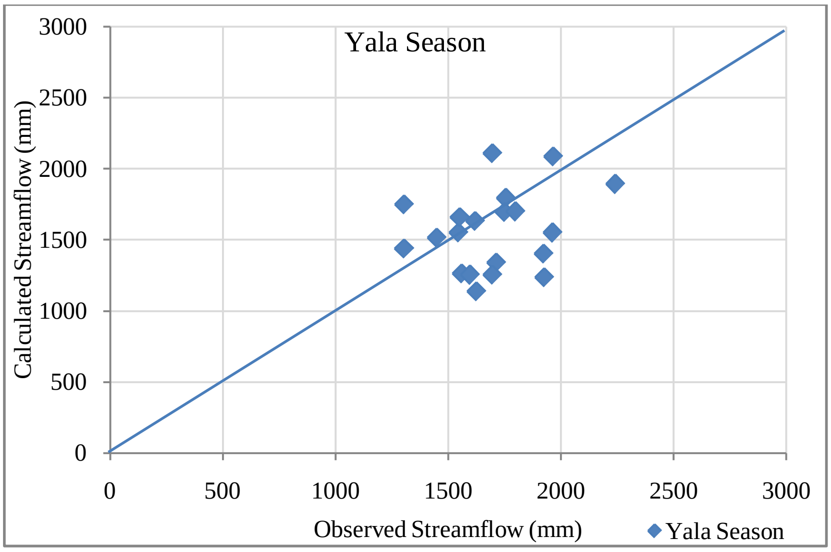


Figure 5-45: Yala Season Streamflow at Gin Ganga(1992-2012)

5.8.1.3 Monthly

Monthly estimated and observed streamflow comparison of Kelani Ganga and Gin Ganga is indicated Figure 5-46 and Figure 5-47. The comparison indicated good matching with monthly value varies from 45-600 mm in Kelani Ganga and 55-600 mm in Gin Ganga.

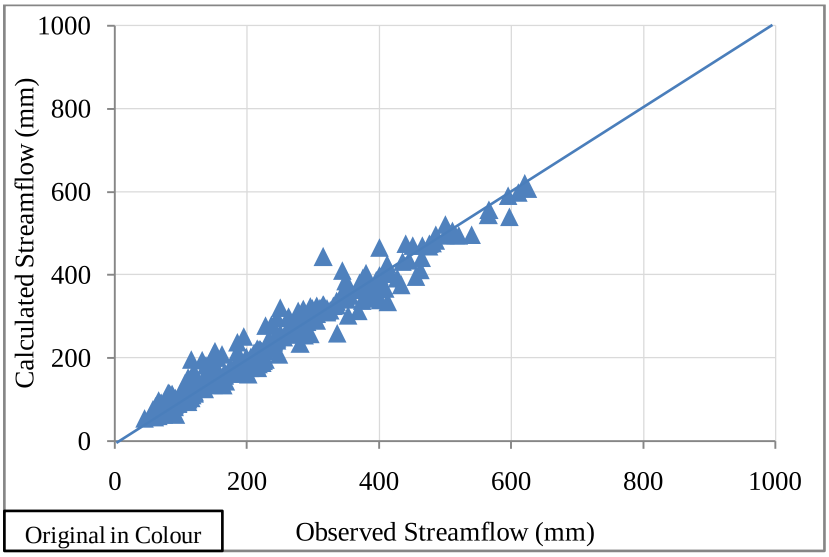


Figure 5-46: Monthly Streamflow at Kelani Ganga (1990-2014)

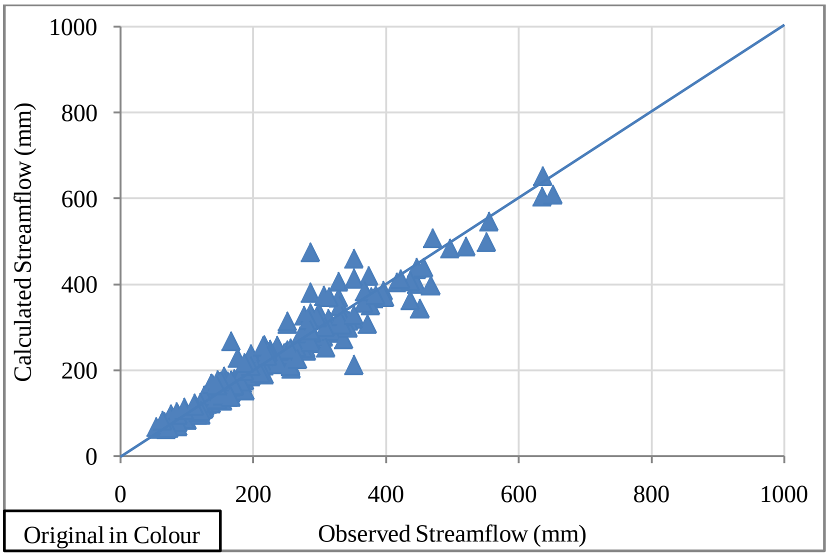


Figure 5-47: Monthly Streamflow at Gin Ganga (1992-2012)

5.8.2 Flow duration curves

Flow duration curve for observed and estimated streamflow of Kelani Ganga is presented in the Figure 6-6 & Figure 6-7 and Gin Ganga in Figure 6-14 & Figure 6-15. Flow duration was analyzed by determining the High, Medium and Low Flow and MRAE was calculated separately for each flow region and total flow.

In Kelani Ganga, MRAE for High, Medium, Low and Total Flow are 0.055, 0.063, 0.127and 0.089 respectively.

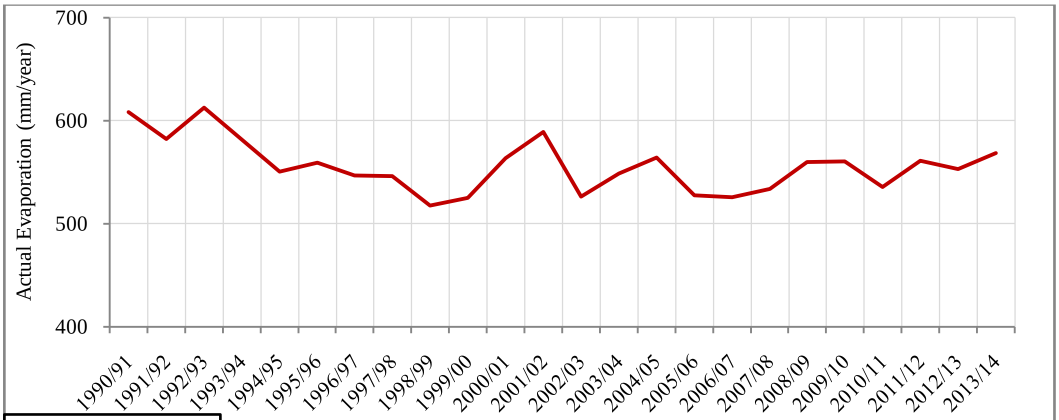
Similarly, in Gin Ganga, MRAE for High, Medium, Low and Total Flow are 0.098, 0.078, 0.125and 0.097 respectively.

5.8.3 Estimated Evaporation (Actual)

5.8.3.1 Kelani Ganga

5.8.3.1.1 Annual Volume

From the Figure 5-48 it was observed that the annual volume varies from minimum of 517 mm/year to maximum of 612 mm/year with an average value of 556 mm/year.

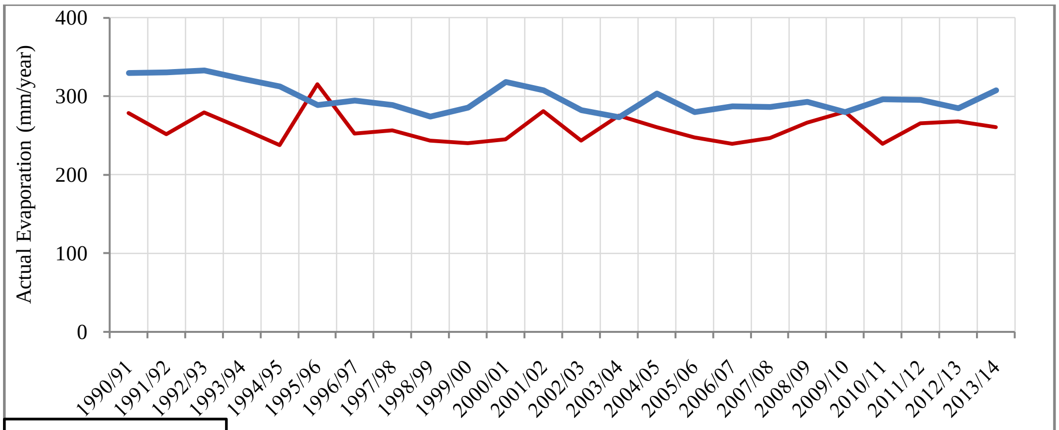


Original in Colour

Figure 5-48: Annual Actual E(t) at Kelani Ganga (1990-2014)

5.8.3.1.2 Seasonal Volume

From the Figure 5-49 it was observed that during Maha season the volume varies from minimum of 238 mm/year to maximum of 316 mm/year with an average value of 260 mm/year and during Yala season the volume varies from minimum of 273 mm/year to maximum of 333 mm/year with an average value of 298 mm/year.



Original in Colour

Figure 5-49: Seasonal Actual E(t) at Kelani Ganga (1990-2014)

5.8.3.1.3 Monthly Volume

From the Figure 5-50 it was observed that the monthly volume varies from minimum of 28 mm/month to maximum of 66 mm/month with an average value of 46 mm/month.

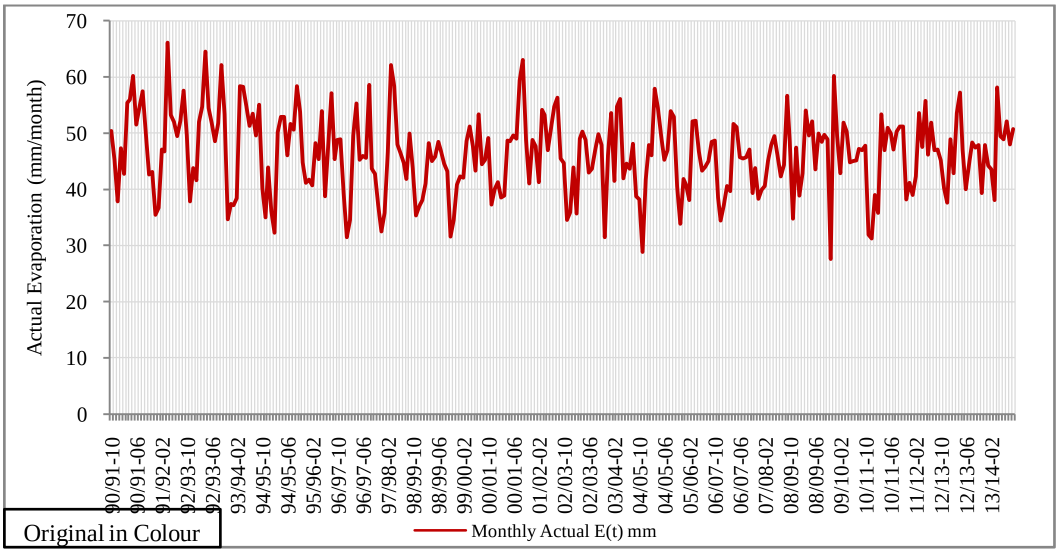


Figure 5-50: Monthly Actual E(t) at Kelani Ganga (1990-2014)

5.8.3.2 Gin Ganga

5.8.3.2.1 Annual Volume

From the Figure 5-51 it was observed that the annual volume varies from minimum of 590 mm/year to maximum of 749 mm/year with an average value of 652 mm/year.

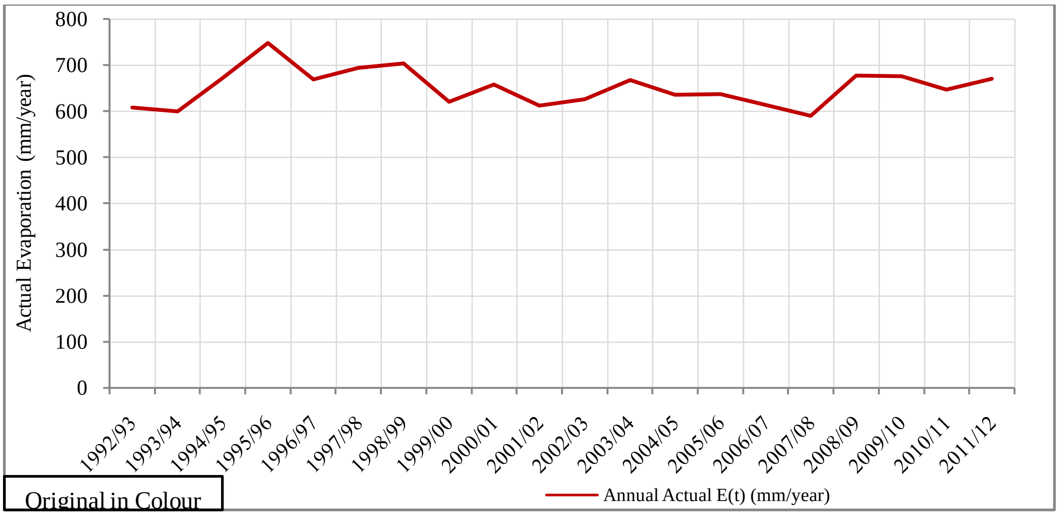


Figure 5-51: Annual Actual E(t) at Gin Ganga (1992-2012)

5.8.3.2.2 Seasonal Volume

From the Figure 5-52 it was observed that during Maha season the volume varies from minimum of 245 mm/year to maximum of 386 mm/year with an average value of 315 mm/year and during Yala season the volume varies from minimum of 294 mm/year to maximum of 363 mm/year with an average value of 337 mm/year.

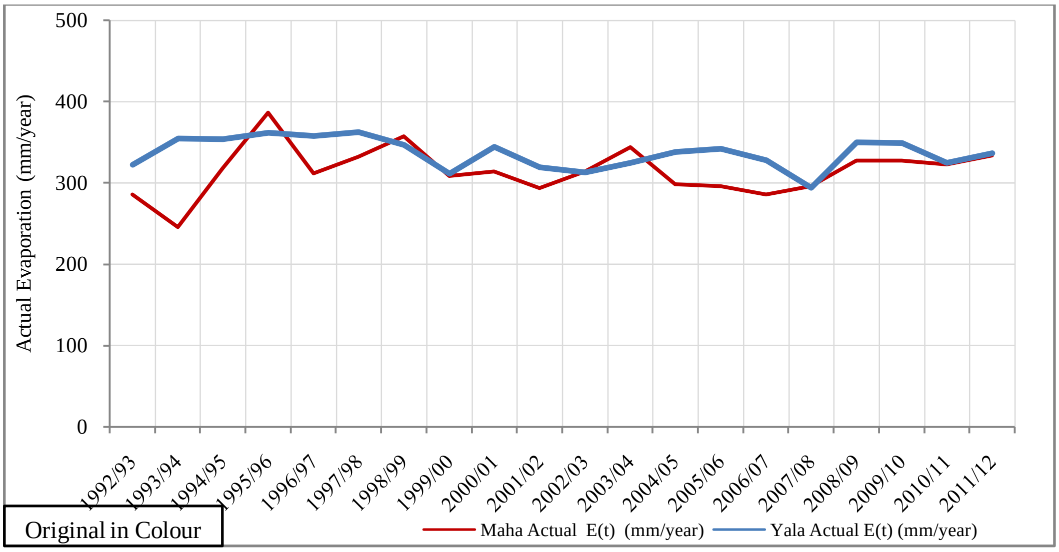


Figure 5-52: Seasonal Actual E(t) at Gin Ganga (1992-2012)

5.8.3.2.3 Monthly Volume

From the Figure 5-53 it was observed that the monthly volume varies from minimum of 28 mm/month to maximum of 76 mm/month with an average value of 54 mm/month.

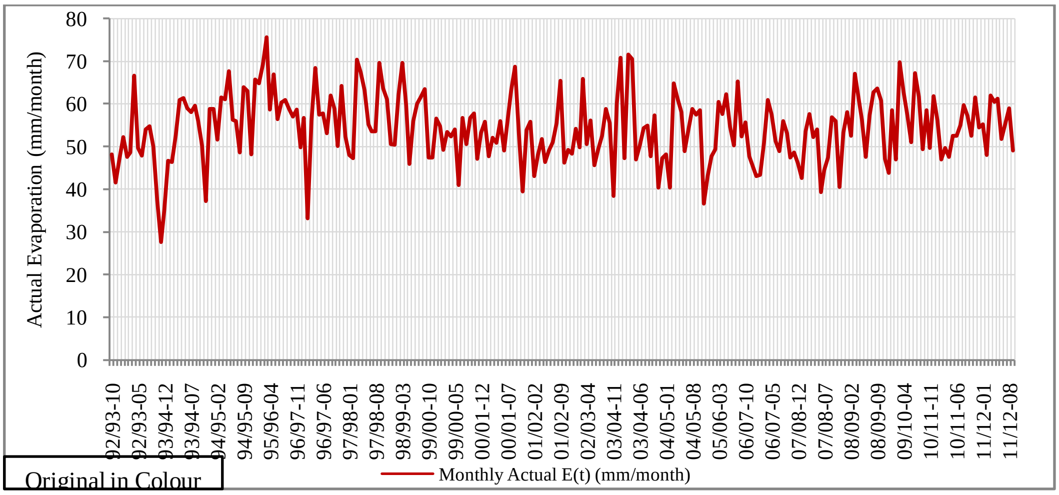


Figure 5-53: Monthly Actual E(t) at Gin Ganga (1992-2012)

5.8.4 Estimated Soil Moisture Content

5.8.4.1 Kelani Ganga

5.8.4.1.1 Annual Volume

From the Figure 5-54 it was observed that the annual volume varies from minimum of 2692 mm/year to maximum of 2886 mm/year with an average value of 2810 mm/year.

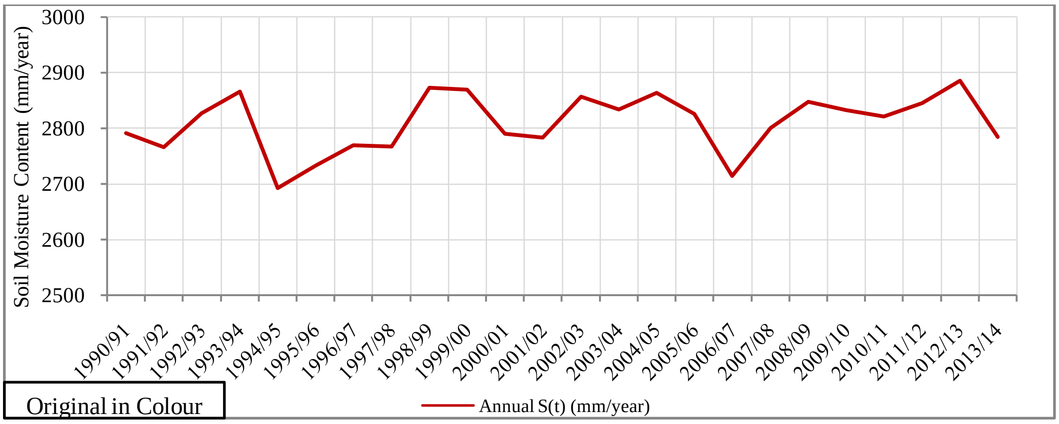


Figure 5-54: Annual Estimated Soil Moisture Content at Kelani Ganga (1990-2014)

5.8.4.1.2 Seasonal Volume

From the Figure 5-55 it was observed that during Maha season the volume varies from minimum of 1237 mm/year to maximum of 1522 mm/year with an average value of 1359 mm/year and during Yala season the volume varies from minimum of 1420 mm/year to maximum of 1489 mm/year with an average value of 1461 mm/year.

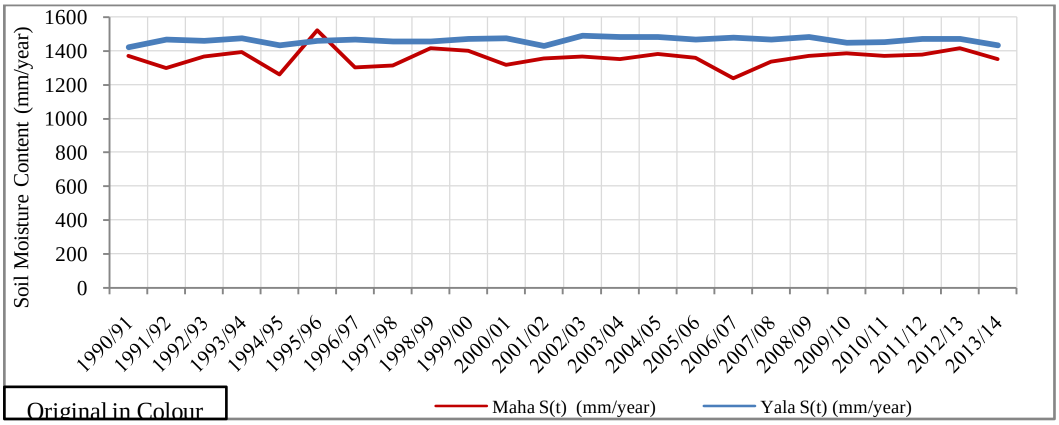


Figure 5-55: Seasonal Estimated Soil Moisture Content at Kelani Ganga (1990-2014)

5.8.4.1.3 Monthly Volume

From the Figure 5-56 it was observed that the monthly volume varies from minimum of 180 mm/month to maximum of 250 mm/month with an average value of 234 mm/month.

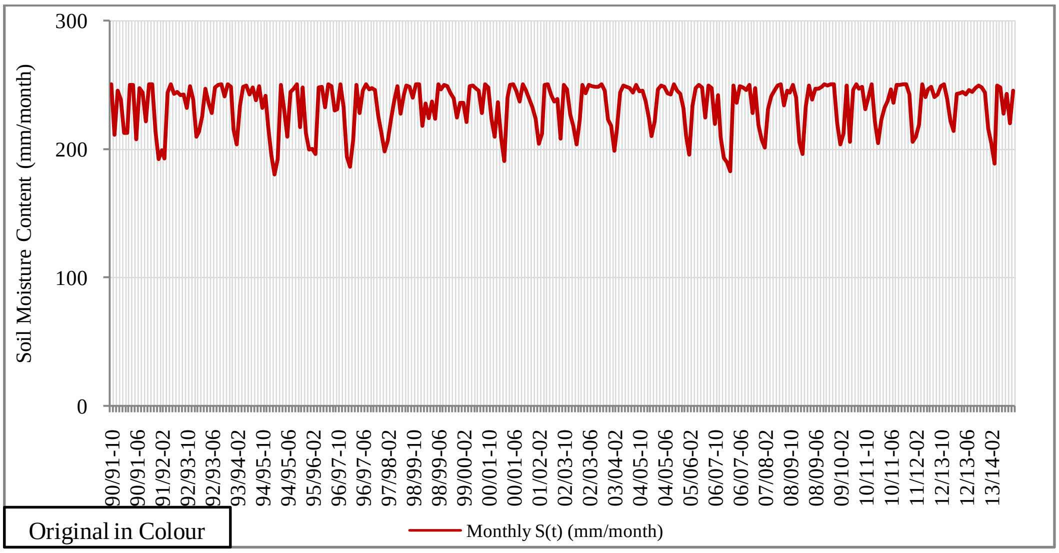


Figure 5-56: Monthly Estimated Soil Moisture Content at Kelani Ganga (1990-2014)

5.8.4.2 Gin Ganga

5.8.4.2.1 Annual Volume

From the Figure 5-57 it was observed that the annual volume varies from minimum of 3875 mm/year to maximum of 4249 mm/year with an average value of 4035 mm/year.

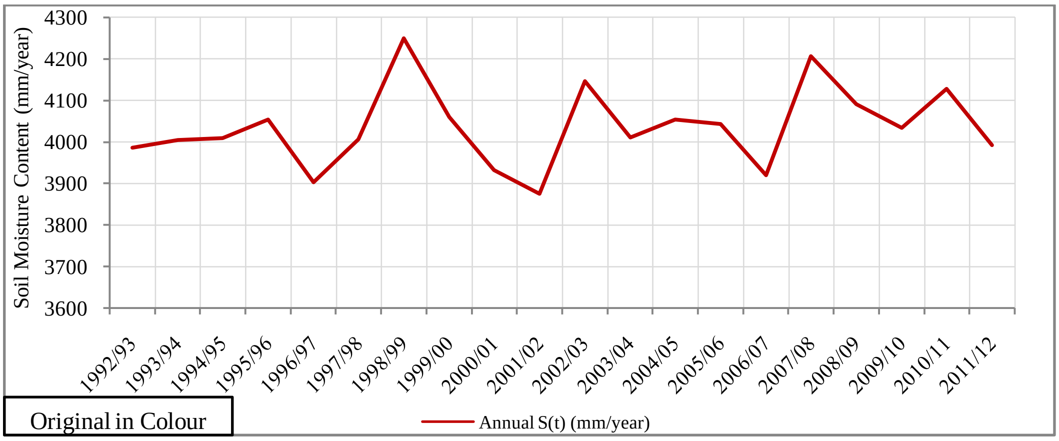


Figure 5-57: Annual Estimated Soil Moisture Content at Gin Ganga (1992-2012)

5.8.4.2.2 Seasonal Volume

From the Figure 5-58 it was observed that during Maha season the volume varies from minimum of 1801 mm/year to maximum of 2133 mm/year with an average value of 1960 mm/year and during Yala season the volume varies from minimum of 1987 mm/year to maximum of 2126 mm/year with an average value of 2075 mm/year.

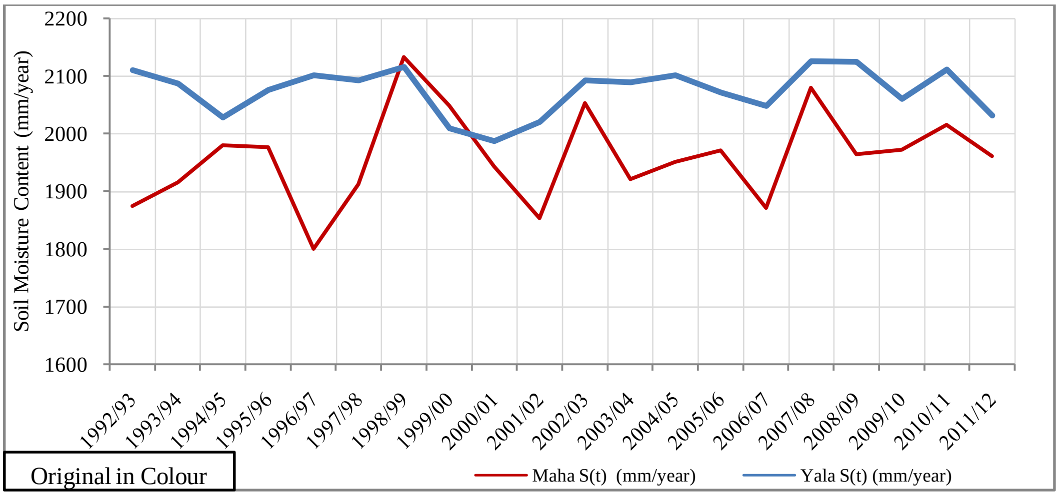


Figure 5-58: Seasonal Estimated Soil Moisture Content at Gin Ganga (1992-2012)

5.8.4.2.3 Monthly Volume

From the Figure 5-39 it was observed that the monthly volume varies from minimum of 244 mm/month to maximum of 368 mm/month with an average value of 336 mm/month.

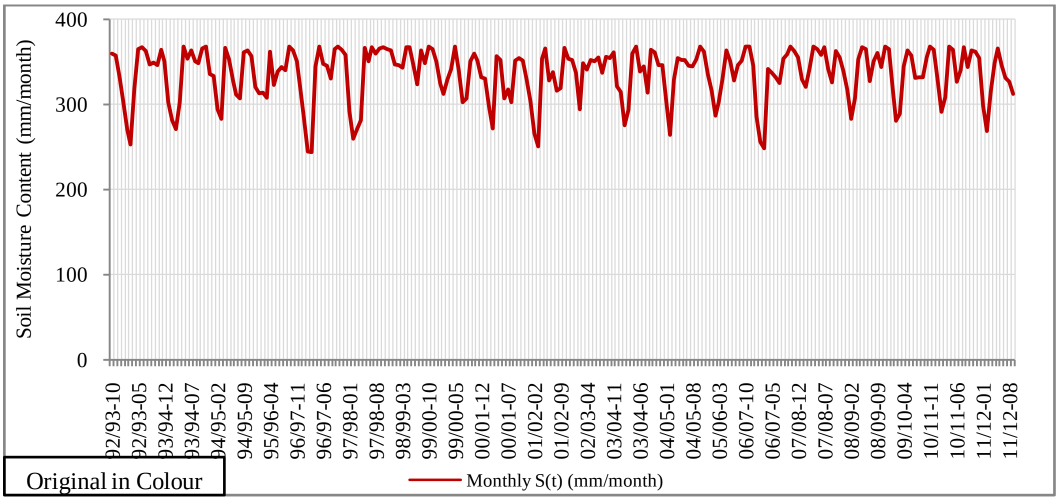


Figure 5-59: Monthly Estimated Soil Moisture Content at Gin Ganga (1992-2012)

5.9 Climate Change

5.9.1 Climate Change in Sri Lanka

In Sri Lanka, the observed changes in climate includes the rate of increase in temperature from 1961 to 1990 is 0.016 ^{0}C per year, decreasing trend in mean annual rainfall (MAR) during 1961-1990 by 144 mm (7%) compared to that during 1931-1960 and country as a whole, the number of consecutive dry days has increased while the number of consecutive wet days has reduced.

Similarly, future climate projections indicated that the temperature increases of 5.44 ^{0}C and 2.93 ^{0}C over South Asia in the summer of 2070-2099. Other regional climate models for South Asia also project widespread warming in the region, including in Sri Lanka, rise in annual mean temperature in the range 2.5–4 ^{0}C for IPCC scenario towards the end of the twenty-first century and IPCC's projections of higher warming during the north east monsoon (NEM) and lower warming during the SWM. The2 degree increase of temperature would affect an increase of 8% in evaporation. While the majority of research project higher values for MAR, a few studies project lower values. Projection indicates 26-34 % decrease in the NEM rainfall and a 16-38 % increase in the SWM rainfall compared to 1961-1990. Some researchers suggested the higher increase in SWM than in NEM. While others predict decreases in both SWM and NEM.

5.9.2 Influence on Model Inputs

5.9.2.1 Influence on Rainfall

Rainfall for the Base Scenario is taken as the 40 years of average rainfall from the Gin Ganga data series.

Under the Scenario 1: North East Monsoon (NEM)decreases by 26% and South West Monsoon (SWM) increases by 16%.

Under the Scenario 2: North East Monsoon (NEM) decreases by 34% and South West Monsoon (SWM) increases by 38%.

Under the Scenario 3: North East Monsoon (NEM) decreases by 34% and South West Monsoon (SWM) decreases by 38% but with higher peak.

Under the Scenario 4: North East Monsoon (NEM) decreases by 34% with high peak and South West Monsoon (SWM) decreases by 16%.

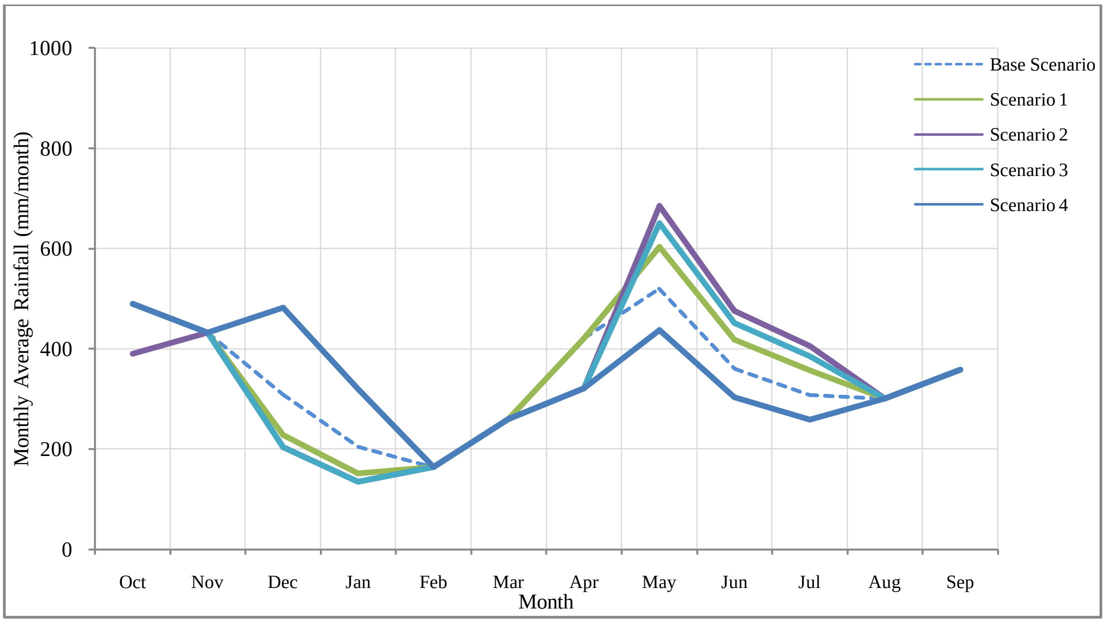


Figure 5-60: Climate change influence on rainfall up to year 2070

The influence of the climate change on rainfall up to year 2050 is illustrated in the Figure 5-60 and year 2070 was taken as the comparison time line because of the availability of GCM predictions.

5.9.2.2 Influence on Temperature and Evaporation

The temperature increase of 5.44 ^{0}C up to year 2070 is considered in this study and 2 degree increase of temperature would affect an increase of 8% evaporation. Therefore, temperature increase of 5.44 ^{0}C would affect an increase of 21.76% evaporation. Influence on temperature and evaporation is considered same under all scenarios.

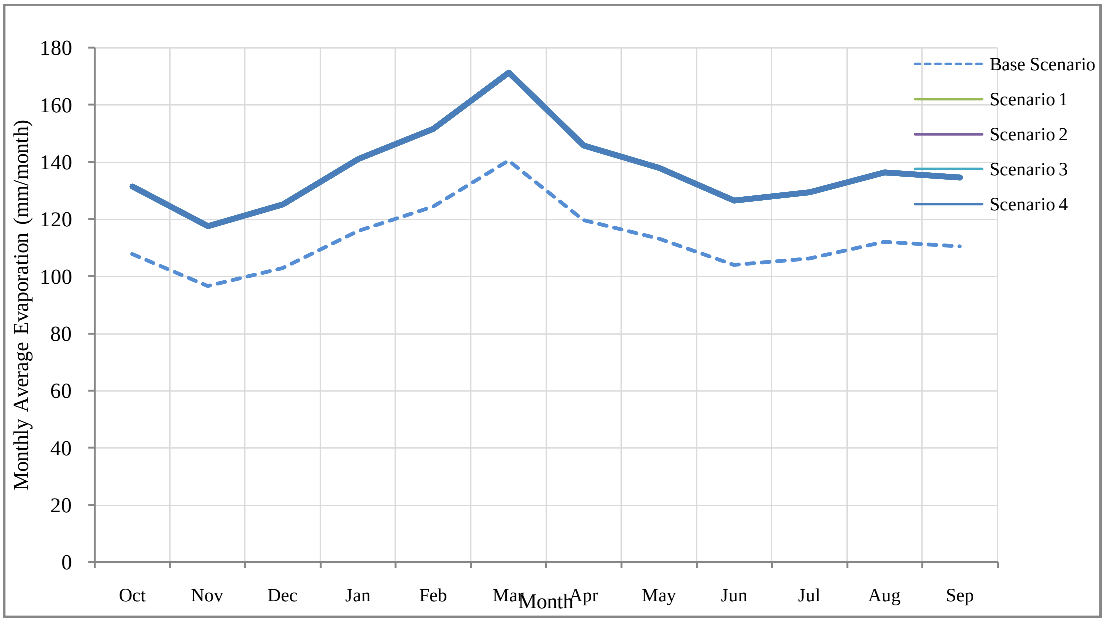


Figure 5-61: Climate change influence on evaporation up to year 2070

5.9.3 Critical Climate Change Scenario

Critical climate change scenario were identified by superimposing the worst case scenario of both observed and projected change in Sri Lanka as indicated in the Table 5-1.

Table 5-1: Critical Climate Change Scenario

Scenario	Change	Precipitation	Temperature	Evaporation
Scenario 1	NEM (Decrease)	26%	5.44°C	21.76%
	SWM (Increase)	16%		
Scenario 2	NEM (Decrease)	34%	5.44°C	21.76%
	SWM (Increase)	38%		
Scenario 3	NEM (Decrease)	34%	5.44°C	21.76%
	SWM (Decrease) with High Peak	38%		
Scenario 4	NEM (Decrease) with High Peak	34%	5.44°C	21.76%
	SWM (Decrease)	16%		

5.9.4 Anticipated Model Estimations with Climate Change

5.9.4.1 Streamflow

Table 5-2: Model Simulated Streamflow with Climate Change

Estimated Streamflow (mm/month)					
Month	Base Scenario	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Oct	269.78	268.75	188.75	267.52	270.58
Nov	319.39	318.17	310.28	316.71	320.33
Dec	214.77	156.80	139.39	140.22	360.67
Jan	138.81	102.80	91.32	91.95	217.37
Feb	105.30	96.44	92.07	92.73	114.40
Mar	149.22	145.59	142.62	143.64	152.52
Apr	289.62	287.77	205.54	207.02	210.95
May	391.09	466.69	536.39	506.83	316.07
Jun	250.41	287.77	321.42	308.06	211.47
Jul	214.43	251.91	286.91	272.64	177.18
Aug	205.67	206.46	203.83	205.57	202.39
Sep	250.21	249.39	246.45	248.25	250.59
Total	2798.70	2838.55	2764.97	2801.13	2804.52
Average	229.90	233.62	234.20	230.33	230.36
Max	391.09	466.69	536.39	506.83	360.67
Min	105.30	96.44	91.32	91.95	114.40

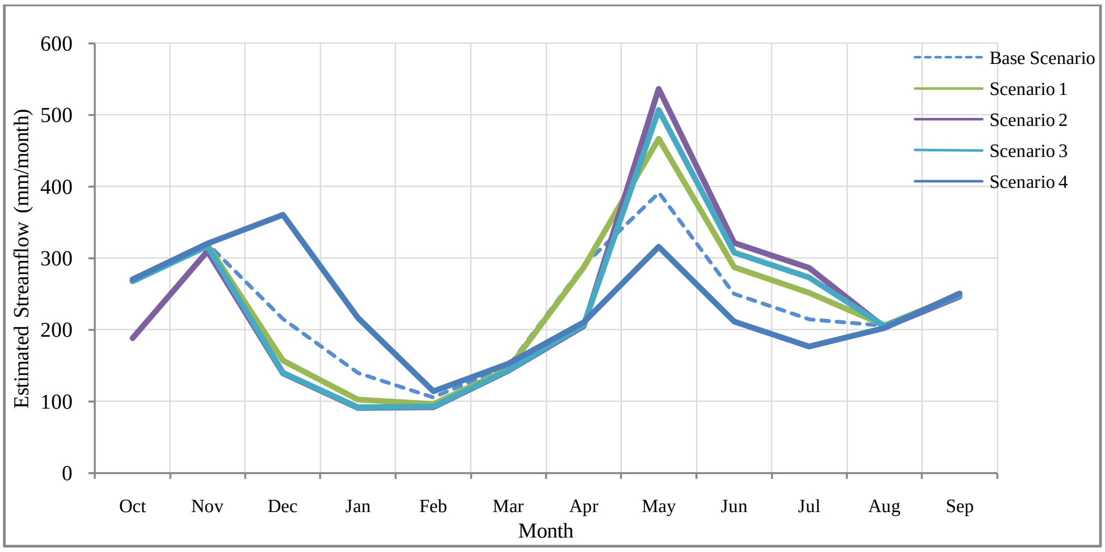


Figure 5-62: Simulated Streamflow with Climate Change

5.9.5 Soil Moisture Content

Table 5-3: Soil Moisture Content with Climate Change

Soil Moisture Content (mm/month)					
Month	Base Scenario	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Oct	250.46	250.46	245.57	250.46	250.46
Nov	248.69	248.69	248.95	248.69	248.69
Dec	248.28	238.87	234.41	234.36	245.39
Jan	233.52	218.56	212.61	212.59	248.45
Feb	219.66	215.02	213.08	213.07	223.91
Mar	236.69	235.80	235.42	235.42	237.48
Apr	250.11	250.13	247.69	247.69	247.85
May	241.92	230.92	217.74	223.78	248.95
Jun	250.28	250.13	248.22	249.21	247.90
Jul	248.25	250.33	250.05	250.42	243.08
Aug	247.36	247.53	247.51	247.54	246.91
Sep	250.27	250.28	250.28	250.28	250.26
Total	2925.49	2886.74	2851.53	2863.51	2939.35
Average	243.18	239.66	236.91	237.55	244.44
Max	250.28	250.33	250.28	250.42	250.26
Min	219.66	215.02	212.61	212.59	223.91

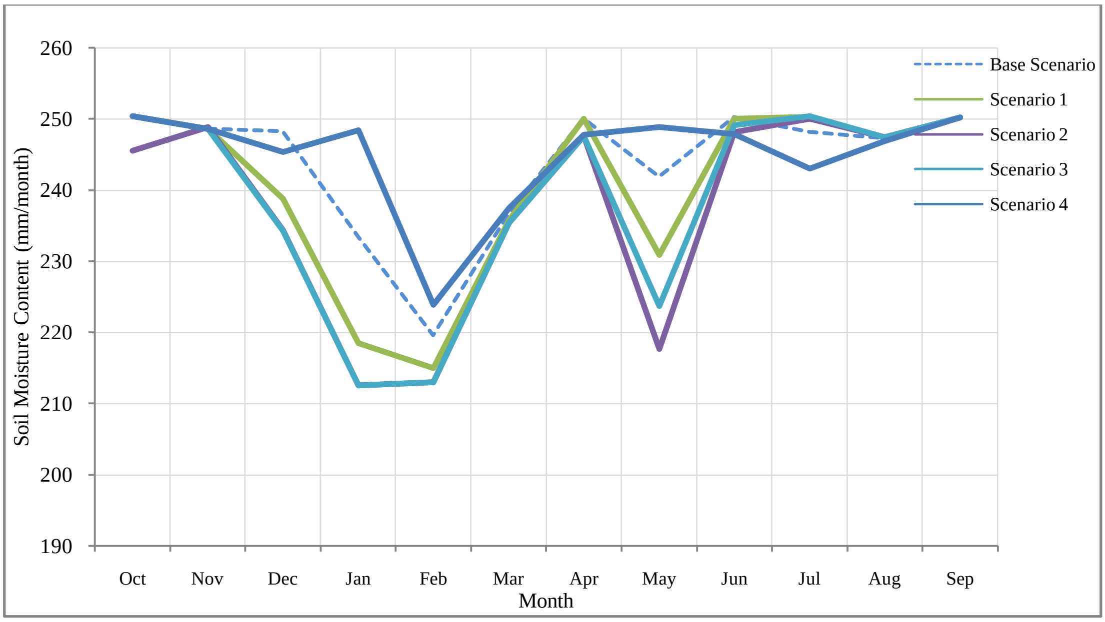


Figure 5-63: Soil Moisture Content with Climate Change

6 RESULTS

6.1 Results for Kelani Ganga

6.1.1 Calibration

6.1.1.1 Annual Water Balance

The comparisons of calculated and observed water balance for Kelani Ganga are indicated in the Table 6-1 and Figure 6-1. Water balance comparison reflects the better performance during calibration where the matching of observed and calculated water balance is quite good with MRAE and Nash-Sutcliffe efficiency value of 0.084 and 0.977 respectively corresponding to the optimum parameter c value of 0.46 and SC value of 899.48.

6.1.1.2 Flow Duration Curve

In order to carry out a detailed analysis of the behavior of model parameters, duration curves were divided into three regions as High Flow, Intermediate Flow and Low Flows. High flows were taken as the streamflow, which occurred for less than 30% of the time, and low flow was taken as flow, which occurred more than 65% of the time. The balance was identified as intermediate flow. MRAE and Nash-Sutcliffe efficiency were computed to identify the performance of optimized model parameters. The result (Table 6-2) indicated that optimized parameters provided a consistent performance. The optimized parameter c and SC is 0.460 and 899.48 respectively. It was observed that the High flows had a good matching with MRAE 0.056 and E 0.887 while medium flows were with MRAE 0.070 and E 0.833 and low flows were with MRAE 0.107 and E 0.756. The total flow MRAE and E is 0.084 and 0.977 respectively. Flow Duration of Normal Plot and Logarithmic Plot is shown in the Figure 6-2 and Figure 6-3 respectively.

6.1.1.3 Outflow Hydrograph

The outflow hydrograph of observed and calculated streamflow corresponding to monthly Thiessen averaged rainfall for calibration period is indicated in the Figure 6-4. The 24 years of calibration period was divided into 6 year interval each to clearly observe variation and patterns and are indicated in the Appendix-E.

Table 6-1: Annual Water Balance of Kelani Ganga (1966-1990)

Year	Thiessen Averaged Rainfall (mm)	Observed Streamflow (mm)	Calculated Streamflow (mm)	Observed Water Balance (mm)	Calculated Water Balance (mm)
1966/67	4697	3401	3355	1295	1342
1967/68	4908	3705	3622	1203	1286
1968/69	4368	3188	3221	1180	1147
1969/70	4676	3476	3456	1200	1220
1970/71	5281	4042	3998	1239	1283
1971/72	4554	3348	3286	1207	1268
1972/73	4634	3283	3353	1350	1281
1973/74	4891	3576	3564	1315	1328
1974/75	4877	3543	3551	1334	1326
1975/76	4733	3473	3473	1261	1260
1976/77	4512	3450	3335	1062	1178
1977/78	4942	3332	3641	1610	1301
1978/79	4541	3234	3372	1307	1170
1979/80	3885	2987	2787	898	1098
1980/81	3849	2817	2742	1032	1107
1981/82	4078	3131	2991	947	1087
1982/83	4327	3057	3076	1270	1251
1983/84	4922	3698	3637	1224	1285
1984/85	4084	2850	2918	1234	1166
1985/86	3792	2891	2695	902	1098
1986/87	4156	3070	2993	1085	1162
1987/88	4603	3447	3387	1156	1216
1988/89	4294	2935	3112	1359	1182
1989/90	3451	2317	2395	1134	1056
Average	4461	3260	3248	1200	1212

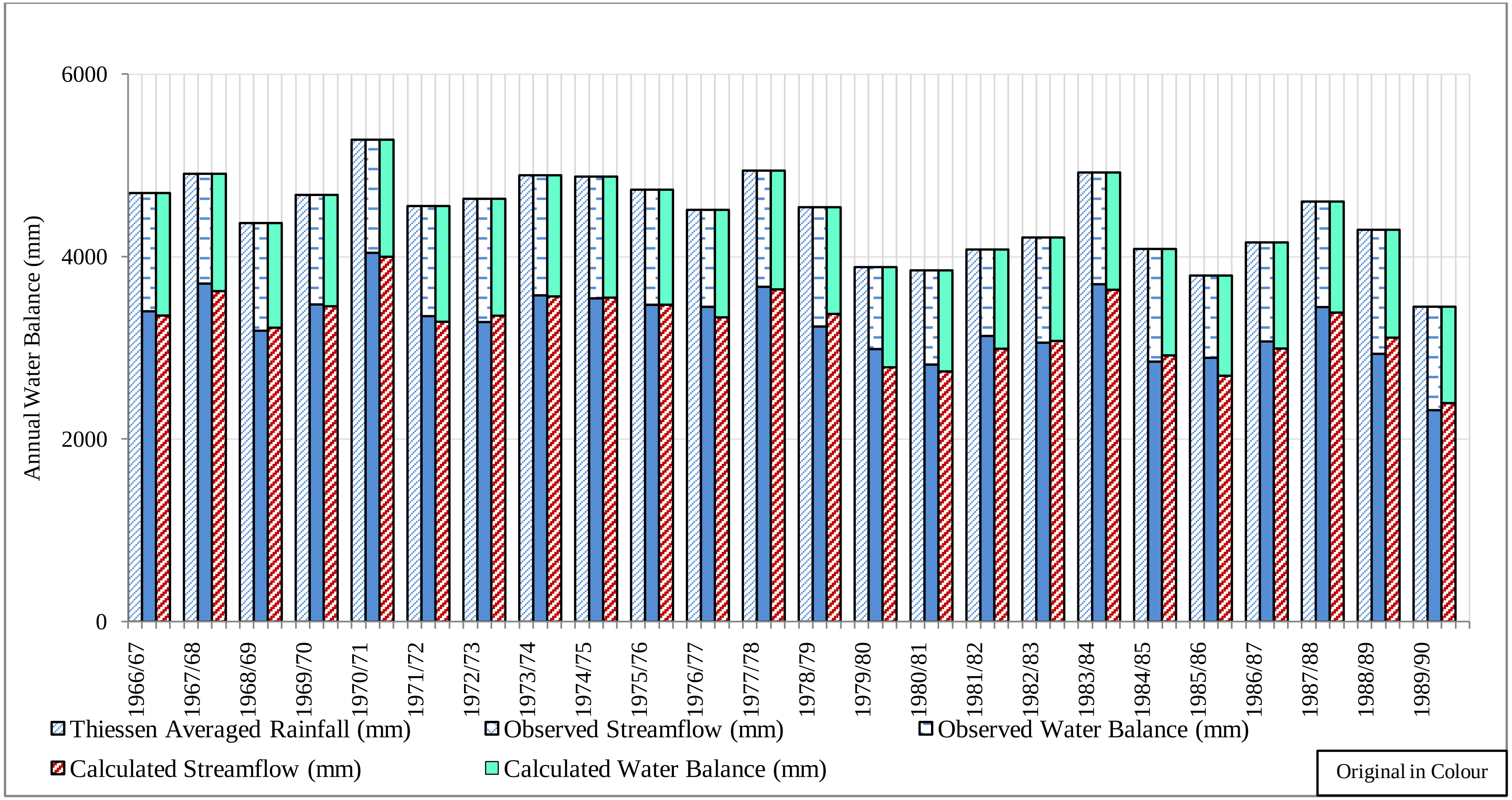


Figure 6-1: Annual Water Balance of Kelani Ganga (1966-1990)

Table 6-2: Kelani Ganga Parameter & Error Values of Flow(1966-1990)

Parameter		**Mean Ratio of Absolute Error (MRAE)**				**Nash-Sutcliffe efficiency (E)**			
c	SC (mm)	High Flow	Medium Flow	Low Flow	Total Flow	High Flow	Medium Flow	Low Flow	Total Flow
0.460	899.48	0.056	0.070	0.107	0.084	0.887	0.833	0.756	0.977

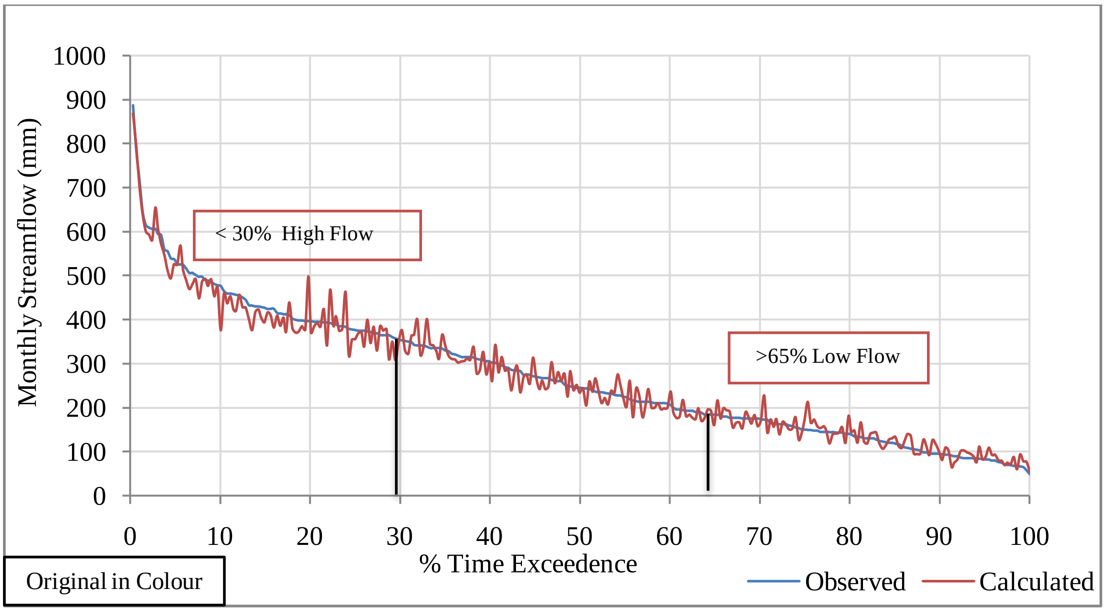


Figure 6-2: Flow Duration (Normal Plot) of Kelani Ganga (1966-1990)

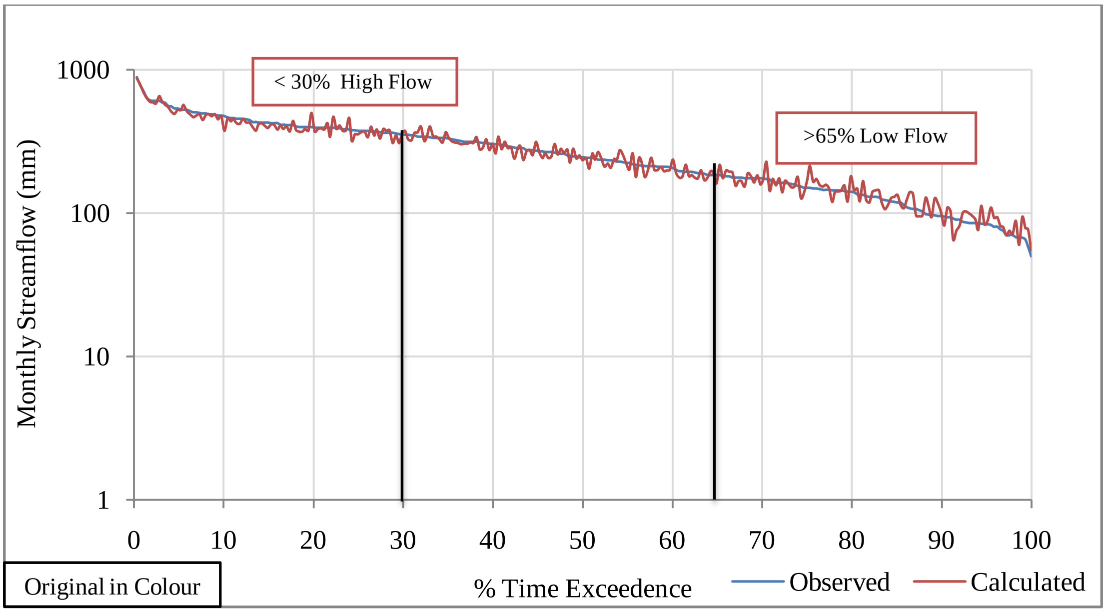


Figure 6-3: Flow Duration (Logarithmic Plot)of Kelani Ganga (1966-1990)

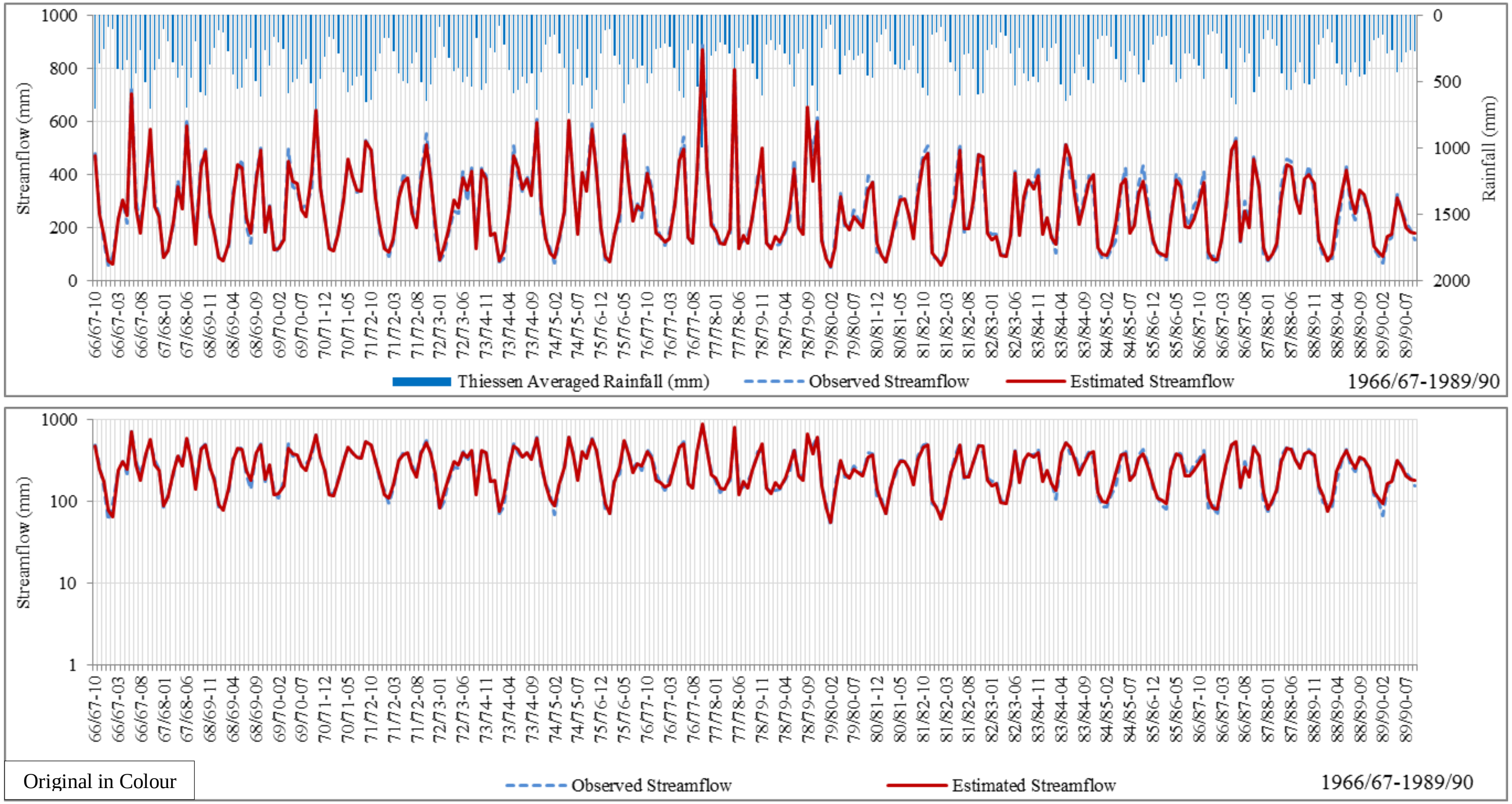


Figure 6-4: Outflow Hydrograph of Kelani Ganga from 1966-1990 (Normal & Logarithmic Plot)

6.1.2 Verification

6.1.2.1 Annual Water Balance

The comparisons of calculated and observed water balance for Kelani Ganga are indicated in the Table 6-3 and Figure 6-5. Water balance comparison reflects the better performance during verification where the matching of observed and calculated water balance is quite good with MRAE and Nash-Sutcliffe efficiency value of 0.089 and 0.977 respectively corresponding to the optimum c value of 0.46 and a SC value of 899.48.

6.1.2.2 Flow Duration Curve

In order to carry out a detailed analysis of the behavior of model parameters, duration curves were divided into three regions as High Flow, Intermediate Flow and Low Flows. High flows were taken as the streamflow, which occurred for less than 30% of the time, and low flow was taken as flow, which occurred more than 65% of the time. The balance was identified as intermediate flow. MRAE and Nash-Sutcliffe efficiency was computed to identify the performance of optimized model parameters. The result (Table 6-4) indicated that optimized parameters provided a consistent performance. The optimized parameter c and SC is 0.460 and 899.48 respectively. It was observed that the High flows are with a good matching having a MRAE of 0.055 and an E of 0.909. Medium flows were with MRAE of 0.063 and an E of 0.816 and low flows were with MRAE of 0.127 and an E of 0.684. The total flow had MRAE and an E as 0.089 and 0.977 respectively. Flow Duration of Normal Plot and Logarithmic Plot is shown in the Figure 6-6 and Figure 6-7 respectively.

6.1.2.3 Outflow Hydrograph

The outflow hydrograph of observed and calculated streamflow corresponding to monthly Thiessen averaged rainfall for verification period is indicated in the Figure 6-8. The 24 years of verification period was divided into 6 year interval each to clearly observe variation and patterns and are indicated in the Appendix-G.

Table 6-3: Annual Water Balance of Kelani Ganga (1990-2014)

Year	Thiessen Averaged Rainfall (mm)	Observed Streamflow (mm)	Calculated Streamflow (mm)	Observed Water Balance (mm)	Calculated Water Balance (mm)
1990/91	4329	3164	3046	1164	1283
1991/92	3756	2766	2639	990	1117
1992/93	4542	3341	3283	1200	1259
1993/94	3696	2681	2609	1015	1087
1994/95	4382	3148	3207	1234	1175
1995/96	4612	3415	3410	1197	1202
1996/97	4199	3080	3043	1119	1156
1997/98	4414	3239	3237	1175	1177
1998/99	4444	3307	3287	1137	1157
1999/00	3423	2451	2425	973	998
2000/01	3019	1958	2056	1061	963
2001/02	3263	2339	2274	924	989
2002/03	3583	2426	2525	1156	1057
2003/04	3516	2488	2483	1028	1033
2004/05	3457	2378	2421	1079	1035
2005/06	3635	2488	2604	1147	1030
2006/07	4032	2704	2933	1329	1099
2007/08	4023	3024	2925	1000	1098
2008/09	4047	2854	2915	1193	1131
2009/10	4334	3149	3161	1185	1173
2010/11	4418	3146	3249	1272	1169
2011/12	3299	2196	2299	1103	1000
2012/13	3912	2778	2808	1134	1104
2013/14	4147	3049	2998	1098	1149
Average	3937	2815	2827	1121	1110

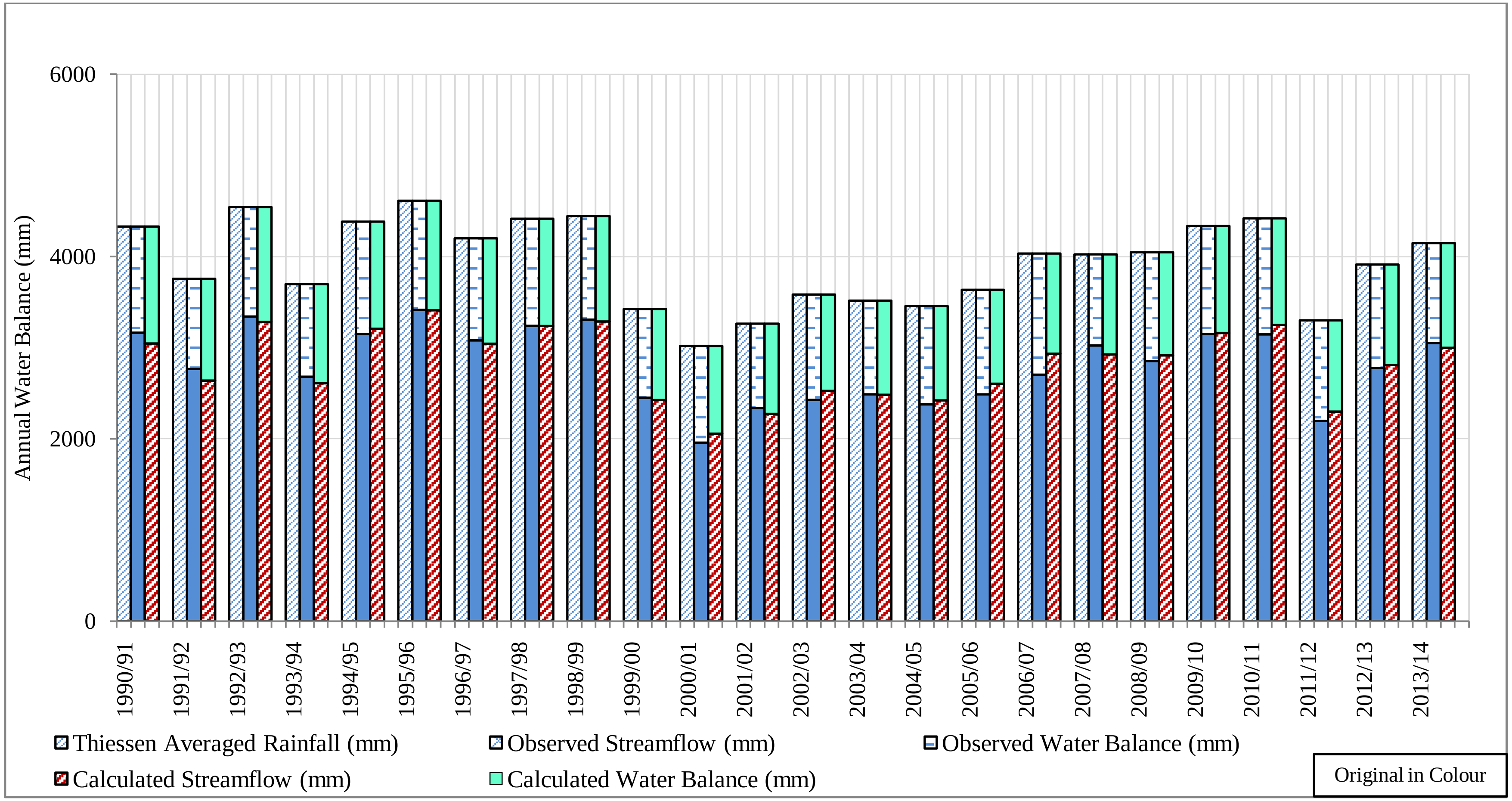


Figure 6-5: Annual Water Balance of Kelani Ganga (1990-2014)

Table 6-4: Kelani Ganga Parameter & Error Values of Flow (1990-2014)

Parameter		**Mean Ratio of Absolute Error (MRAE)**				**Nash-Sutcliffe efficiency €**			
c	SC (mm)	High Flow	Medium Flow	Low Flow	Total Flow	High Flow	Medium Flow	Low Flow	Total Flow
0.46	899	0.055	0.063	0.127	0.089	0.909	0.816	0.684	0.977

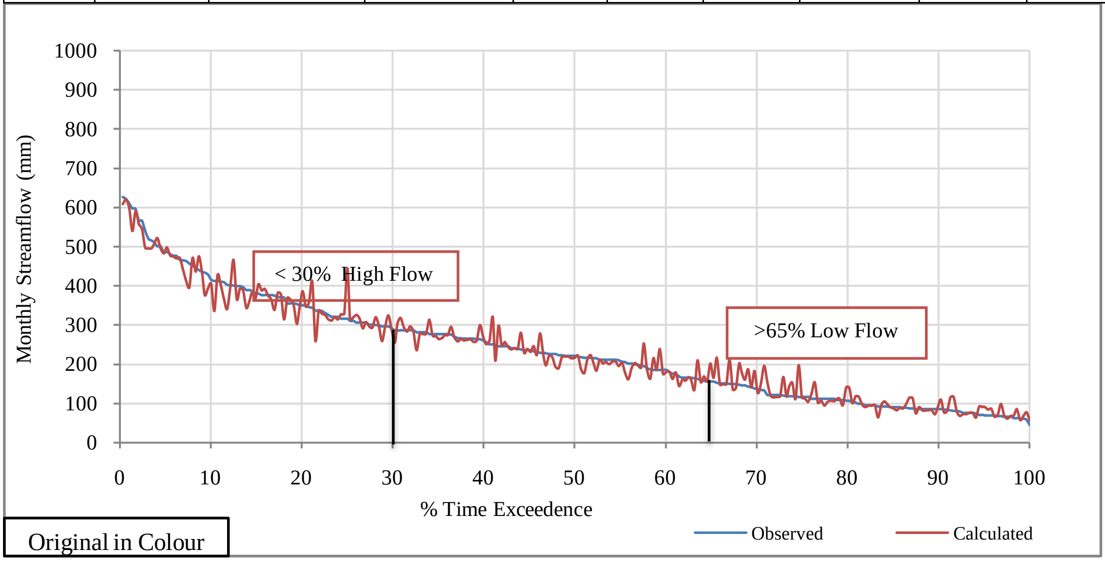


Figure 6-6: Flow Duration (Normal Plot) of Kelani Ganga (1990-2014)

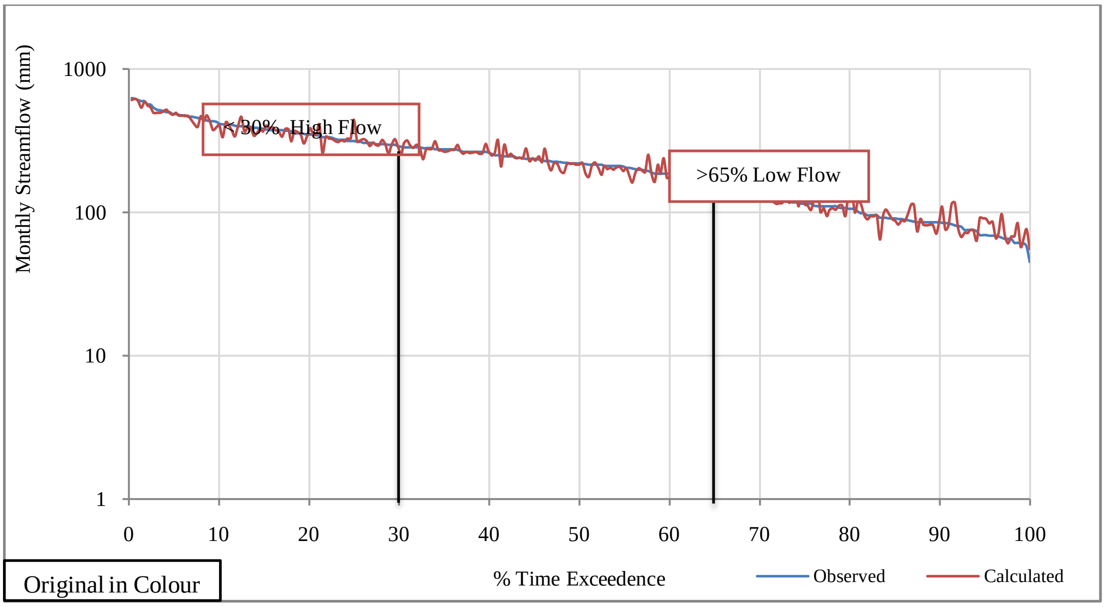


Figure 6-7: Flow Duration (Logarithmic Plot) of Kelani Ganga (1990-2014)

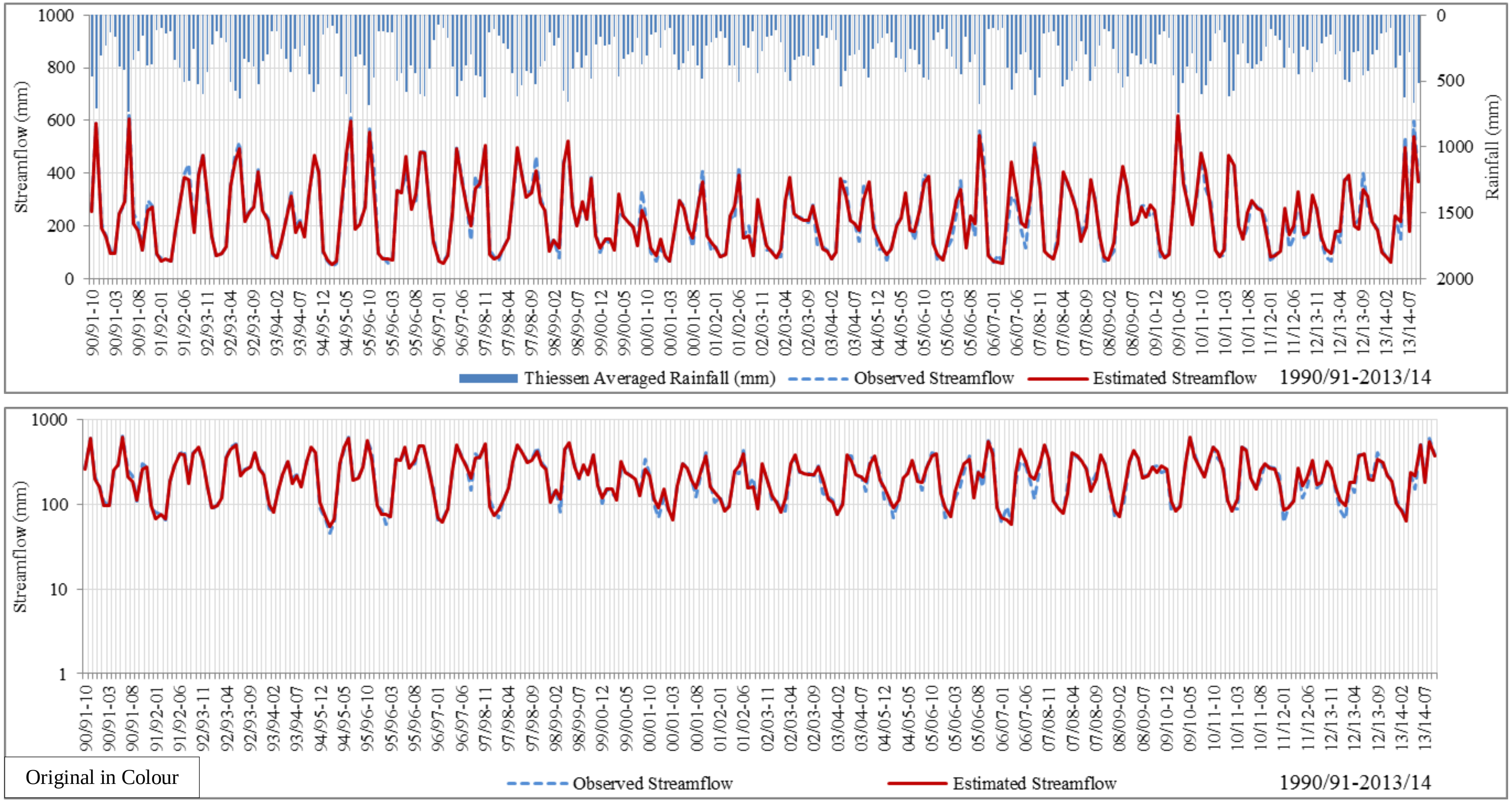


Figure 6-8: Outflow Hydrograph of Kelani Ganga from 1990-2014 (Normal & Logarithmic Plot)

6.2 Results for Gin Ganga

6.2.1 Calibration

6.2.1.1 Annual Water Balance

The comparisons of calculated and observed water balance for Gin Ganga are indicated in the Table 6-5 and Figure 6-9. Water balance comparison reflects the better performance during calibration where the matching of observed and calculated water balance is quite good with MRAE and Nash-Sutcliffe efficiency values of 0.081 and 0.955 respectively. Corresponding optimum parameter values of c and SC are 0.51 and 1322 respectively.

6.2.1.2 Flow Duration Curve

In order to carry out a detailed analysis of the behavior of model parameters, duration curves were divided into three regions as High Flow, Intermediate Flow and Low Flows. High flows were taken as the streamflow, which occurred for less than 35% of the time, and low flow was taken as flow, which occurred more than 70% of the time. The balance was identified as intermediate flow. MRAE and Nash-Sutcliffe efficiency was computed to identify the performance of optimized model parameters. The result (Table 6-6) indicated that optimized parameters provided a consistent performance. The optimized parameter c and SC is 0.51 and 1321.76 respectively. It was observed that the high flows are with a good matching having a MRAE of 0.064 and an E of 0.827. Medium flows were with MRAE of 0.059 and an E of 0.661 and low flows were with MRAE of 0.130 and an E of 0.473. The total flow had MRAE and E as 0.081 and 0.955 respectively. Flow Duration matching of Normal Plot and Logarithmic Plot is shown in the Figure 6-2 and Figure 6-3 respectively.

6.2.1.3 Outflow Hydrograph

The outflow hydrograph of observed and calculated streamflow corresponding to monthly Thiessen averaged rainfall for the calibration period is indicated in the Figure 6-12. The 20 years of calibration period was divided into 5 year interval each to clearly observe variation and patterns and are indicated in the Appendix-F.

Table 6-5: Annual Water Balance of Gin Ganga (1972-1992)

Year	Thiessen Averaged Rainfall (mm)	Observed Streamflow (mm)	Calculated Streamflow (mm)	Observed Water Balance (mm)	Calculated Water Balance (mm)
1972/73	4411	3175	3131	1237	1280
1973/74	4605	3152	3316	1452	1289
1974/75	3941	2671	2769	1271	1173
1975/76	4093	2983	2933	1111	1160
1976/77	4436	3263	3160	1173	1276
1977/78	4374	3175	3089	1199	1285
1978/79	4344	2987	3099	1356	1245
1979/80	4030	2742	2769	1287	1261
1980/81	4432	3212	3193	1220	1239
1981/82	4055	3013	2878	1042	1178
1982/83	3880	2763	2671	1117	1208
1983/84	4853	3585	3505	1268	1347
1984/85	4626	3538	3329	1088	1297
1985/86	4624	3185	3302	1440	1322
1986/87	3775	2799	2638	976	1137
1987/88	5000	3863	3649	1136	1350
1988/89	3978	2871	2830	1107	1148
1989/90	3860	2831	2688	1029	1172
1990/91	4134	2949	2931	1185	1202
1991/92	4024	2844	2842	1180	1182
Average	4274	3080	3036	1194	1238

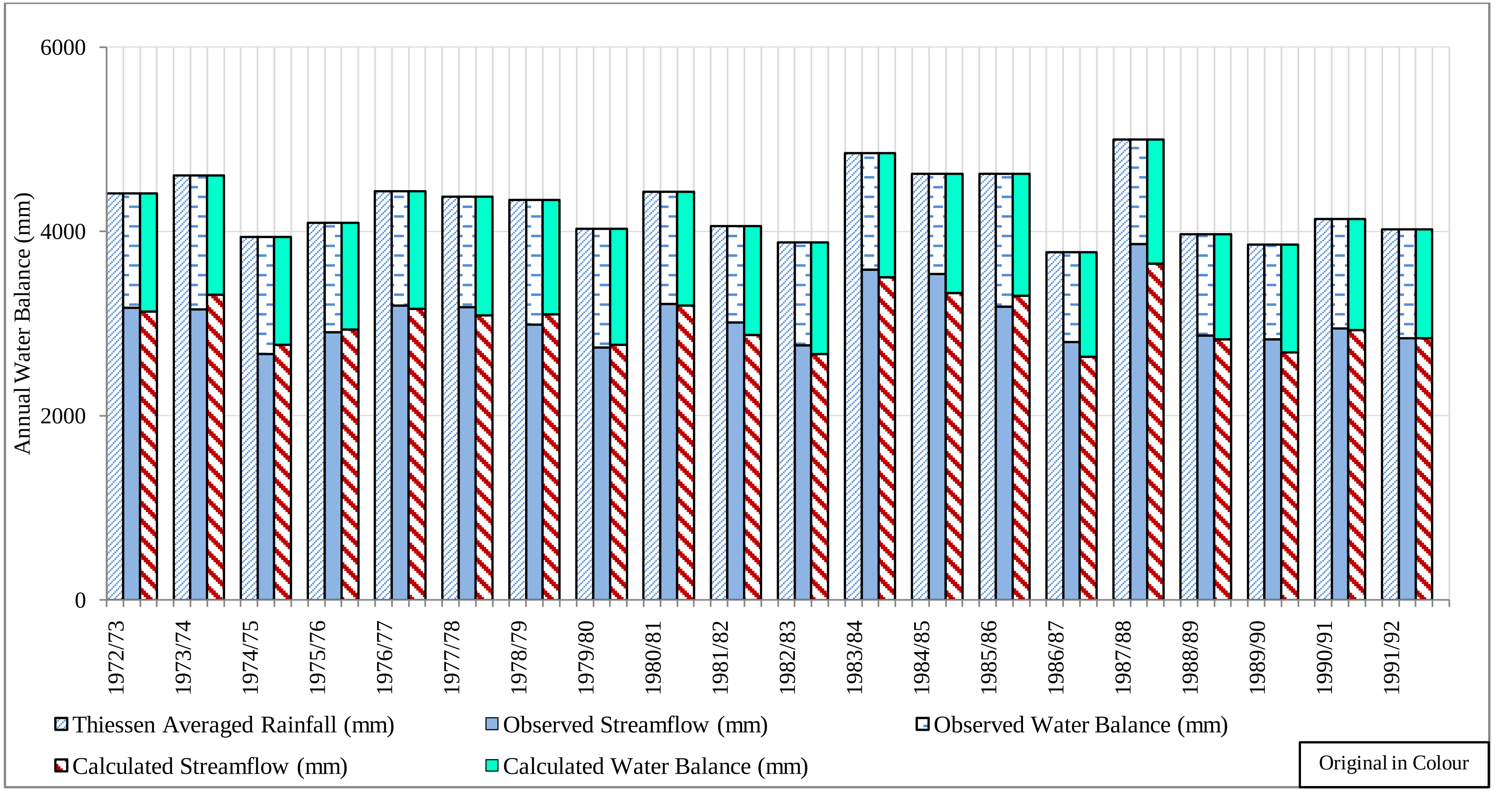


Figure 6-9: Annual Water Balance of Gin Ganga (1972-1992)

Table 6-6: Gin Ganga Parameter & Error Values of Flow (1972-1992)

Parameter		**Mean Ratio of Absolute Error (MRAE)**				**Nash-Sutcliffe efficiency (E)**			
c	SC (mm)	High Flow	Medium Flow	Low Flow	Total Flow	High Flow	Medium Flow	Low Flow	Total Flow
0.51	1322	0.064	0.059	0.130	0.081	0.827	0.661	0.473	0.955

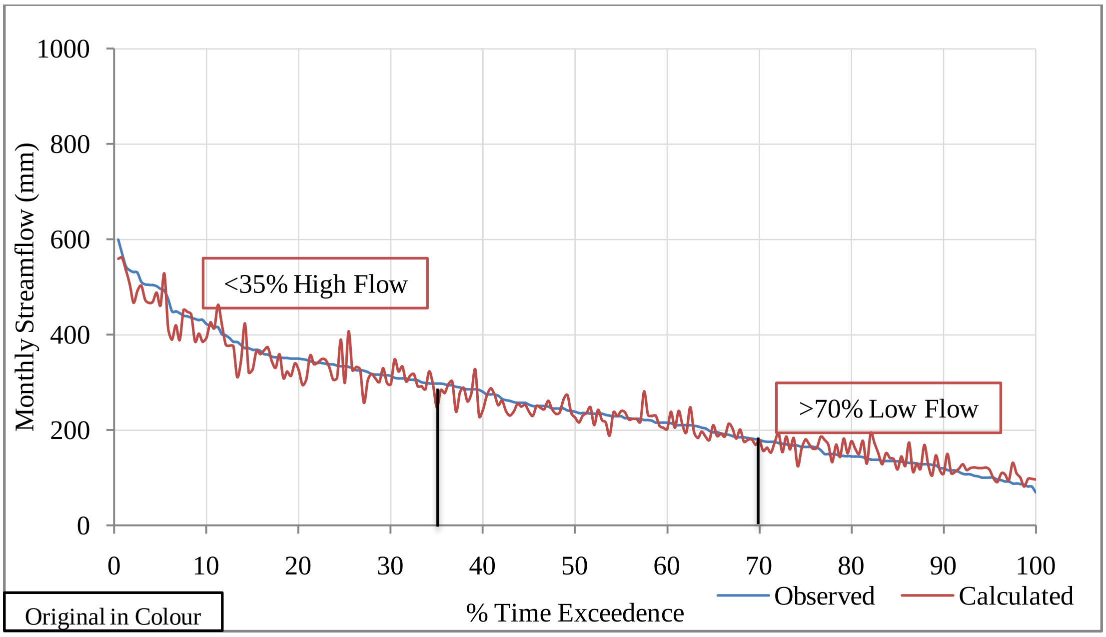


Figure 6-10: Flow Duration (Normal Plot) of Gin Ganga (1972-1992)

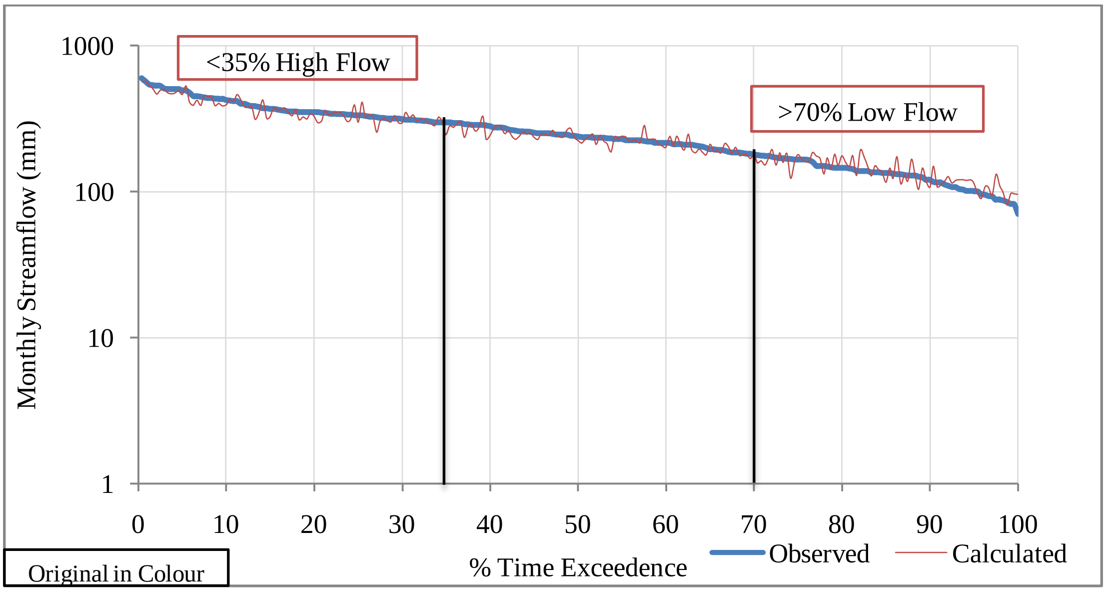


Figure 6-11: Flow Duration (Logarithmic Plot) of Gin Ganga (1972-1992)

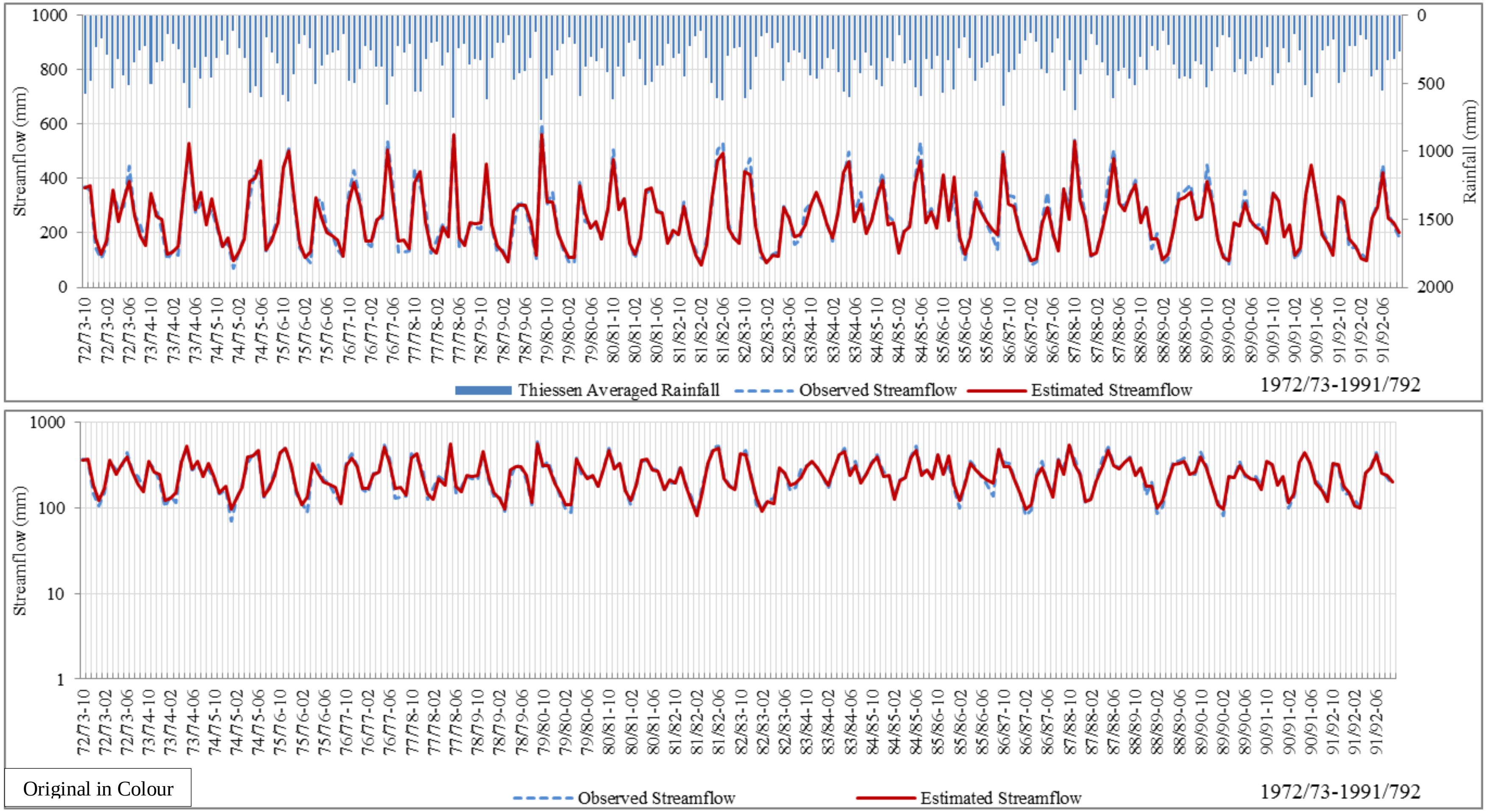


Figure 6-12: Outflow Hydrograph of Gin Ganga from 1972-1992 (Normal & Logarithmic Plot)

6.2.2 Verification

6.2.2.1 Annual Water Balance

The comparison of calculated and observed water balance for Gin Ganga are indicated in the Table 6-7 and Figure 6-13. Water balance comparison reflects a better performance during verification where the matching of observed and calculated water balance is quite good with MRAE and Nash-Sutcliffe efficiency value of 0.097 and 0.921 respectively. The corresponding optimum parameter c and SC values are 0.51 and 1322 respectively.

6.2.2.2 Flow Duration Curve

In order to carry out a detailed analysis of the behavior of model parameters, duration curves were divided into three regions as High Flow, Intermediate Flow and Low Flows. High flows were taken as the streamflow, which occurred for less than 35% of the time, and low flow was taken as flow, which occurred more than 70% of the time. The balance was identified as intermediate flow. MRAE and Nash-Sutcliffe efficiency was computed to identify the performance of optimized model parameters. The result (Table 6-8) indicated that optimized parameters provided a consistent performance. The optimized parameters c and SC are 0.51 and 1321.76 respectively. It was observed that the high flows are with a good matching having MRAE 0.098 and an E of 0.741 while medium flows were with MRAE of 0.078 and an E of 0.363 and low flows were with MRAE of 0.125 and an E of 0.738. The total flow had MRAE and E as 0.097 and 0.921 respectively. Flow Duration matching of Normal Plot and Logarithmic Plot is shown in the Figure 6-14 and Figure 6-15 respectively.

6.2.2.3 Outflow Hydrograph

The outflow hydrograph of observed and calculated streamflow corresponding to monthly Thiessen averaged rainfall for verification period is indicated in the Figure 6-16. The 20 years of calibration period was divided into 5 year interval each to clearly observe variation and patterns and are indicated in the Appendix-H.

Table 6-7: Annual Water Balance of Gin Ganga (1922-2012)

Year	Thiessen Averaged Rainfall (mm)	Observed Streamflow (mm)	Calculated Streamflow (mm)	Observed Water Balance (mm)	Calculated Water Balance (mm)
1992/93	4312	3168	3102	1143	1209
1993/94	4229	3106	3032	1123	1197
1994/95	4576	2964	3251	1612	1325
1995/96	3839	2610	2576	1229	1263
1996/97	3611	2648	2460	963	1151
1997/98	4371	3101	3071	1270	1301
1998/99	4686	3337	3341	1349	1345
1999/00	3834	2732	2682	1102	1151
2000/01	3306	2224	2211	1082	1095
2001/02	3175	2126	2168	1049	1007
2002/03	4390	3116	3113	1274	1277
2003/04	3778	2482	2591	1297	1187
2004/05	3619	2479	2501	1140	1118
2005/06	3769	2503	2617	1266	1153
2006/07	3598	2598	2487	1000	1111
2007/08	4619	3405	3393	1214	1226
2008/09	4090	2870	2822	1220	1268
2009/10	3982	2669	2786	1313	1197
2010/11	4234	2972	2996	1261	1237
2011/12	3597	2464	2447	1133	1150
Average	3981	2779	2782	1202	1198

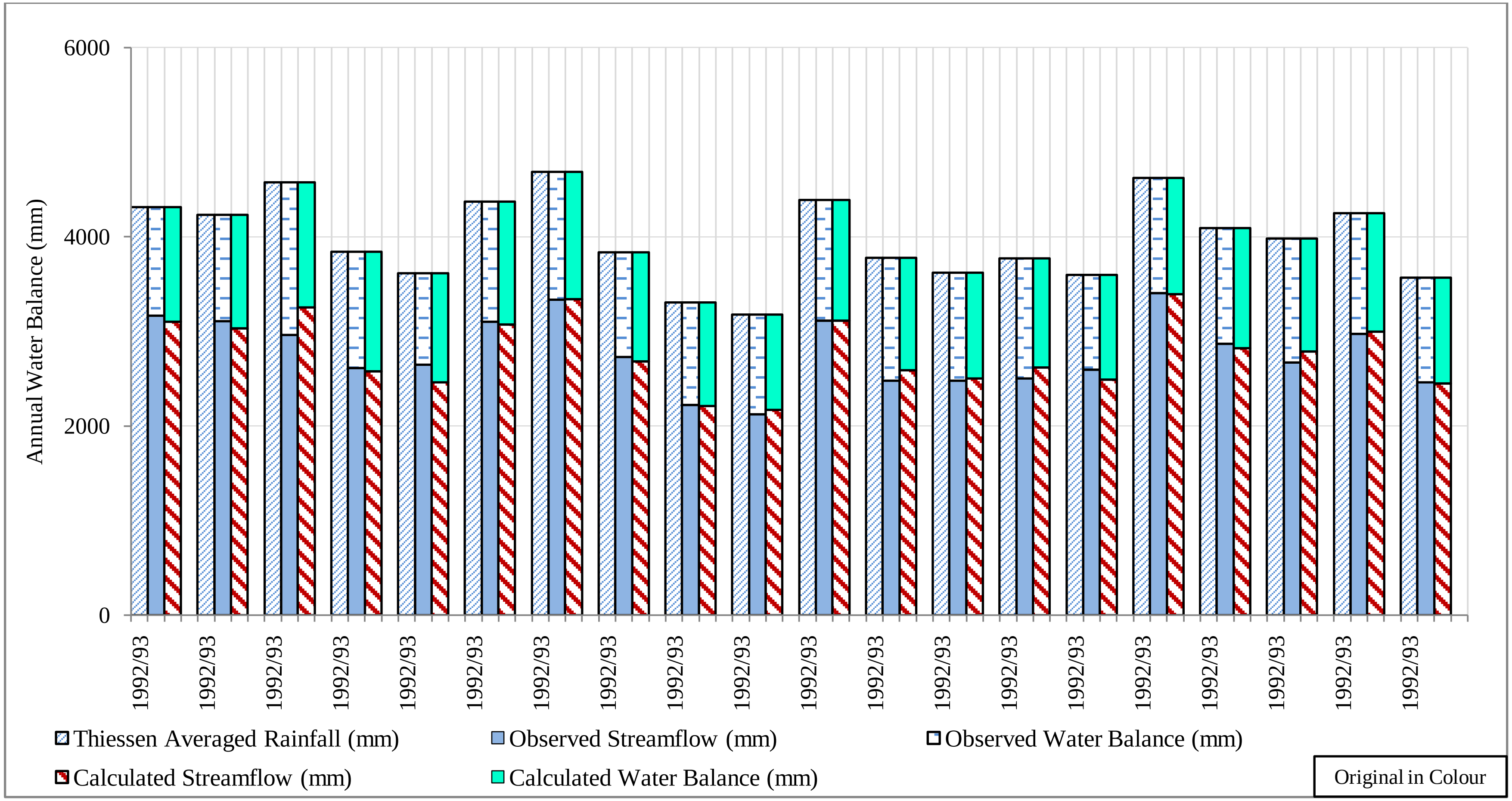


Figure 6-13: Annual Water Balance of Gin Ganga (1992-2012)

Table 6-8: Gin Ganga Parameter & Error Values of Flow (1992-2012)

Parameter		**Mean Ratio of Absolute Error (MRAE)**				**Nash-Sutcliffe efficiency (E)**			
c	SC (mm)	High Flow	Medium Flow	Low Flow	Total Flow	High Flow	Medium Flow	Low Flow	Total Flow
0.51	1322	0.098	0.081	0.121	0.097	0.745	0.416	0.765	0.921

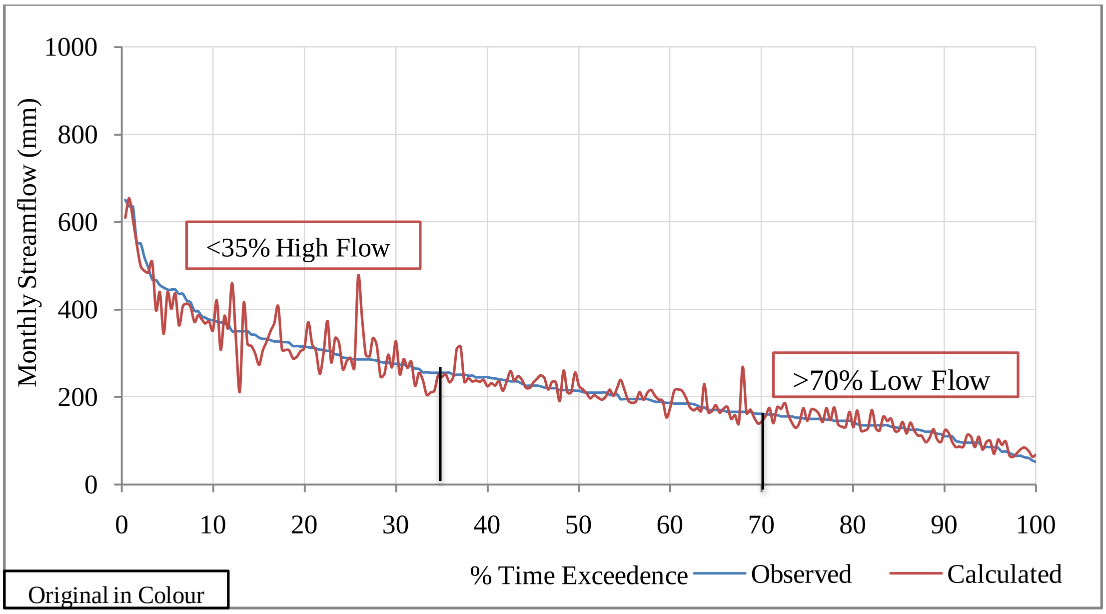


Figure 6-14: Flow Duration (Normal Plot) of Gin Ganga (1992-2012)

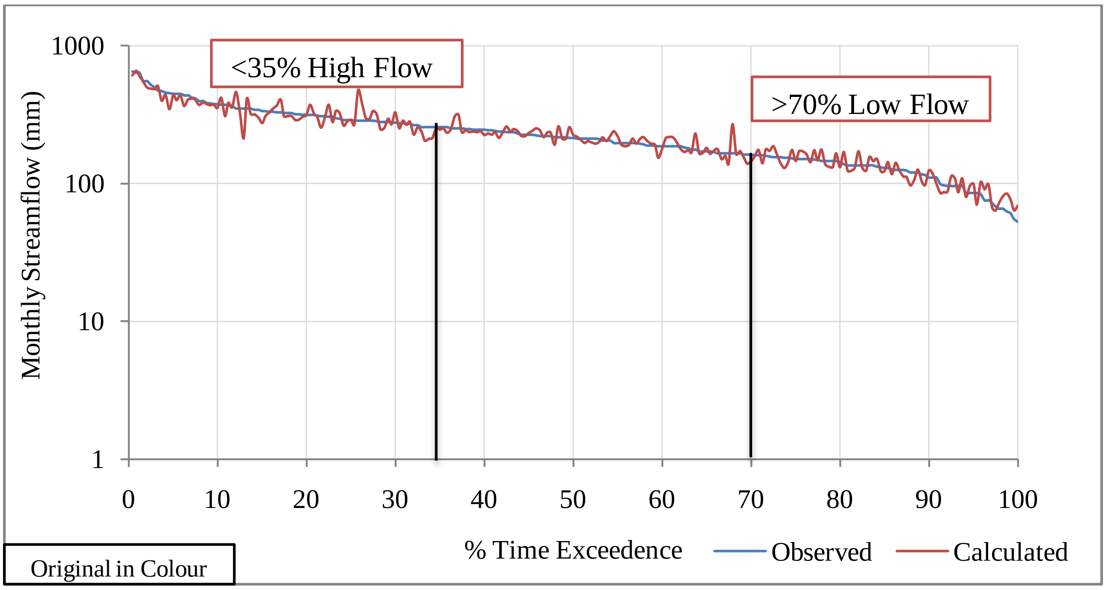


Figure 6-15: Flow Duration (Logarithmic Plot) of Gin Ganga (1992-2012)

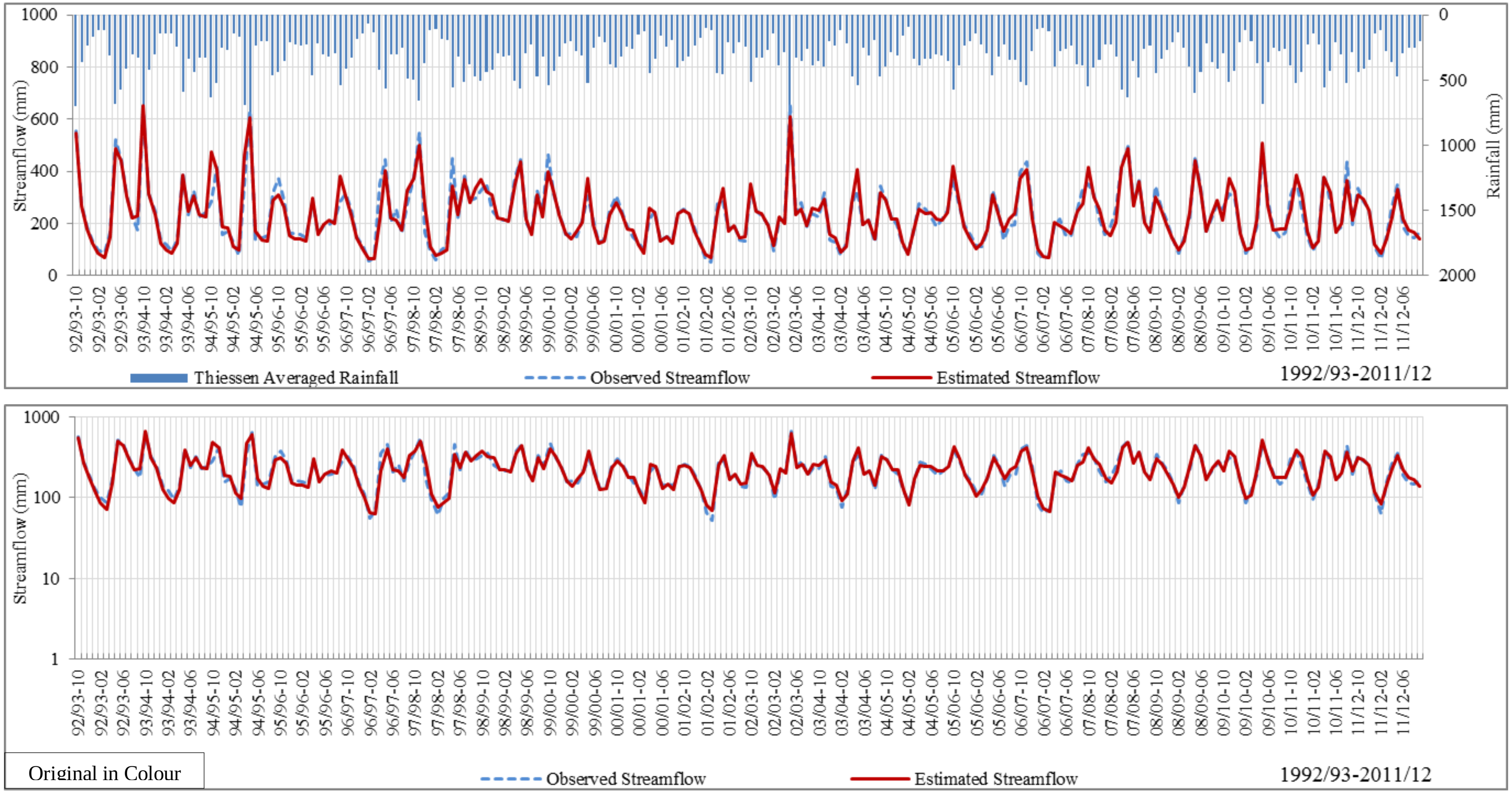


Figure 6-16: Outflow Hydrograph of Gin Ganga from 1992-2012 (Normal & Logarithmic Plot)

6.3 Summary Results

6.3.1 Thiessen Averaged Rainfall

Table 6-9: Annual Rainfall (mm/year)

Annual Rainfall (mm/year)		
	Kelani Ganga	Gin Ganga
Maximum	5281.096	4999.571
Minimum	220.500	3175.182
Average	2505.097	4127.276
Variability	4323906.019	173744.934
Trend	5611.176	4398.509
STDV	2079.400	416.827

Table 6-10: Monthly Rainfall (mm/month)

Monthly Rainfall (mm/month)		
	Kelani Ganga	**Gin Ganga**
Maximum	999.466	816.340
Minimum	68.939	70.927
Average	349.892	343.940
Variability	27035.807	20852.429
Trend	394.824	367.384
STDV	164.426	144.404

Table 6-11: Seasonal Rainfall (mm/season)

Seasonal Rainfall (mm/season)				
	Kelani Ganga		**Gin Ganga**	
	Yala	Maha	Yala	Maha
Maximum	3106.191	2631.744	2835.780	2304.184
Minimum	1865.301	1054.339	1786.444	1274.371
Average	2463.806	1734.894	2268.242	1859.034
Variability	116075.538	84540.882	73513.696	78585.042
Trend	2684.993	2049.049	2382.924	2015.585
STDV	340.699	290.759	271.134	280.330

6.3.2 Streamflow

Table 6-12: Annual Streamflow (mm/year)

Annual Streamflow (mm/year)		
	Kelani Ganga	**Gin Ganga**
Maximum	4041.852	3863.234
Minimum	98.924	2126.220
Average	1841.803	2929.343
Variability	2293681.445	132655.309
Trend	4117.316	3182.056
STDV	1514.490	364.219

Table 6-13: Monthly Streamflow (mm/month)

Monthly Streamflow (mm/month)		
	Kelani Ganga	**Gin Ganga**
Maximum	4611.587	650.500
Minimum	44.045	52.500
Average	493.964	244.112
Variability	771885.436	13003.062
Trend	203.723	266.028
STDV	878.570	114.031

Table 6-14: Seasonal Streamflow (mm/season)

Seasonal Streamflow (mm/season)				
	Kelani Ganga		**Gin Ganga**	
	Yala	Maha	Yala	Maha
Maximum	2371.377	1670.476	2239.553	1718.300
Minimum	1181.377	659.610	1116.000	915.661
Average	1815.666	1222.220	1610.304	1319.040
Variability	96669.396	46490.934	63658.591	48106.434
Trend	2071.088	1431.615	1749.775	1432.281
STDV	310.917	215.618	252.307	219.332

6.3.3 Pan Evaporation

Table 6-15: Annual Pan Evaporation (mm/year)

Annual Pan Evaporation (mm/year)		
	Kelani Ganga	**Gin Ganga**
Maximum	1560.970	1542.590
Minimum	1148.230	1166.403
Average	1321.008	1354.619
Variability	8247.513	6972.877
Trend	1392.070	1368.789
STDV	90.816	83.504

Table 6-16: Monthly Pan Evaporation (mm/month)

Monthly Pan Evaporation (mm/month)		
	Kelani Ganga	**Gin Ganga**
Maximum	176.700	192.200
Minimum	46.037	54.093
Average	110.084	112.885
Variability	347.153	376.874
Trend	115.966	114.052
STDV	18.632	19.413

Table 6-17: Seasonal Pan Evaporation (mm/season)

Seasonal Pan Evaporation (mm/season)				
	Kelani Ganga		**Gin Ganga**	
	Yala	Maha	Yala	Maha
Maximum	745.200	832.780	814.340	851.500
Minimum	589.430	520.386	581.275	528.654
Average	667.373	653.635	668.691	689.367
Variability	1875.403	4166.026	2032.288	4431.459
Trend	693.915	698.155	664.646	706.323
STDV	43.306	64.545	45.081	66.569

6.3.4 Soil Moisture (From the Model)

Table 6-18: Annual Soil Moisture (mm/year)

Annual Soil Moisture (mm/year)				
	Kelani Ganga		**Gin Ganga**	
	Calibration	Verification	Calibration	Verification
Maximum	2902.633	2885.852	4273.104	4249.089
Minimum	2723.665	2692.282	3993.955	3875.314
Average	2833.133	2810.105	4111.686	4035.023
Variability	1774.005	2735.064	6007.116	9180.882
Trend	2828.545	2783.560	4107.910	4001.600
STDV	42.119	52.298	77.506	95.817

Table 6-19: Monthly Soil Moisture (mm/month)

Monthly Soil Moisture (mm/month)				
	Kelani Ganga		**Gin Ganga**	
	Calibration	Verification	Calibration	Verification
Maximum	250.470	250.339	368.062	368.130
Minimum	157.764	180.439	265.827	243.960
Average	236.094	234.175	342.641	336.252
Variability	255.990	314.676	633.536	906.151
Trend	235.382	231.524	342.324	333.288
STDV	16.000	17.739	25.170	30.102

Table 6-20: Seasonal Soil Moisture (mm/season) (Calibration)

Seasonal Soil Moisture (mm/season)				
Calibration				
	Kelani Ganga		**Gin Ganga**	
	Yala	Maha	Yala	Maha
Maximum	1486.510	1452.922	2186.689	2132.600
Minimum	1368.381	1287.434	2020.390	1917.297
Average	1454.149	1378.984	2101.773	2009.914
Variability	770.839	1377.428	2008.215	3686.400
Trend	1441.907	1386.637	2085.272	2022.638
STDV	27.764	37.114	44.813	60.716

Table 6-21: Seasonal Soil Moisture (mm/season) (Verification)

Seasonal Soil Moisture (mm/season)				
Verification				
	Kelani Ganga		**Gin Ganga**	
	Yala	Maha	Yala	Maha
Maximum	1488.798	1522.485	2126.388	2133.124
Minimum	1420.343	1237.052	1987.338	1801.044
Average	1461.032	1359.401	2074.604	1960.419
Variability	330.371	3246.327	1671.569	6443.617
Trend	1455.783	1354.216	2071.643	1929.957
STDV	18.176	56.977	40.885	80.272

6.3.5 Actual Evaporation (From the Model)

Table 6-22: Annual Actual Evaporation (mm/year)

Annual Actual Evaporation (mm/year)				
	Kelani Ganga		**Gin Ganga**	
	Calibration	Verification	Calibration	Verification
Maximum	674.915	612.490	742.055	748.576
Minimum	527.751	517.288	609.359	590.152
Average	596.780	555.917	667.372	651.680
Variability	1417.575	651.028	846.491	1577.936
Trend	602.213	572.488	669.270	657.508
STDV	37.651	25.515	29.095	39.723

Table 6-23: Monthly Actual Evaporation (mm/month)

Monthly Actual Evaporation (mm/month)				
	Kelani Ganga		**Gin Ganga**	
	Calibration	Verification	Calibration	Verification
Maximum	75.575	66.053	84.698	75.642
Minimum	21.177	27.634	36.720	27.588
Average	49.732	46.326	55.614	54.307
Variability	74.204	47.339	76.884	61.282
Trend	50.016	47.533	55.783	54.634
STDV	8.614	6.880	8.768	7.828

Table 6-24: Seasonal Actual Evaporation (mm/season) (Calibration)

Seasonal Actual Evaporation (mm/season)				
Calibration				
	Kelani Ganga		**Gin Ganga**	
	Yala	Maha	Yala	Maha
Maximum	339.579	346.086	361.827	397.244
Minimum	270.565	222.409	300.223	284.480
Average	310.007	286.772	332.182	335.190
Variability	314.731	765.209	310.543	570.942
Trend	310.063	292.149	328.659	340.611
STDV	17.741	27.662	17.622	23.894

Table 6-25: Seasonal Actual Evaporation (mm/season) (Verification)

Seasonal Actual Evaporation (mm/season)				
Verification				
	Kelani Ganga		**Gin Ganga**	
	Yala	Maha	Yala	Maha
Maximum	333.020	315.726	362.595	386.411
Minimum	273.101	237.704	294.242	245.487
Average	297.952	259.856	336.844	314.836
Variability	331.361	352.411	357.471	886.577
Trend	313.954	263.376	347.234	310.273
STDV	18.203	18.773	18.907	29.775

6.3.6 Annual Water Balance

Table 6-26: Annual Water Balance (mm/year)

Annual Water Balance (mm/year)		
	Kelani Ganga	**Gin Ganga**
Maximum	1609.826	1612.403
Minimum	898.022	963.192
Average	1160.814	1197.933
Variability	18959.489	18047.138
Trend	1231.339	1216.453
STDV	137.693	134.340

6.3.7 Parameter Optimization

Table 6-27: Comparison of Optimized Parameters

Parameters	**Kelani Ganga**	**Gin Ganga**
c	0.460	0.510
SC	899.475 mm	1321.758 mm

Table 6-28: Comparison of Error Estimations

		Kelani Ganga		**Gin Ganga**	
		Calibration	Verification	Calibration	Verification
Mean Ratio of Absolute Error (MRAE)	Entire Data	0.084	0.089	0.081	0.097
	High Flow	0.056	0.055	0.064	0.098
	Intermediate Flow	0.070	0.063	0.059	0.078
	Low Flow	0.107	0.127	0.130	0.125
Nash Sutcliffe Coeff. (E)	Entire Data	0.977	0.977	0.955	0.921
	High Flow	0.887	0.909	0.827	0.741
	Intermediate Flow	0.833	0.816	0.661	0.363
	Low Flow	0.756	0.684	0.473	0.738

7 DISCUSSION

7.1 Discussion of Summary Results

7.1.1 Thiessen Averaged Rainfall

Thiessen averaged rainfall for both Kelani Ganga and Gin Ganga basins in monthly, annual and seasonal are presented in Table 6-9, Table 6-10 and Table 6-11 respectively. For better understanding and analysis the statistics of Maximum, Minimum, Average, Variability, Trend and Standard Deviation were computed and presented. Kelani Ganga and Gin Ganga basins are located in the wet zone with an average annual rainfall recorded with 2505 mm/year and 4127 mm/year respectively, an average monthly rainfall recorded with 350 mm/month and 344 mm/month respectively and an average seasonal rainfall recorded high for Yala season with 2464 mm/season and 2268 mm/season and while low for Maha season with 1735 mm/season and 1859 mm/season respectively. It was observed that in both the catchments there is a decreasing trend in MAR with 1.5% Mean since 1980s owing to the reduced in SWM rainfall. The seasonal comparison indicated that Inter-seasonal rainfall variation is high during Yala season compared to Maha season. This is mainly because of heavy rainfall during Yala season due to south west monsoon from the Bay of Bengal.

7.1.2 Streamflow

Streamflow for both Kelani Ganga and Gin Ganga basins in monthly, annual and seasonal are presented in Table 6-12, Table 6-13 and Table 6-14 respectively. Kelani Ganga and Gin Ganga basins are located in the wet zone with an average annual streamflow recorded with 1842 mm/year and 2929 mm/year respectively, an average monthly streamflow recorded with 494 mm/month and 244 mm/month respectively and an average seasonal streamflow recorded high for Yala season with 1816 mm/season and 1610 mm/season and while low for Maha season with 1222 mm/season and 1319 mm/season respectively.

7.1.3 Pan Evaporation

Pan Evaporation for both Kelani Ganga and Gin Ganga basins in monthly, annual and seasonal are presented in Table 6-15, Table 6-16 and Table 6-17 respectively. For Kelani Ganga and Gin Ganga basins an average annual pan evaporation was recorded with 1321 mm/year and 1355 mm/year and an average monthly pan evaporation recorded with 110 mm/month and 113 mm/month respectively. In Kelani Ganga basin an average seasonal pan evaporation recorded high for Yala season with 667 mm/season and while low for Maha season with 653 mm/season. Whereas in Gin Ganga basin an average seasonal pan evaporation recorded low for Yala season with 669 mm/season and while high for Maha season with 689 mm/season. The reason could be due to the altitude differences and types of land-use area. In both the catchments, variation in monthly pan evaporation is small because the temperature remains relatively constant throughout the year in Sri Lanka.

Monthly, annual and seasonal comparison of rainfall, streamflow and pan evaporation has indicated that April through September has experienced as much as 55 % of the mean while October through March has experienced as much as 45 % of the mean.

7.1.4 Soil Moisture Content

Soil Moisture Content obtained from the Model for both Kelani Ganga and Gin Ganga basins in monthly, annual and seasonal are presented in Table 6-18, Table 6-19 and Table 6-20 (Calibration) & Table 6-21 (Verification) respectively. For Kelani Ganga basin an average annual soil moisture content was recorded with 2833 mm/year during calibration period and 2810 mm/year during verification period, an average monthly soil moisture content was recorded with 236 mm/month during calibration period and 234 mm/month during verification period and an average seasonal soil moisture content was recorded with 1454 mm/season (Yala) & 1379 mm/season (Maha) during calibration period and 1461 mm/season (Yala) & 1359 mm/season (Maha) during verification period. Similarly, for Gin Ganga basin an average annual soil moisture content was recorded with 4112 mm/year during calibration period and 4035 mm/year during verification period, an average monthly soil moisture content was recorded with 343 mm/month during calibration period and

336 mm/month during verification period and an average seasonal soil moisture content was recorded with 2102 mm/season (Yala) & 2010 mm/season (Maha) during calibration period and 2075 mm/season (Yala) & 1960 mm/season (Maha) during verification period. It was observed that soil moisture content is higher during Yala season than Maha season in both the basins. It is mainly due to south west monsoon from the Bay of Bengal.

7.1.5 Actual Evaporation

Actual Evaporation obtained from the Model for both Kelani Ganga and Gin Ganga basins in monthly, annual and seasonal are presented in Table 6-22, Table 6-23 and Table 6-24 (Calibration) & Table 6-25 (Verification) respectively. For Kelani Ganga basin an average annual actual evaporation was recorded with 597 mm/year during calibration period and 556 mm/year during verification period, an average monthly actual evaporation was recorded with 50 mm/month during calibration period and 46 mm/month during verification period and an average seasonal actual evaporation was recorded with 310 mm/season (Yala) & 287 mm/season (Maha) during calibration period and 298 mm/season (Yala) & 260 mm/season (Maha) during verification period. Similarly, for Gin Ganga basin an average annual actual evaporation was recorded with 667 mm/year during calibration period and 652 mm/year during verification period, an average monthly actual evaporation was recorded with 56 mm/month during calibration period and 54 mm/month during verification period and an average seasonal actual evaporation was recorded with 332 mm/season (Yala) & 335 mm/season (Maha) during calibration period and 337 mm/season (Yala) & 315 mm/season (Maha) during verification period.

7.1.6 Annual water balance

Annual water balance for both Kelani Ganga and Gin Ganga basins are presented in Table 6-26. Annual water balance observed for Kelani Ganga basin with maximum of 1610 mm/year, minimum of 898 mm/year and with an average of 1160 mm/year. Similarly, for Gin Ganga basin annual water balance with maximum of 1610 mm/year, minimum of 963 mm/year and with an average of 1197 mm/year.

7.1.7 Parameter Optimization

The parameter c range is taken from 0.10-1.0 and SC from 200-3500 mm as recommended in the literatures. The optimum value of the two parameters are obtained using MRAE as the objective function. The optimized parameters c & SC values obtained for Kelani Ganga and Gin Ganga basins are well within the range recommended by literatures as indicated in the Table 6-27. For Kelani Ganga the parameters c & SC values are 0.460 and 899.475 mm respectively and for Gin Ganga the parameters c & SC values are 0.510 and 1321.758 mm respectively. The parameters c is very sensitive, and small changes may cause large changes in the simulated results while parameter SC is very robust and insensitive to the initial values of the parameters.

Model calibration for Kelani Ganga and Gin Ganga basins reveals the better performance where the matching of observed and calculated streamflow is very good as presented in Table 6-28. In Kelani Ganga basin the MRAE value of the entire dataset, high flow, intermediate flow and low flow are 0.084, 0.056, 0.070 and 0.107 respectively and Nash-Sutcliffe efficiency value of the entire dataset, high flow, intermediate flow and low flow are 0.977, 0.887, 0.833 and 0.756 respectively. Similarly, in Gin Ganga basin the MRAE value of the entire dataset, high flow, intermediate flow and low flow are 0.097, 0.098, 0.078 and 0.125 respectively and Nash-Sutcliffe efficiency value of the entire dataset, high flow, intermediate flow and low flow are 0.921, 0.741, 0.363 and 0.738 respectively.

Verification of the Model was found to be satisfactory for both Kelani Ganga and Gin Ganga basins as presented in Table 6-28. In Kelani Ganga basin the MRAE value of the entire dataset, high flow, intermediate flow and low flow are 0.089, 0.055, 0.063 and 0.127 respectively and Nash-Sutcliffe efficiency value of the entire dataset, high flow, intermediate flow and low flow are 0.977, 0.909, 0.816 and 0.684 respectively. Similarly, in Gin Ganga basin the MRAE value of the entire dataset, high flow, intermediate flow and low flow are 0.081, 0.064, 0.059 and 0.130 respectively and Nash-Sutcliffe efficiency value of the entire dataset, high flow, intermediate flow and low flow are 0.955, 0.827, 0.661 and 0.471 respectively.

It was observed that the validation period errors were higher than those obtained for Calibration period. However, Outflow Hydrograph plots revealed the good matching with the error indicators reflected within an acceptable values.

7.2 Model Performance

Model perform very well for both Kelani Ganga and Gin Ganga basin with monthly hydroclimatological datasets which are most readily available with an average MRAE 0.088 and Nash-Sutcliffe efficiency 0.957. Monthly precipitation and evaporation seem to be sufficient for evaluation of climate change impacts on the streamflow.

The two parameter monthly water balance model have proven to be a valuable tool not only for assessing the hydrologic characteristics of diverse watersheds but also for evaluating the hydrologic consequences of climatic change. For practical reasons the monthly water balance model can be used for the purposes of planning water resources and predicting the effects of climatic change, the monthly variation of discharges may be sufficient.

It appears that two parameters may be sufficient to reproduce most of the information in a hydrological record on a monthly scale in humid regions. Since monthly water balance models require fewer parameters to explain hydrological phenomena, the information contained per parameter is then increased, which permits a more accurate determination of parameters and more reliable correlations between parameter values and catchment characteristics. Consequently, applicability to ungauged catchments is another important advantage of such models.

7.3 Modelling Difficulties

Models are a simplification of reality, so it is necessary to build assumptions into the model. Therefore, modelling is one of the most difficult task and time consuming beginning from the data collection and checking, model development and data inputting to simulations. Data collection and checking is challenging and its requires lot of time and effort to make sure that the data resolutions are sufficient, relevant and uniform in order to use for model simulations. It is difficult to assume an initial values during data input. For instance in order get an initial value of S(t-1) i.e., Water content at the end of the $(t-1)^{th}$ month, warming up period for five years needs to carry out in order get the stable initial value. Parameter optimization is also very difficult since the parameters c is very sensitive, and small changes may cause large changes in the simulated results while parameter SC is very robust and insensitive to the initial values of the parameters. Moreover, model development is complex process and the complexity of each process representation is constrained by observations, computational resources and knowledge. Thus model development requires vast knowledge, experiences and skills.

8 CONCLUSION & RECOMMENDATION

8.1 Conclusion

1. TPMWB model was successfully calibrated and verified for Kelani Ganga & Gin Ganga watershed showing that average values of 0.485 and 1110.50 mm for parameter c & SC respectively could simulate monthly streamflow with average MRAE 0.088 and average Nash-Sutcliffe efficiency 0.957.
2. The optimum parameter values determined for Kelani Ganga & Gin Ganga is; c value 0.460 and 0.510 and SC value 899.48 mm and 1321.758 mm respectively.
3. For its simplicity and high efficiency of performance, the TPMWB model has proven to be valuable tool not only for assessing the hydrologic characteristics of diverse watersheds but also for evaluating the hydrologic consequences of climate change in case of Kelani Ganga and Gin Ganga in Sri Lanka.

8.2 Recommendation

- The two-parameter monthly water balance model proposed in the article has proved to be quite efficient in simulating the monthly runoff with the simple structure and two parameters. Therefore, this model is highly recommended where monthly hydro-climatological data are most readily available.
- For just simulating the monthly runoff this two-parameter water balance model is highly recommended to incorporate in the water resources planning program.
- The model is not applicable if there are large water bodies such as lakes or reservoir in the upstream of catchment.
- In the case of conceptual model development and validation exercise, parameter optimization using realistic conditions and suitable objective function is necessary and highly recommended.
- It is advisable and recommended to use optimized c (0.40-0.50) and SC (800-1400) for runoff simulation in an ungauged watershed having similar watershed characteristics.
- It is also recommended to have more data for calibration and verification for more accuracy of model predictions of results.

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APPENDIX-A

DATA CHECKING KELANI GANGA

APPENDIX A: DATA CHECKING KELANI GANGA

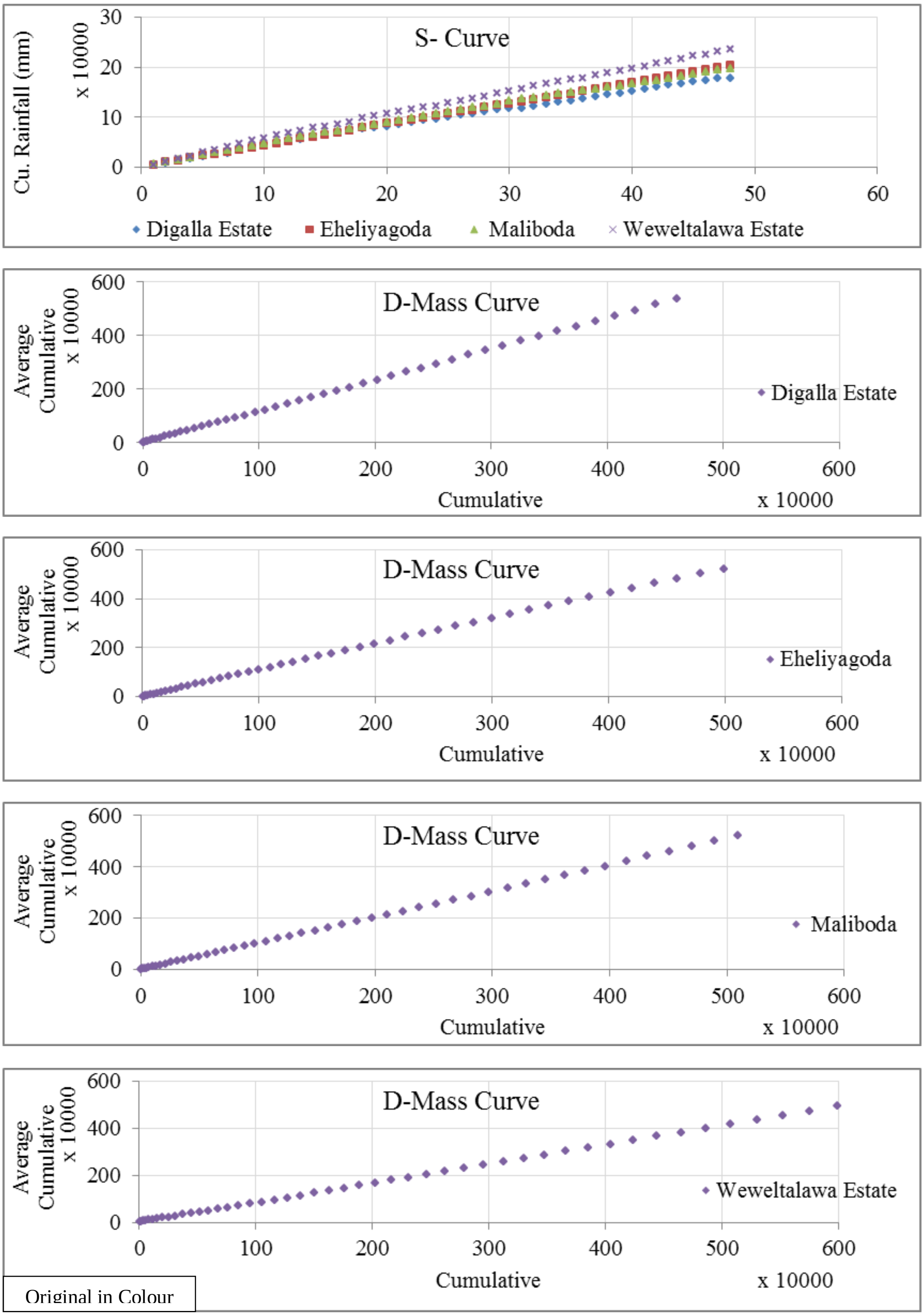


Figure A- 1: S-Curve & D-Mass Curve Analysis for Kelani Ganga (1966-2014)

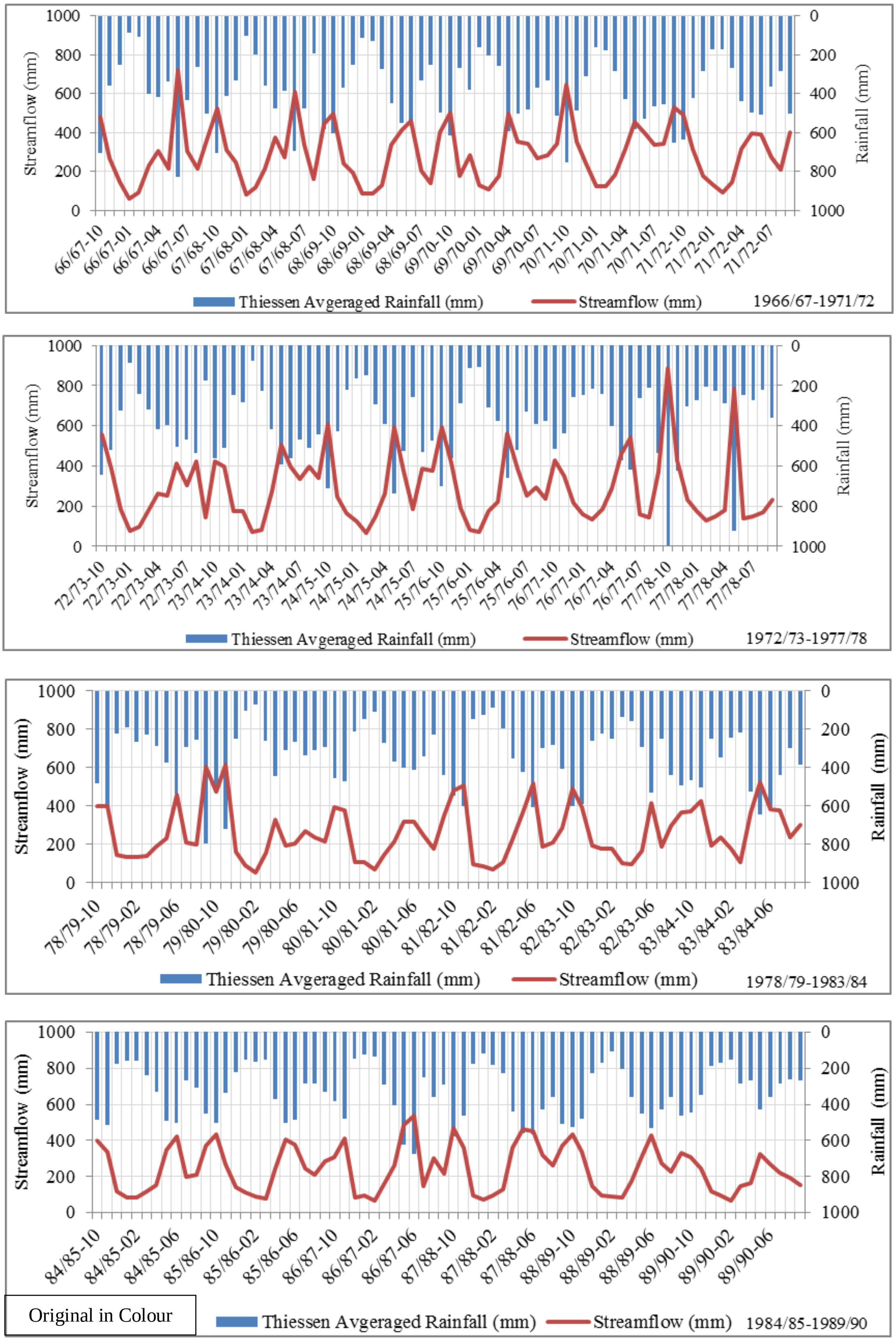


Figure A- 2: Streamflow Corresponding Monthly Rainfall for Kelani Ganga (1966-1990)

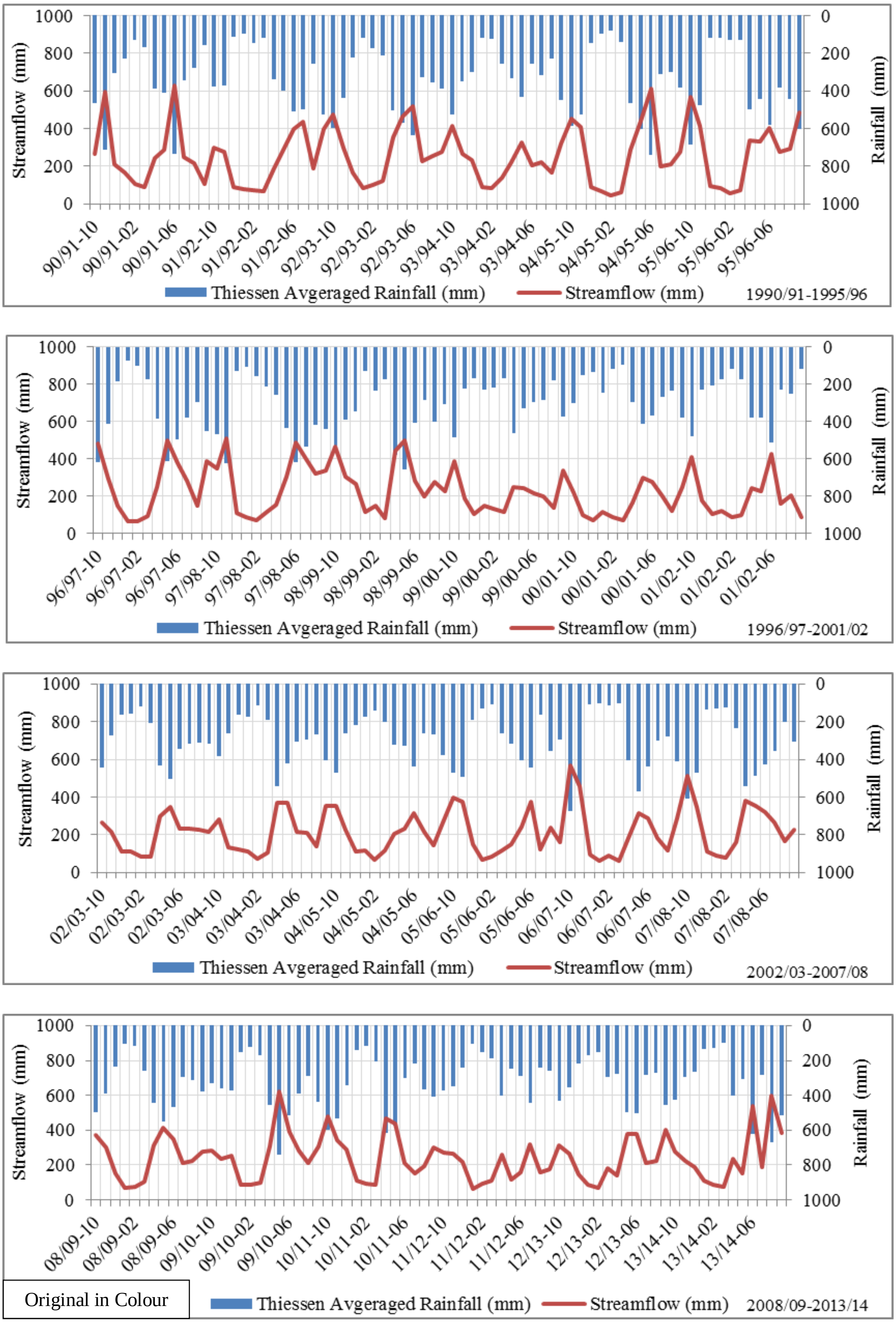


Figure A- 3: Streamflow Corresponding Monthly Rainfall for Kelani Ganga (1991-2014)

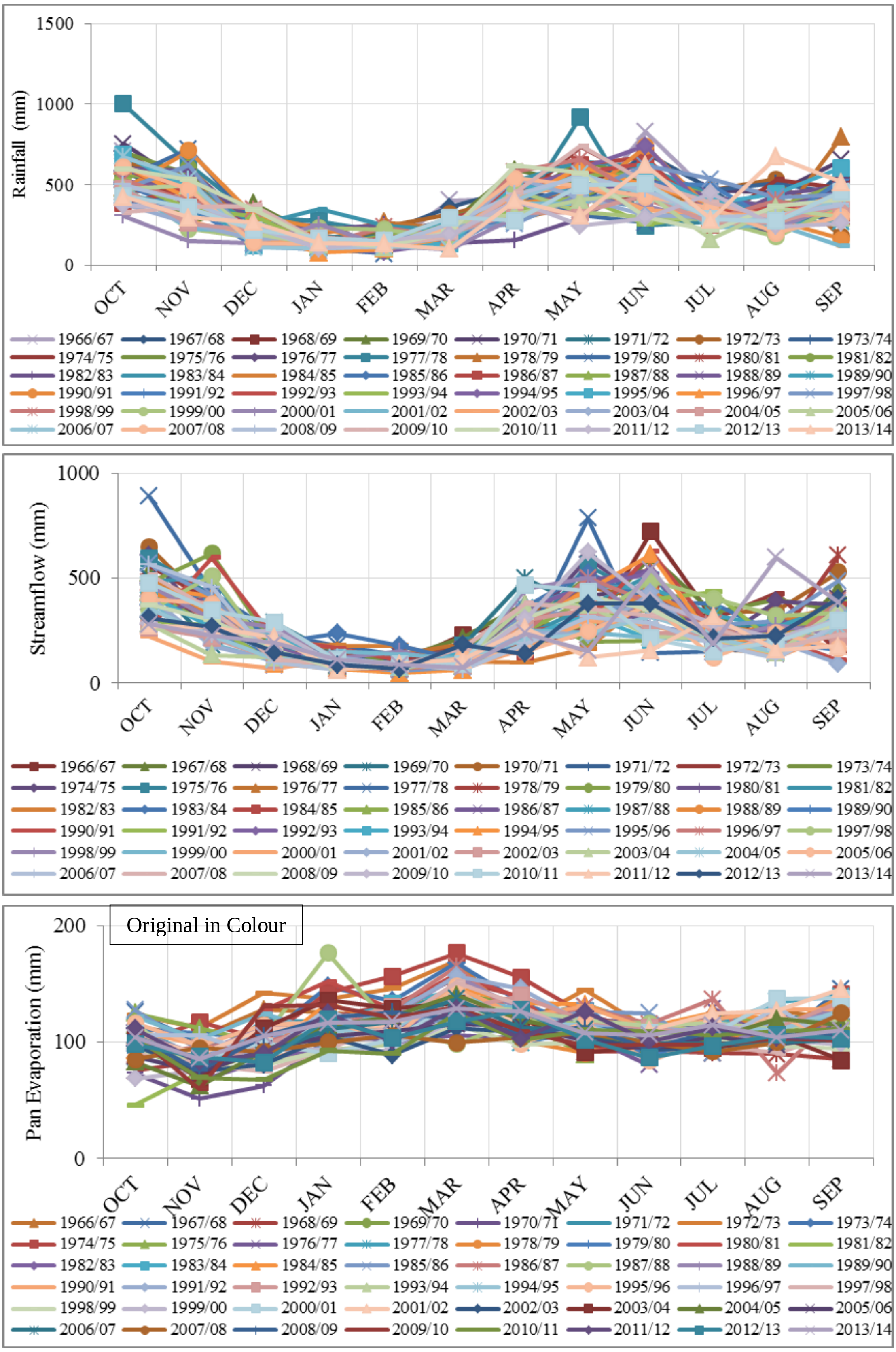


Figure A- 4: Monthly Rainfall, Streamflow and Evaporation for Kelani Ganga (1966-2014)

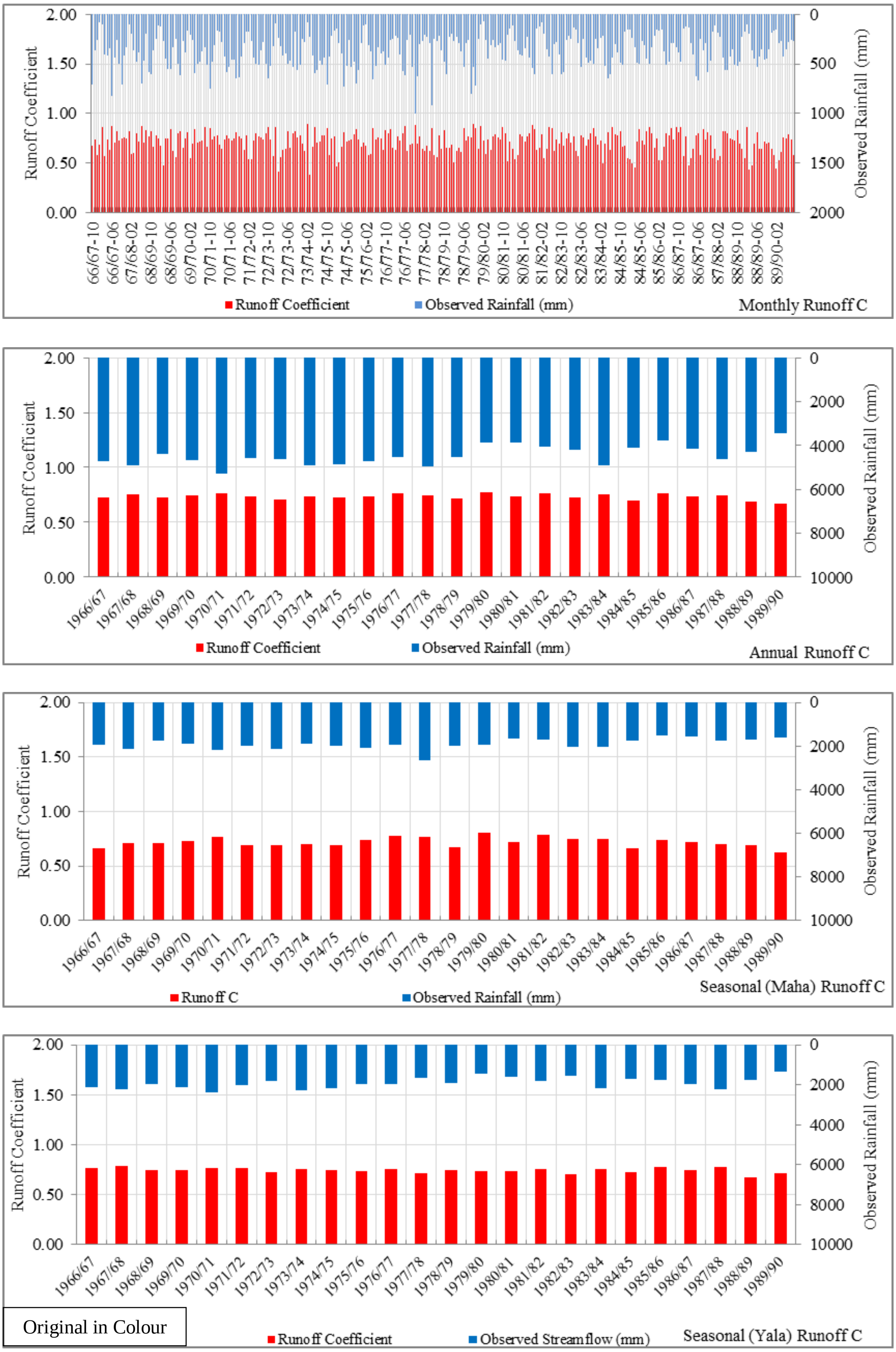


Figure A- 5: Monthly, Annual & Seasonal Runoff Coefficient for Kelani Ganga (1966-1990)

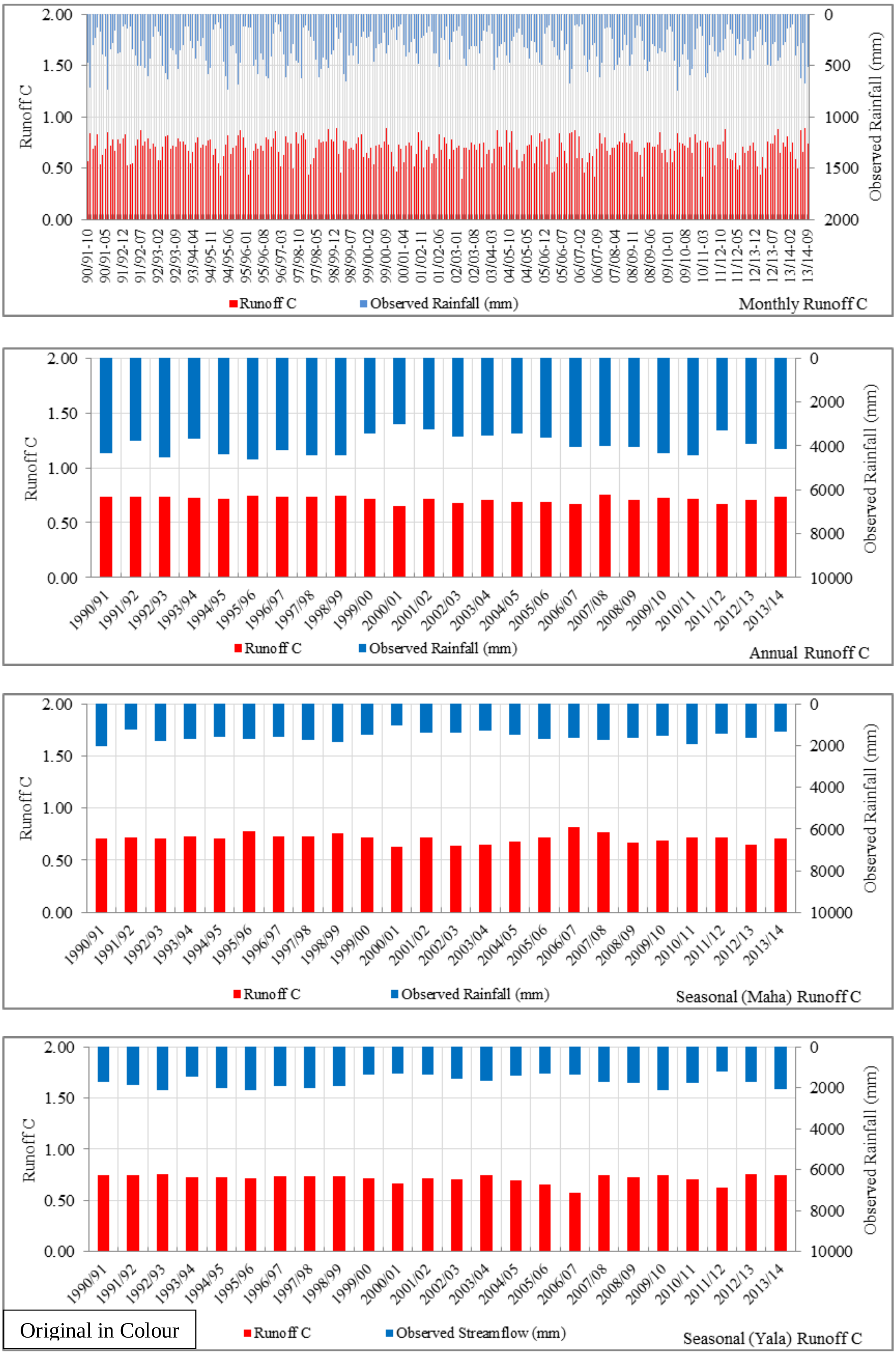


Figure A- 6: Monthly, Annual & Seasonal Runoff Coefficient for Kelani Ganga1990-2014

Table A- 1: Parameter Optimization using MRAE for Kelani Ganga

c/SC	0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90	1.00
255	0.307	0.227	0.170	0.146	0.154	0.192	0.251	0.322	0.391	0.457
538	0.304	0.216	0.147	0.113	0.118	0.163	0.230	0.300	0.369	0.434
705	0.319	0.224	0.144	0.096	0.099	0.142	0.210	0.281	0.350	0.415
818	0.332	0.236	0.149	0.093	0.090	0.131	0.196	0.268	0.337	0.402
990	0.353	0.256	0.166	0.099	0.088	0.119	0.179	0.248	0.317	0.383
1148	0.373	0.276	0.186	0.115	0.093	0.116	0.166	0.232	0.300	0.366
1389	0.403	0.306	0.215	0.146	0.113	0.122	0.158	0.213	0.278	0.343
1820	0.454	0.356	0.267	0.200	0.159	0.149	0.165	0.202	0.253	0.311
2384	0.511	0.413	0.327	0.261	0.215	0.192	0.190	0.209	0.244	0.291
3123	0.573	0.476	0.392	0.326	0.275	0.243	0.229	0.233	0.252	0.284

Table A- 2: Parameter Optimization using Nash-Sutcliffe efficiency for Kelani Ganga

c/SC	0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90	1.00
255	0.676	0.816	0.901	0.937	0.927	0.878	0.792	0.676	0.532	0.366
538	0.678	0.823	0.913	0.953	0.949	0.904	0.824	0.712	0.573	0.411
705	0.683	0.829	0.921	0.963	0.961	0.918	0.840	0.730	0.593	0.432
818	0.683	0.830	0.924	0.967	0.966	0.924	0.847	0.738	0.602	0.442
990	0.677	0.826	0.921	0.967	0.967	0.928	0.852	0.745	0.611	0.453
1148	0.665	0.817	0.914	0.961	0.964	0.926	0.853	0.747	0.615	0.458
1389	0.640	0.795	0.895	0.946	0.952	0.918	0.847	0.745	0.615	0.461
1820	0.581	0.743	0.850	0.908	0.920	0.891	0.827	0.730	0.605	0.456
2384	0.495	0.667	0.783	0.850	0.870	0.849	0.792	0.702	0.583	0.440
3123	0.387	0.571	0.698	0.775	0.805	0.794	0.745	0.663	0.552	0.415

Table A- 3: Best Sets of Optimized Parameters for Kelani Ganga

Parameter	c	SC
1	0.46	990.00
2	0.46	895.50
3	0.46	899.475

APPENDIX-B

DATA CHECKING GIN GANGA

APPENDIX-B: DATA CHECKING GIN GANGA

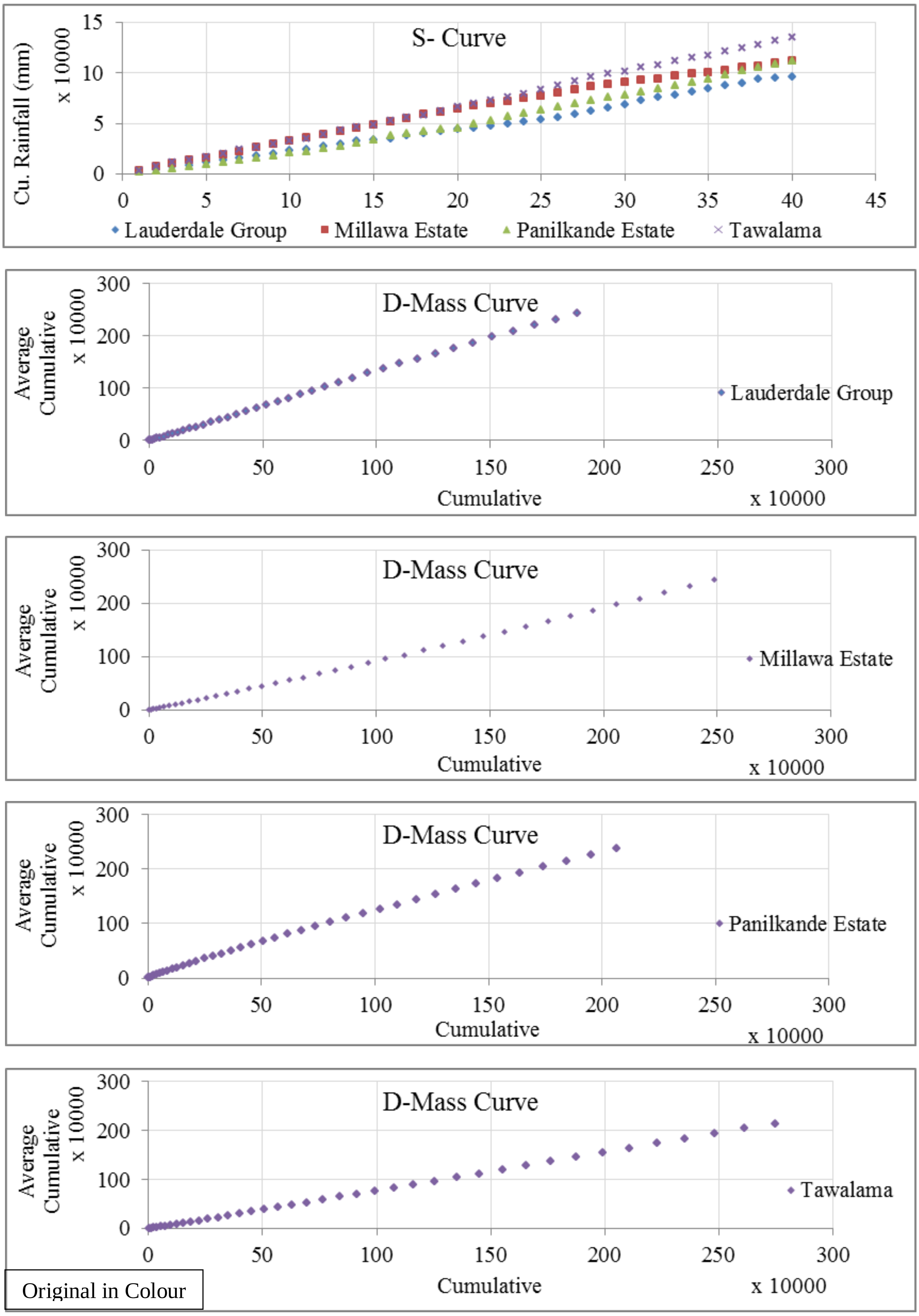


Figure B- 1: S-Curve & D-Mass Curve Analysis for Gin Ganga (1972-2012)

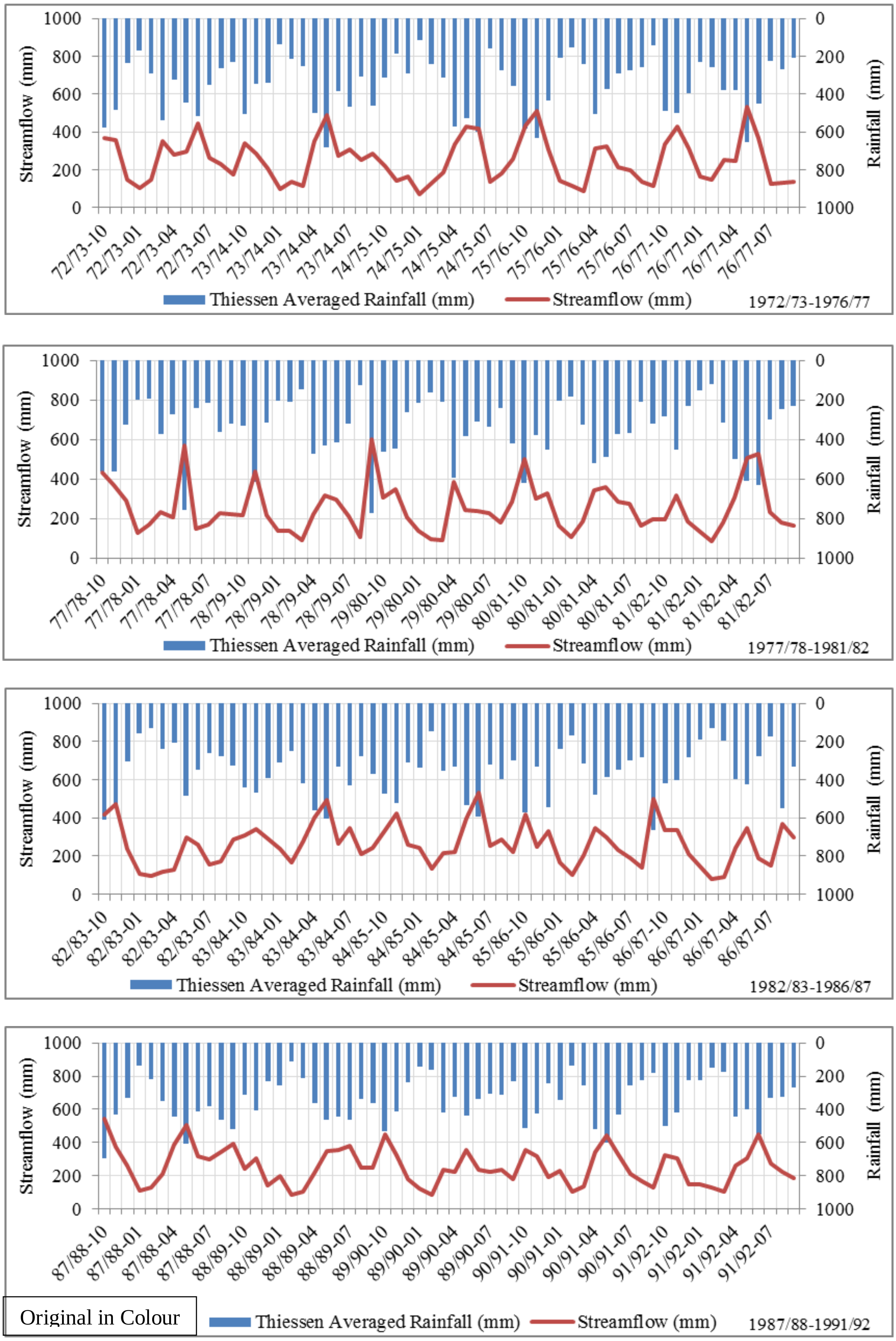


Figure B- 2: Streamflow Corresponding Monthly Rainfall for Gin Ganga (1972-1992)

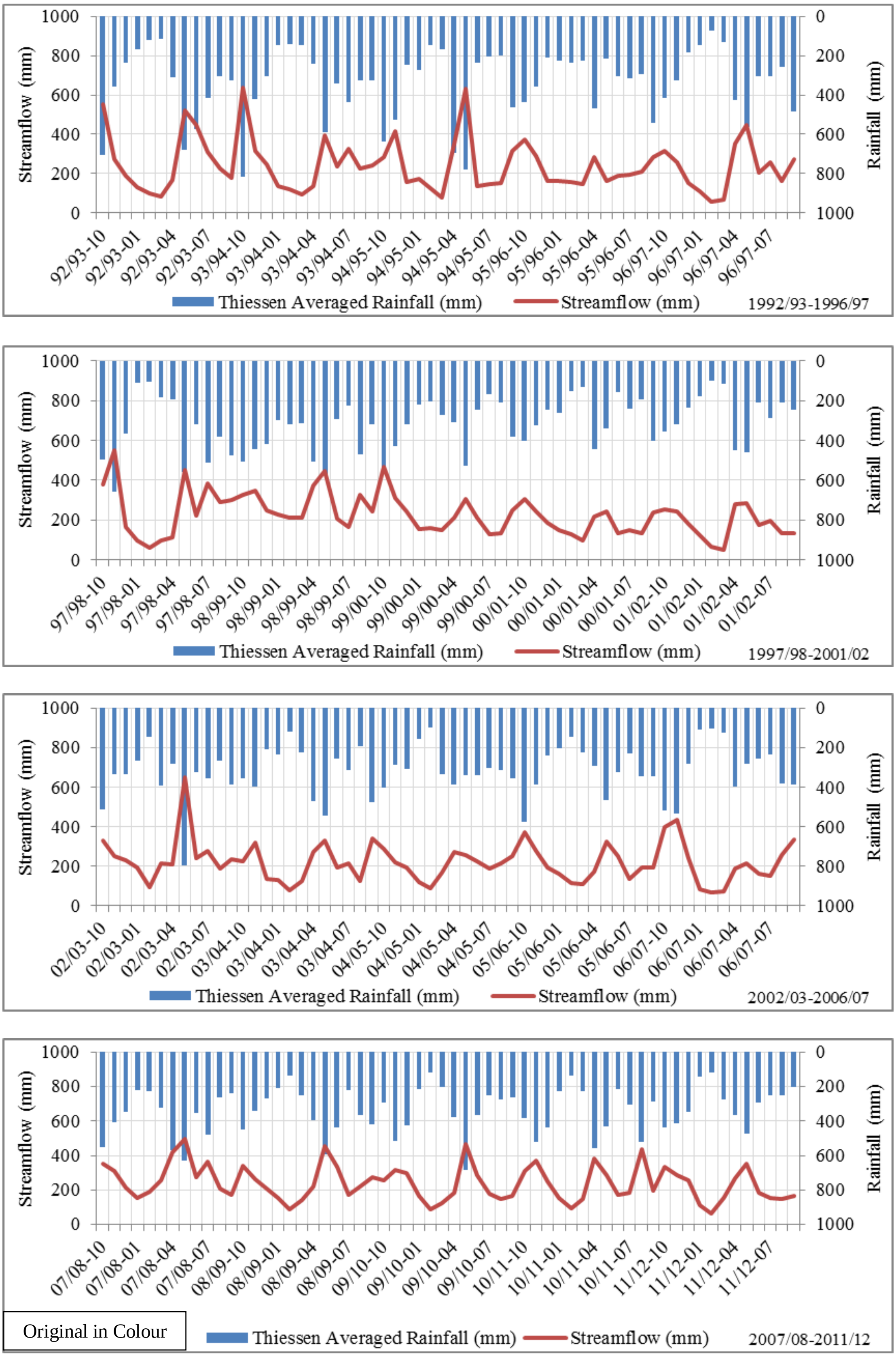


Figure B- 3: Streamflow Corresponding Monthly Rainfall for Gin Ganga (1992-2012)

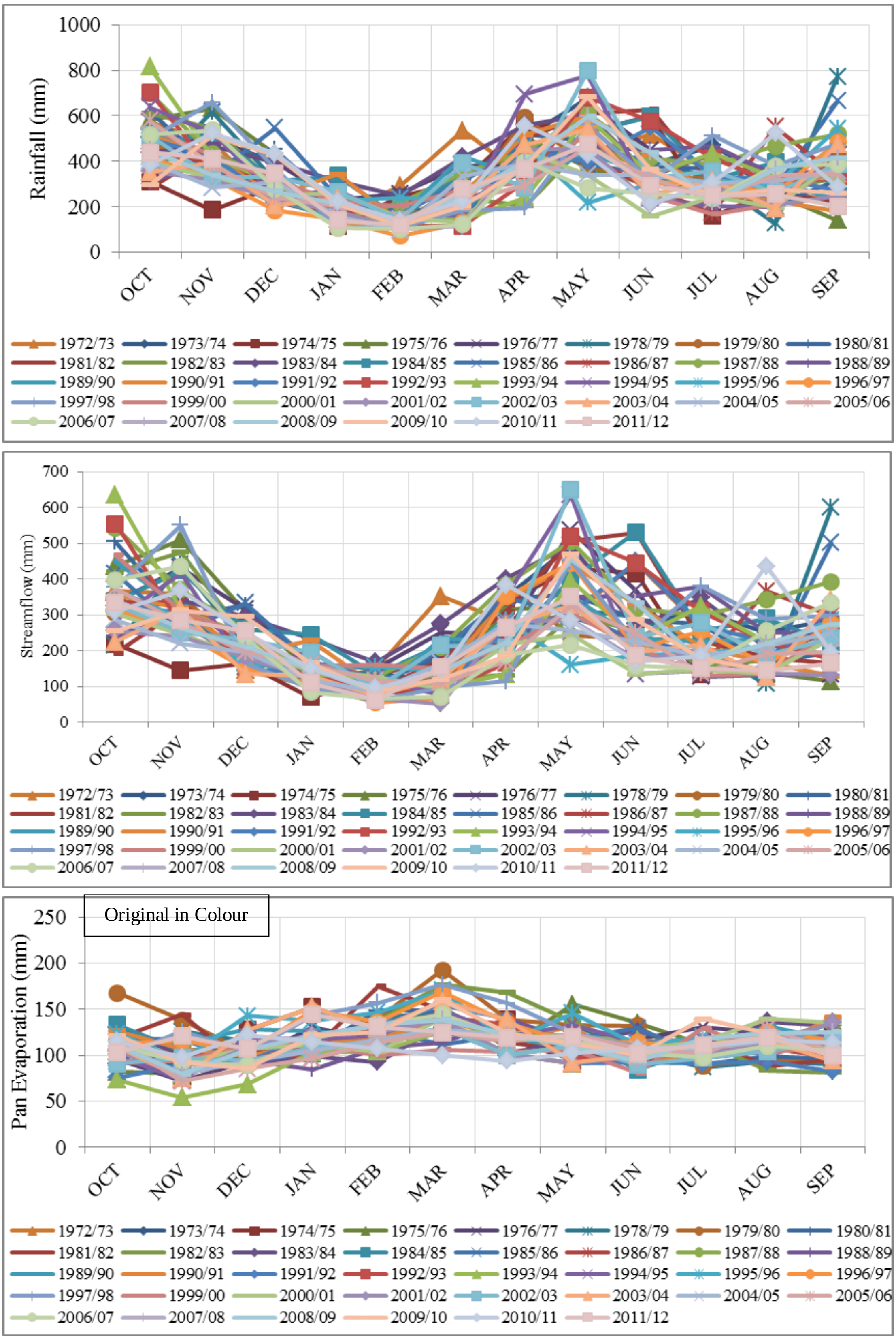


Figure B- 4: Monthly Rainfall, Streamflow and Evaporation for Gin Ganga (1972-2012)

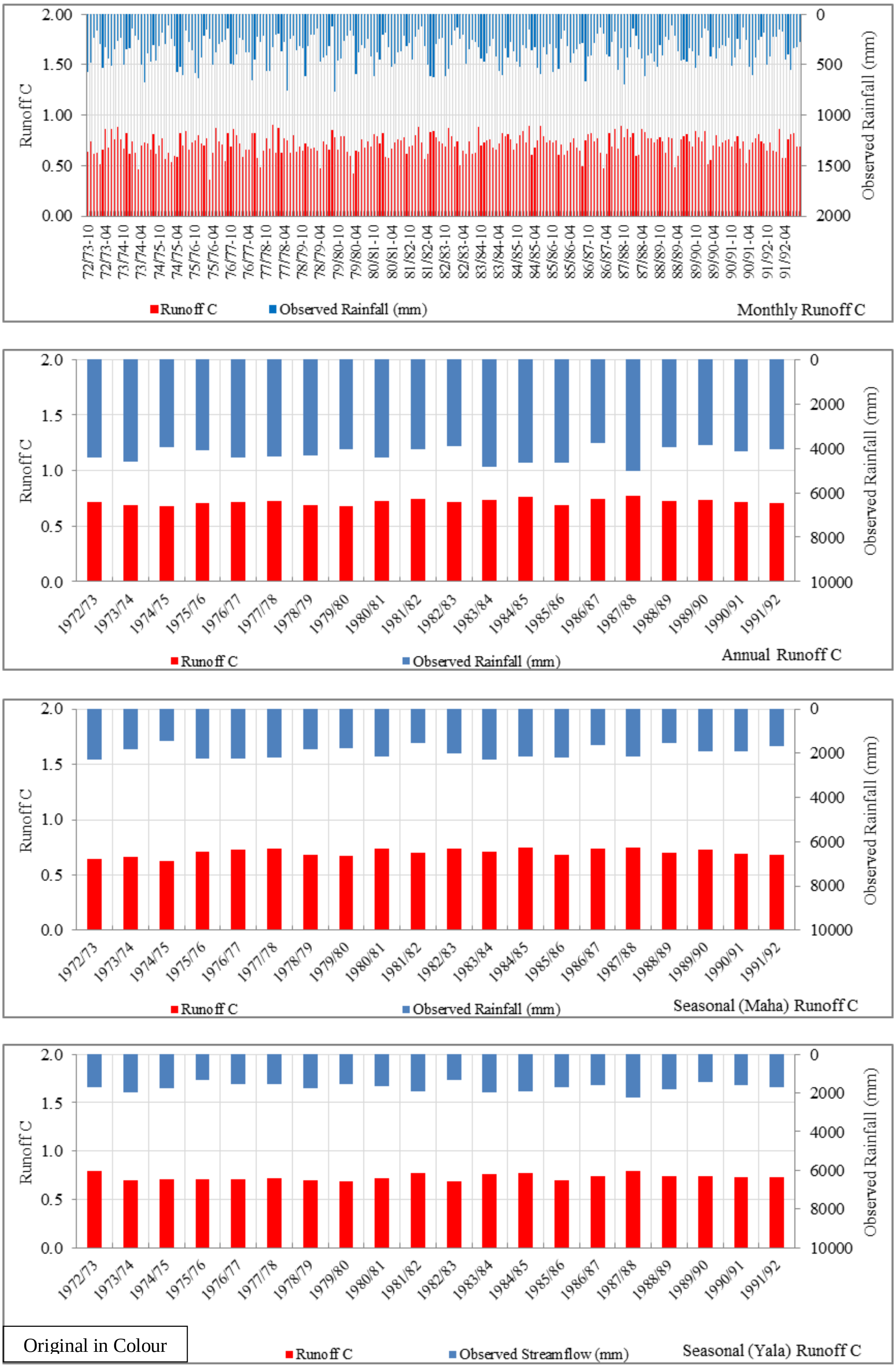


Figure B- 5: Monthly, Annual & Seasonal Runoff Coefficient for Gin Ganga (1972-1992)

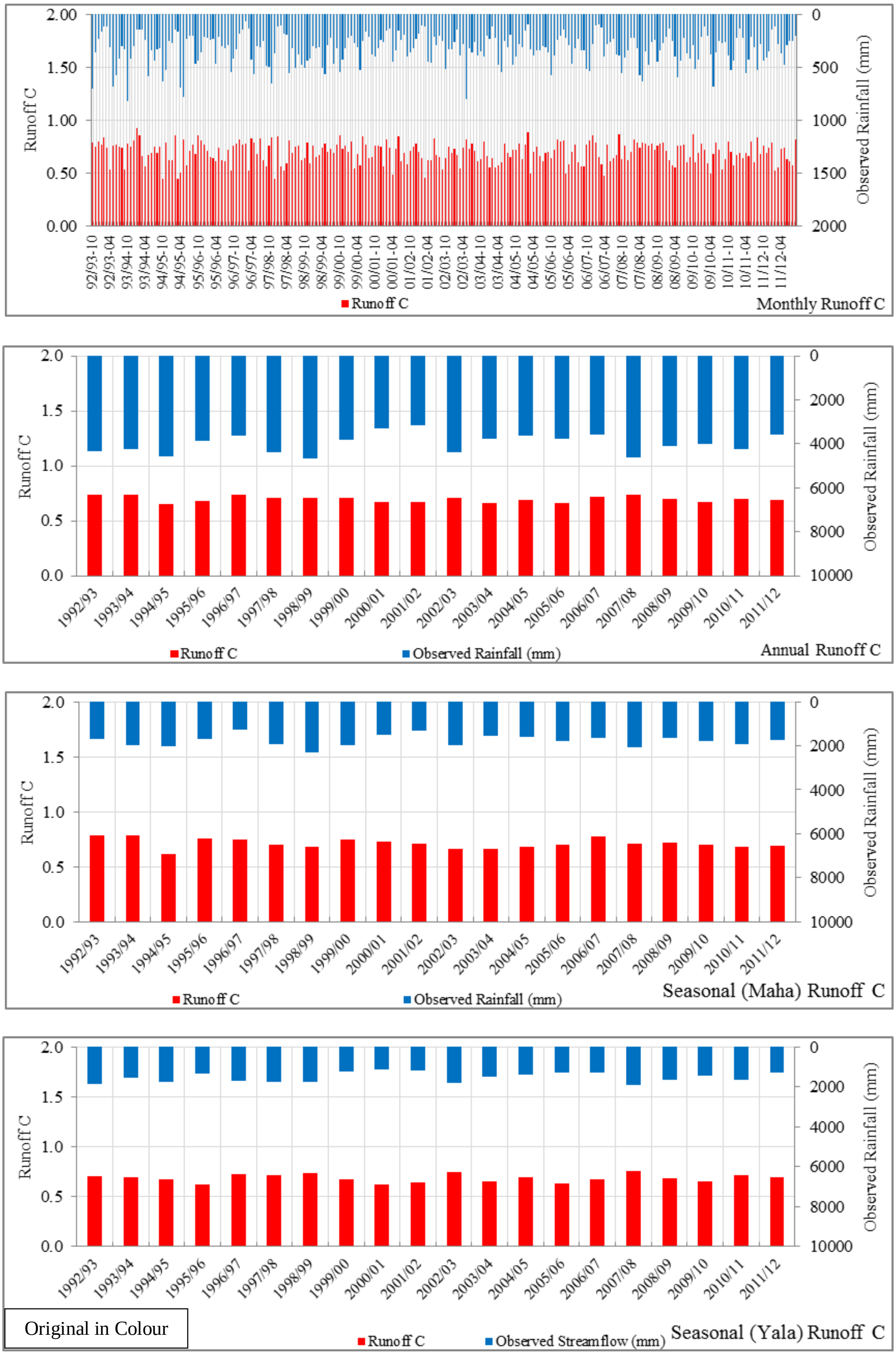


Figure B- 6: Monthly, Annual & Seasonal Runoff Coefficient for Gin Ganga 1992-2012

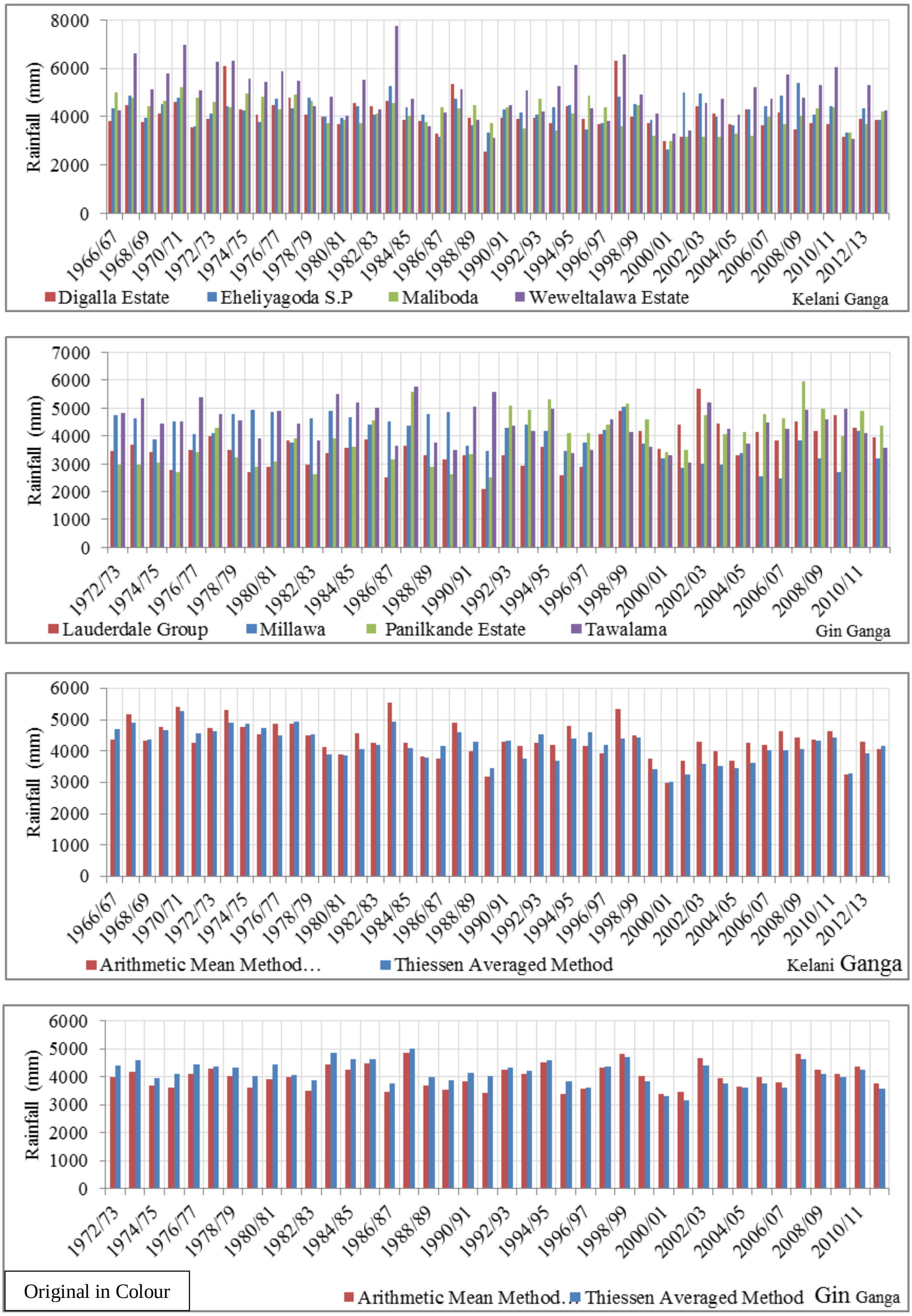


Figure B- 7: Variability of rainfall station wise and Total Rainfall by Thiessen Average and Arithmetic Mean Method for Kelani Ganga & Gin Ganga.

Table B- 1: Parameter Optimization using MRAE for Gin Ganga

c/SC	0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90	1.00
411	0.3316	0.2400	0.1878	0.1636	0.1693	0.1948	0.2427	0.3042	0.3698	0.4329
703	0.3236	0.2560	0.1664	0.1263	0.1189	0.1497	0.2065	0.2732	0.3399	0.4044
850	0.3360	0.2438	0.1846	0.1145	0.1005	0.1299	0.1903	0.2579	0.3256	0.3910
1114	0.3612	0.2655	0.1786	0.1273	0.0835	0.1079	0.1657	0.2338	0.3033	0.3695
1292	0.3776	0.2811	0.1922	0.1169	0.0971	0.1027	0.1541	0.2200	0.2897	0.3565
1434	0.3900	0.2933	0.2033	0.1258	0.0849	0.1120	0.1472	0.2108	0.2797	0.3469
1839	0.4223	0.3254	0.2347	0.1564	0.1103	0.1080	0.1424	0.1929	0.2564	0.3231
2409	0.4616	0.3642	0.2739	0.1984	0.1509	0.1318	0.1440	0.1829	0.2374	0.2982
3156	0.5022	0.4042	0.3173	0.2452	0.1951	0.1664	0.1618	0.1848	0.2261	0.2804
4450	0.5539	0.4576	0.3733	0.3044	0.2506	0.2138	0.1970	0.2017	0.2273	0.2673

Table B- 2: Parameter Optimization using Nash-Sutcliffe efficiency for Gin Ganga

c/SC	0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90	1.00
411	0.11	0.526	0.697	0.791	0.813	0.7725	0.676	0.529	0.341	0.116
703	0.33	0.48	0.771	0.867	0.892	0.8533	0.758	0.613	0.424	0.199
850	0.37	0.627	0.71	0.898	0.922	0.8831	0.787	0.642	0.453	0.227
1114	0.39	0.654	0.829	0.87	0.950	0.9114	0.816	0.670	0.482	0.256
1292	0.39	0.656	0.832	0.929	0.92	0.9174	0.823	0.678	0.490	0.265
1434	0.39	0.650	0.828	0.927	0.954	0.9041	0.823	0.680	0.493	0.269
1839	0.35	0.617	0.800	0.903	0.935	0.9019	0.82	0.672	0.488	0.267
2409	0.27	0.550	0.741	0.852	0.891	0.8645	0.781	0.67	0.467	0.251
3156	0.17	0.459	0.660	0.780	0.828	0.8096	0.733	0.606	0.46	0.222
4450	0.01	0.320	0.535	0.669	0.729	0.7225	0.657	0.539	0.374	0.21

Table B- 3: Best Sets of Optimized Parameters for Gin Ganga

Parameters	C	SC
1	0.51	1292.0
2	0.51	1277.1
3	0.51	1322

APPENDIX-C

ANALYSIS KELANI GANGA

APPENDIX-C: ANALYSIS KELANI GANGA

Table C- 1: Warming up period for soil water content at Kelani Ganga (1966-1990)

Warming up Period	St-1 (mm)
0	0
1	138.88
2	138.88
3	139.06
4	138.88
5	138.88

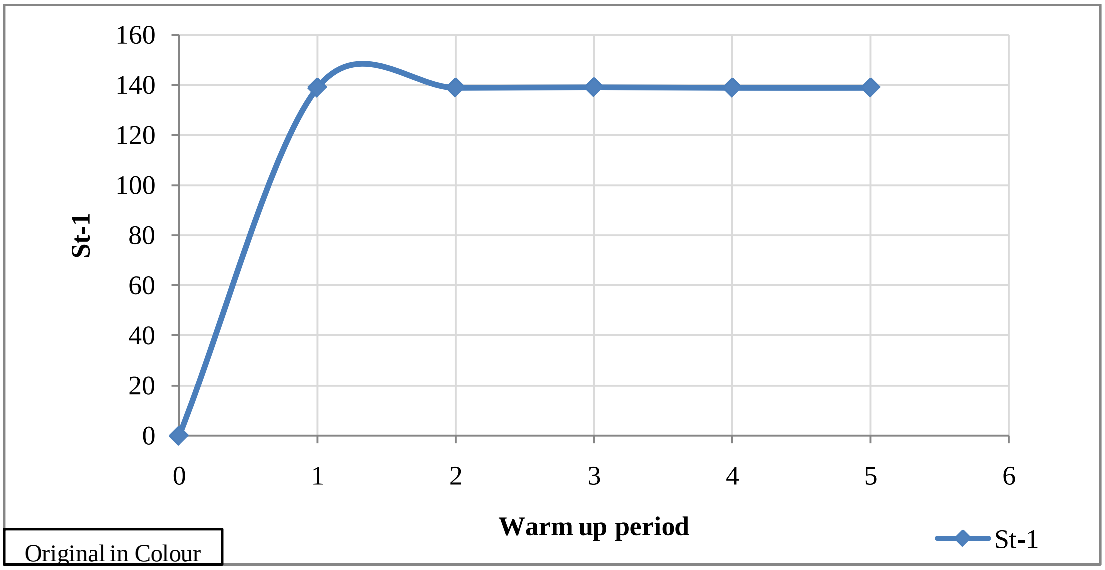


Figure C- 1: Warming up period for soil water content at Kelani Ganga (1966-1990)

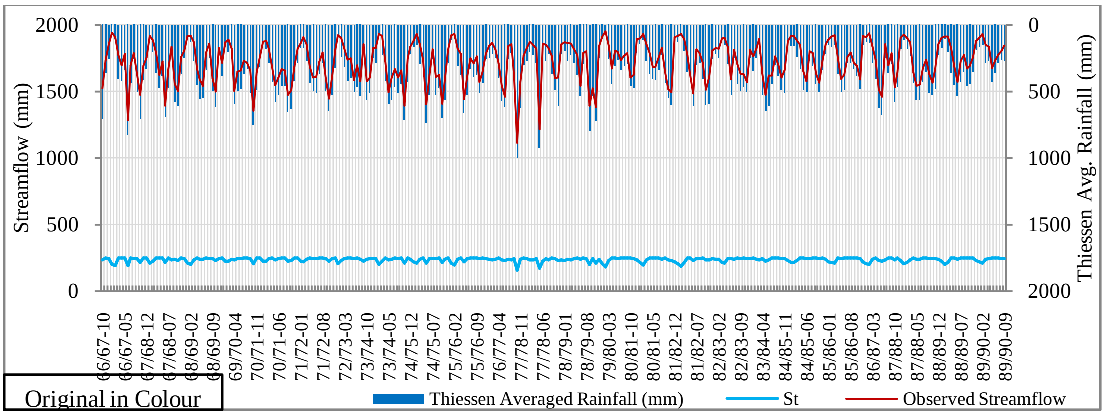


Figure C- 2: Soil Moisture Content corresponding to observed Rainfall & Streamflow for Kelani Ganga (1966-1990)

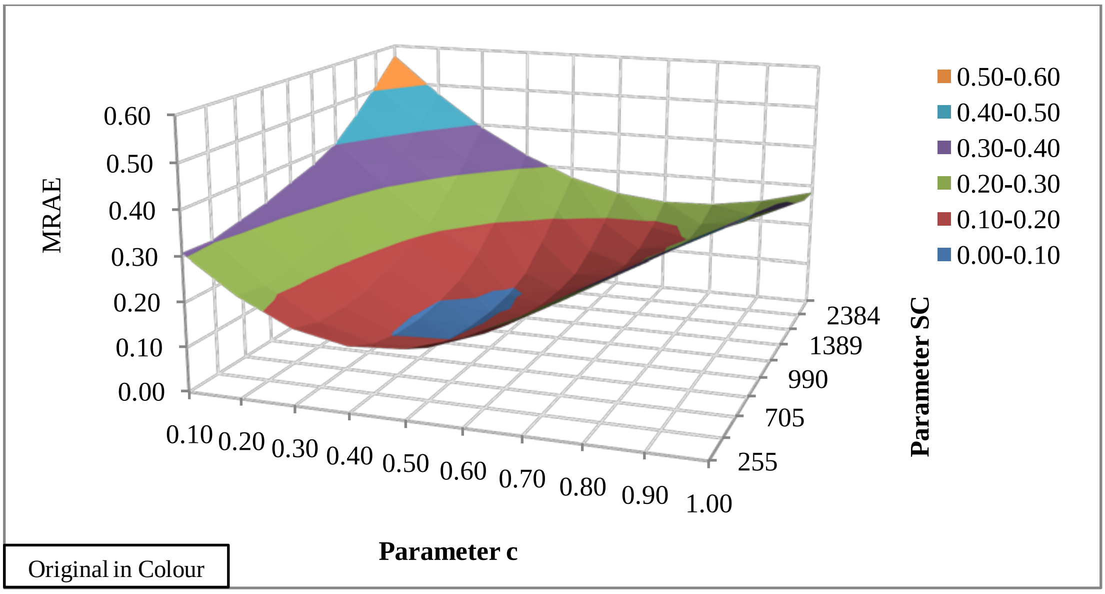


Figure C- 3: Parameter Optimization Using MRAE at Kelani Ganga

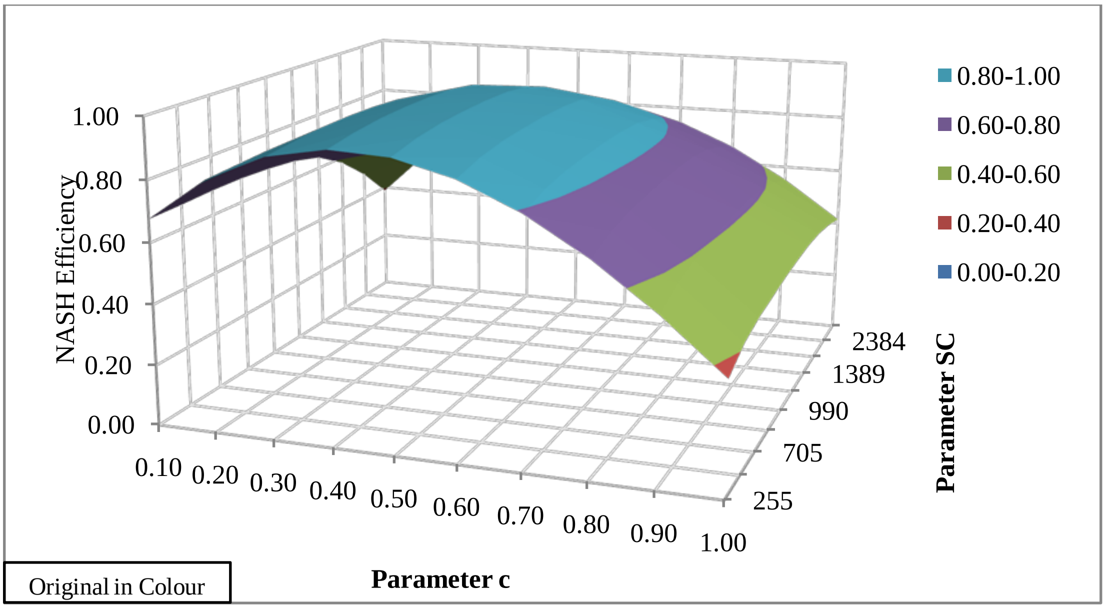


Figure C- 4: Parameter Optimization Using Nash-Sutcliffe efficiency at Kelani Ganga

Table C- 2: MRAE Monthly Water Balance for Kelani Ganga (1966-1990)

Parameter c	MRAE SC=255	MRAE SC=538	MRAE SC=705	MRAE SC=818	MRAE SC=990	MRAE SC=1148	MRAE SC=1389	MRAE SC=1820	MRAE SC=2384	MRAE SC=3123
0.10	0.307	0.304	0.319	0.332	0.353	0.373	0.403	0.454	0.511	0.573
0.20	0.227	0.216	0.224	0.236	0.256	0.276	0.306	0.356	0.413	0.476
0.30	0.170	0.147	0.144	0.149	0.166	0.186	0.215	0.267	0.327	0.392
0.40	0.146	0.113	0.096	0.093	0.099	0.115	0.146	0.200	0.261	0.326
0.50	0.154	0.118	0.099	0.090	0.088	0.093	0.113	0.159	0.215	0.275
0.60	0.192	0.163	0.142	0.131	0.119	0.116	0.122	0.149	0.192	0.243
0.70	0.251	0.230	0.210	0.196	0.179	0.166	0.158	0.165	0.190	0.229
0.80	0.322	0.300	0.281	0.268	0.248	0.232	0.213	0.202	0.209	0.233
0.90	0.391	0.369	0.350	0.337	0.317	0.300	0.278	0.253	0.244	0.252
1.00	0.457	0.434	0.415	0.402	0.383	0.366	0.343	0.311	0.291	0.284

Table C- 3: MRAE Seasonal Water Balance (Maha) for Kelani Ganga (1966-1990)

Parameter c	MRAE SC=255	MRAE SC=538	MRAE SC=705	MRAE SC=818	MRAE SC=990	MRAE SC=1148	MRAE SC=1389	MRAE SC=1820	MRAE SC=2384	MRAE SC=3123
0.10	0.264	0.266	0.281	0.293	0.312	0.329	0.354	0.395	0.441	0.490
0.20	0.172	0.177	0.193	0.204	0.223	0.240	0.265	0.306	0.350	0.398
0.30	0.087	0.095	0.109	0.120	0.138	0.155	0.180	0.220	0.263	0.314
0.40	0.046	0.041	0.042	0.048	0.061	0.075	0.098	0.140	0.186	0.235
0.50	0.088	0.072	0.059	0.050	0.038	0.035	0.040	0.068	0.111	0.159
0.60	0.159	0.145	0.128	0.115	0.096	0.080	0.060	0.041	0.049	0.087
0.70	0.233	0.217	0.199	0.186	0.168	0.151	0.128	0.092	0.061	0.047
0.80	0.303	0.285	0.267	0.254	0.236	0.219	0.197	0.162	0.124	0.086
0.90	0.370	0.349	0.331	0.318	0.300	0.284	0.262	0.228	0.192	0.155
1.00	0.433	0.410	0.392	0.379	0.361	0.346	0.324	0.292	0.257	0.221

Table C- 4: MRAE Seasonal Water Balance (Yala) for Kelani Ganga (1966-1990)

Parameter c	MRAE SC=255	MRAE SC=538	MRAE SC=705	MRAE SC=818	MRAE SC=990	MRAE SC=1148	MRAE SC=1389	MRAE SC=1820	MRAE SC=2384	MRAE SC=3123
0.10	0.252	0.260	0.264	0.266	0.270	0.273	0.277	0.284	0.292	0.298
0.20	0.171	0.179	0.183	0.185	0.189	0.192	0.196	0.203	0.210	0.217
0.30	0.093	0.101	0.105	0.107	0.110	0.113	0.118	0.125	0.132	0.138
0.40	0.027	0.031	0.034	0.036	0.038	0.041	0.045	0.051	0.057	0.063
0.50	0.059	0.052	0.048	0.046	0.043	0.040	0.037	0.033	0.031	0.031
0.60	0.124	0.118	0.114	0.112	0.109	0.106	0.102	0.095	0.089	0.083
0.70	0.192	0.185	0.182	0.180	0.177	0.174	0.170	0.163	0.157	0.151
0.80	0.256	0.250	0.247	0.245	0.242	0.239	0.235	0.229	0.222	0.217
0.90	0.318	0.313	0.310	0.307	0.304	0.301	0.297	0.291	0.285	0.280
1.00	0.378	0.372	0.369	0.367	0.364	0.361	0.357	0.351	0.345	0.340

Table C- 5: MRAE Annual Water Balance for Kelani Ganga (1966-1990)

Parameter c	MRAE SC=255	MRAE SC=538	MRAE SC=705	MRAE SC=818	MRAE SC=990	MRAE SC=1148	MRAE SC=1389	MRAE SC=1820	MRAE SC=2384	MRAE SC=3123
0.10	0.255	0.260	0.269	0.275	0.285	0.294	0.308	0.329	0.352	0.377
0.20	0.170	0.176	0.185	0.192	0.202	0.211	0.224	0.245	0.268	0.291
0.30	0.088	0.095	0.104	0.111	0.121	0.130	0.143	0.163	0.186	0.209
0.40	0.0248	0.028	0.034	0.039	0.046	0.052	0.065	0.085	0.107	0.130
0.50	0.067	0.058	0.050	0.045	0.036	0.031	0.0254	0.027	0.039	0.059
0.60	0.140	0.130	0.120	0.114	0.104	0.095	0.083	0.064	0.046	0.034
0.70	0.209	0.199	0.189	0.183	0.173	0.164	0.152	0.133	0.113	0.093
0.80	0.276	0.265	0.255	0.249	0.239	0.230	0.219	0.200	0.181	0.161
0.90	0.340	0.328	0.318	0.312	0.302	0.294	0.282	0.264	0.246	0.227
1.00	0.400	0.388	0.378	0.372	0.362	0.354	0.343	0.326	0.308	0.290

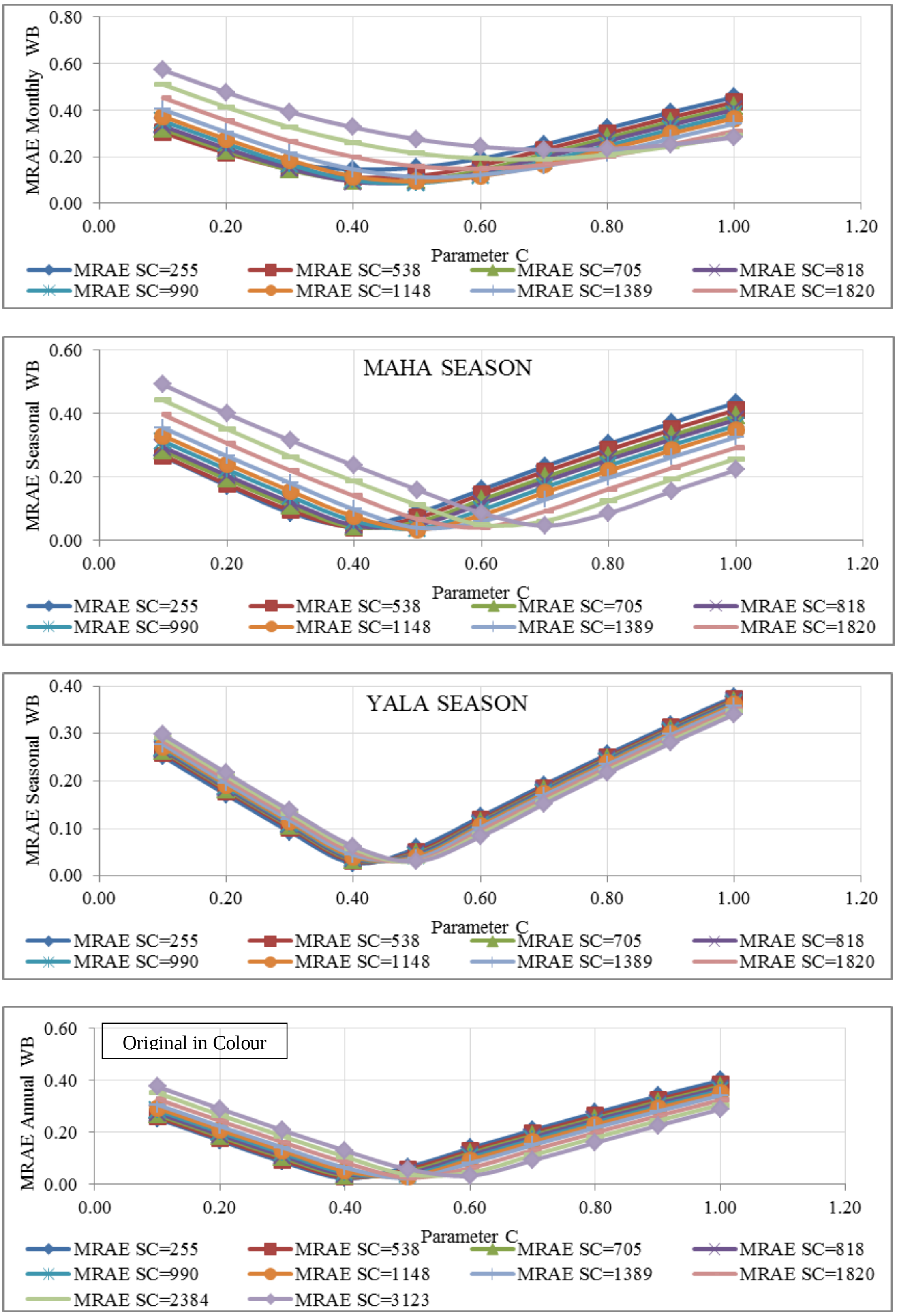


Figure C- 5: MRAE Monthly, Seasonal and Annual Water Balance for Kelani Ganga (1966-1990)

APPENDIX-D

ANALYSIS GIN GANGA

APPENDIX-D: ANALYSIS GIN GANGA

Table D- 1: Warming up period for soil water content at Gin Ganga (1972-1992)

Warm up Period	St-1
0	0
1	280.00
2	280.00
3	280.00
4	280.00
5	280.00

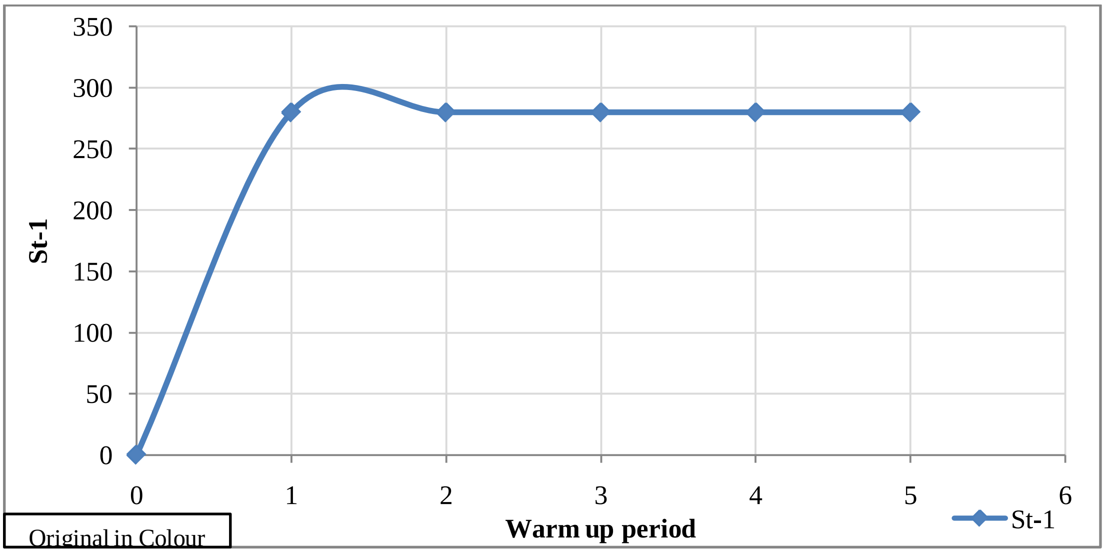


Figure D- 1: Warming up period for soil water content at Gin Ganga (1972-1992)

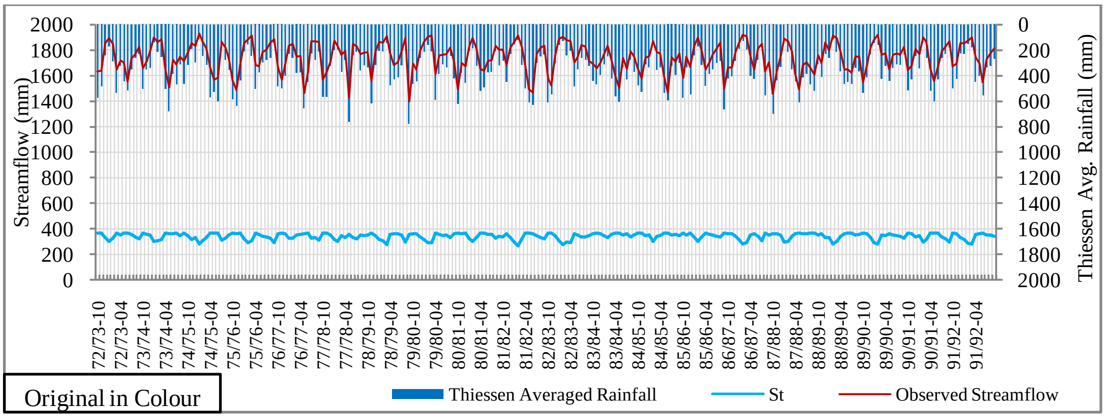


Figure D- 2: Soil Moisture Content corresponding to observed Rainfall & Streamflow for Gin Ganga (1972-1992)

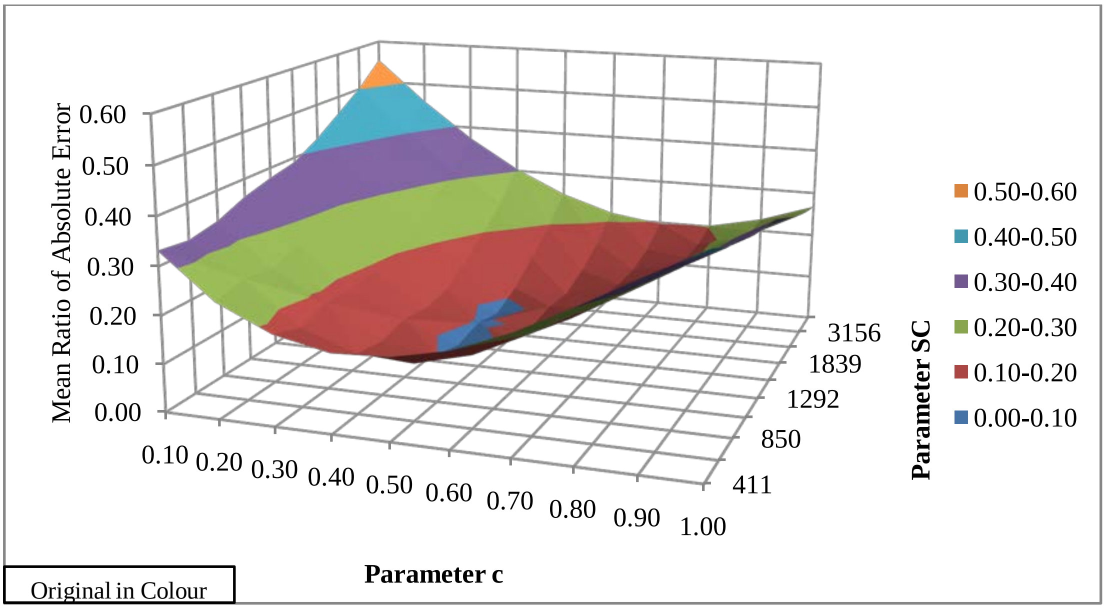


Figure D- 3: Parameter Optimization Using MRAE at Gin Ganga

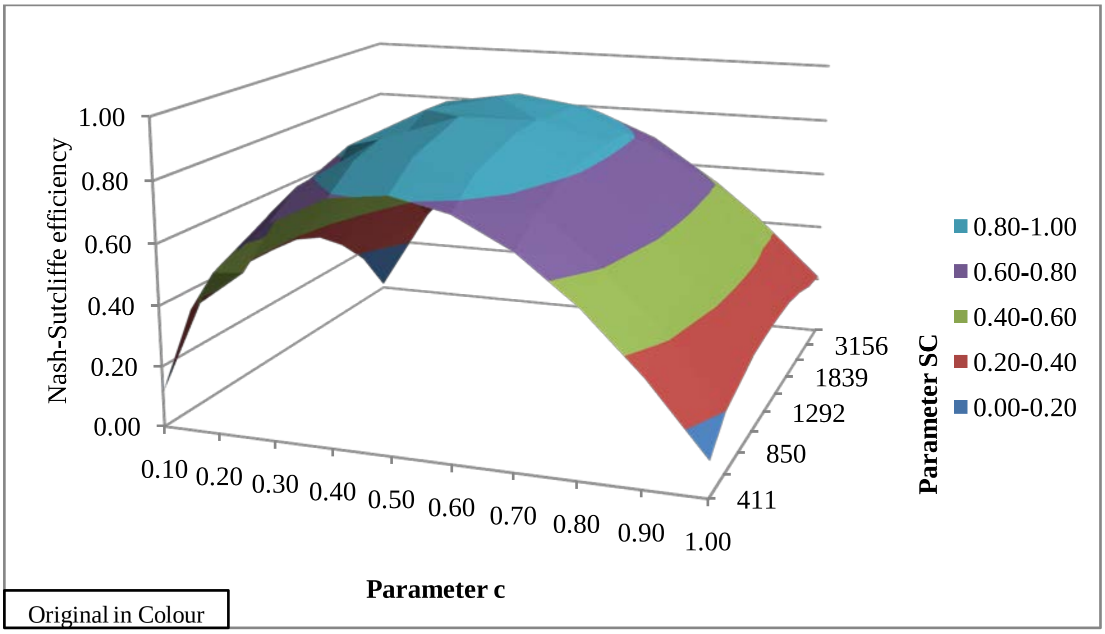


Figure D- 4: Parameter Optimization Using Nash-Sutcliffe efficiency at Gin Ganga

Table D- 2: MRAE Monthly Water Balance for Gin Ganga (1972-1992)

Parameter c	MRAE $_{SC=411}$	MRAE $_{SC=703}$	MRAE $_{SC=850}$	MRAE $_{SC=1114}$	MRAE $_{SC=1292}$	MRAE $_{SC=1434}$	MRAE $_{SC=1839}$	MRAE $_{SC=2409}$	MRAE $_{SC=3156}$	MRAE $_{SC=4450}$
0.10	0.332	0.324	0.336	0.361	0.378	0.390	0.422	0.462	0.502	0.554
0.20	0.240	0.256	0.244	0.265	0.281	0.293	0.325	0.364	0.404	0.458
0.30	0.188	0.166	0.185	0.179	0.192	0.203	0.235	0.274	0.317	0.373
0.40	0.164	0.126	0.114	0.127	0.117	0.126	0.156	0.198	0.245	0.304
0.50	0.169	0.119	0.101	0.084	0.097	0.085	0.110	0.151	0.195	0.251
0.60	0.195	0.150	0.130	0.108	0.103	0.112	0.108	0.132	0.166	0.214
0.70	0.243	0.207	0.190	0.166	0.154	0.147	0.142	0.144	0.162	0.197
0.80	0.304	0.273	0.258	0.234	0.220	0.211	0.193	0.183	0.185	0.202
0.90	0.370	0.340	0.326	0.303	0.290	0.280	0.256	0.237	0.226	0.227
1.00	0.433	0.404	0.391	0.370	0.356	0.347	0.323	0.298	0.280	0.267

Table D- 3: MRAE Seasonal Water Balance (Maha) for Gin Ganga (1972-1992)

Parameter c	MRAE $_{SC=411}$	MRAE $_{SC=703}$	MRAE $_{SC=850}$	MRAE $_{SC=1114}$	MRAE $_{SC=1292}$	MRAE $_{SC=1434}$	MRAE $_{SC=1839}$	MRAE $_{SC=2409}$	MRAE $_{SC=3156}$	MRAE $_{SC=4450}$
0.10	0.303	0.317	0.326	0.344	0.356	0.365	0.388	0.415	0.444	0.479
0.20	0.209	0.224	0.233	0.252	0.263	0.272	0.295	0.322	0.350	0.384
0.30	0.119	0.134	0.144	0.162	0.174	0.183	0.206	0.232	0.259	0.297
0.40	0.053	0.055	0.061	0.077	0.089	0.097	0.120	0.145	0.173	0.215
0.50	0.073	0.054	0.048	0.041	0.041	0.042	0.050	0.070	0.098	0.137
0.60	0.140	0.118	0.106	0.085	0.072	0.063	0.050	0.053	0.063	0.080
0.70	0.207	0.187	0.176	0.158	0.147	0.138	0.118	0.094	0.079	0.080
0.80	0.278	0.258	0.247	0.229	0.218	0.210	0.190	0.167	0.144	0.119
0.90	0.346	0.325	0.315	0.297	0.286	0.278	0.259	0.237	0.215	0.189
1.00	0.410	0.389	0.379	0.361	0.351	0.343	0.324	0.303	0.282	0.258

Table D- 4: MRAE Seasonal Water Balance (Yala) for Gin Ganga (1972-1992)

Parameter c	$MRAE_{SC=411}$	$MRAE_{SC=703}$	$MRAE_{SC=850}$	$MRAE_{SC=1114}$	$MRAE_{SC=1292}$	$MRAE_{SC=1434}$	$MRAE_{SC=1839}$	$MRAE_{SC=2409}$	$MRAE_{SC=3156}$	$MRAE_{SC=4450}$
0.10	0.270	0.284	0.291	0.301	0.307	0.311	0.321	0.331	0.339	0.348
0.20	0.187	0.201	0.208	0.217	0.223	0.227	0.236	0.245	0.253	0.261
0.30	0.109	0.121	0.127	0.136	0.142	0.145	0.154	0.163	0.170	0.178
0.40	0.051	0.053	0.055	0.060	0.064	0.067	0.075	0.083	0.090	0.097
0.50	0.060	0.049	0.044	0.038	0.035	0.033	0.031	0.030	0.033	0.040
0.60	0.117	0.104	0.098	0.090	0.086	0.082	0.075	0.068	0.064	0.060
0.70	0.186	0.173	0.168	0.160	0.156	0.153	0.146	0.139	0.133	0.128
0.80	0.252	0.240	0.235	0.227	0.223	0.220	0.214	0.207	0.202	0.197
0.90	0.315	0.303	0.299	0.292	0.288	0.285	0.279	0.273	0.268	0.264
1.00	0.375	0.364	0.360	0.353	0.350	0.347	0.342	0.336	0.331	0.327

Table D- 5: MRAE Annual Water Balance for Gin Ganga (1972-1992)

Parameter c	$MRAE_{SC=411}$	$MRAE_{SC=703}$	$MRAE_{SC=850}$	$MRAE_{SC=1114}$	$MRAE_{SC=1292}$	$MRAE_{SC=1434}$	$MRAE_{SC=1839}$	$MRAE_{SC=2409}$	$MRAE_{SC=3156}$	$MRAE_{SC=4450}$
0.10	0.284	0.297	0.305	0.318	0.326	0.332	0.347	0.364	0.380	0.400
0.20	0.197	0.210	0.218	0.231	0.239	0.245	0.259	0.276	0.292	0.310
0.30	0.112	0.126	0.134	0.147	0.155	0.160	0.175	0.191	0.206	0.224
0.40	0.043	0.049	0.054	0.066	0.073	0.079	0.093	0.108	0.123	0.140
0.50	0.054	0.043	0.038	0.030	0.027	0.027	0.030	0.036	0.049	0.067
0.60	0.121	0.106	0.099	0.087	0.080	0.074	0.061	0.048	0.040	0.036
0.70	0.193	0.178	0.170	0.159	0.151	0.146	0.134	0.120	0.107	0.092
0.80	0.261	0.246	0.239	0.227	0.220	0.215	0.203	0.190	0.177	0.163
0.90	0.326	0.311	0.304	0.293	0.286	0.281	0.270	0.257	0.245	0.232
1.00	0.388	0.373	0.366	0.355	0.349	0.344	0.333	0.321	0.310	0.297

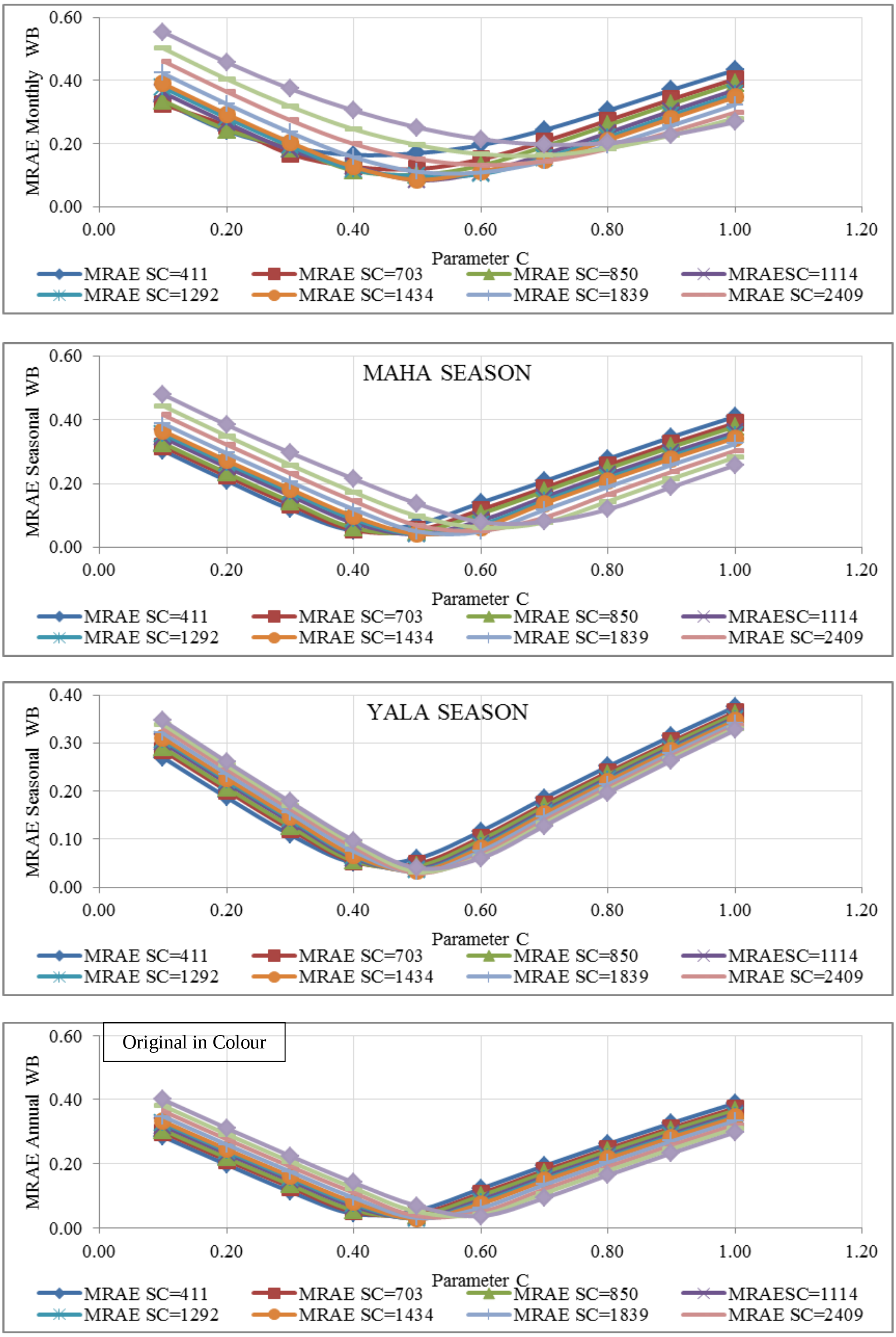


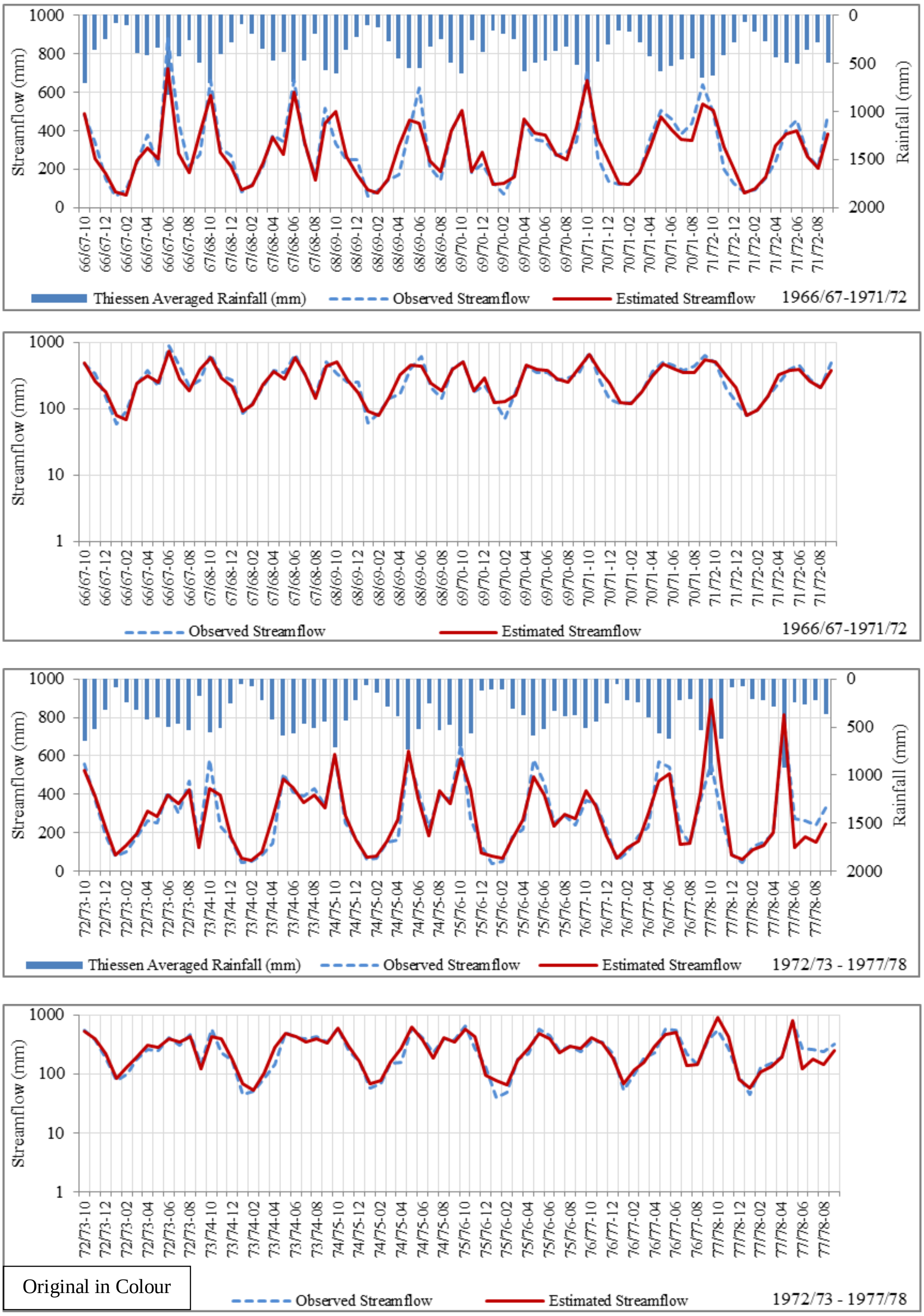
Figure D- 5: MRAE Monthly, Seasonal &Annual Water Balance for Gin Ganga (1972-1992)

APPENDIX-E

RESULTS KELANI GANGA

(CALIBRATION)

APPENDIX-E: CALIBRATION RESULTS KELANI GANGA



Original in Colour

Figure E- 1: Outflow Hydrograph for Kelani Ganga 1966-1978 (Normal & Logarithmic Plot)

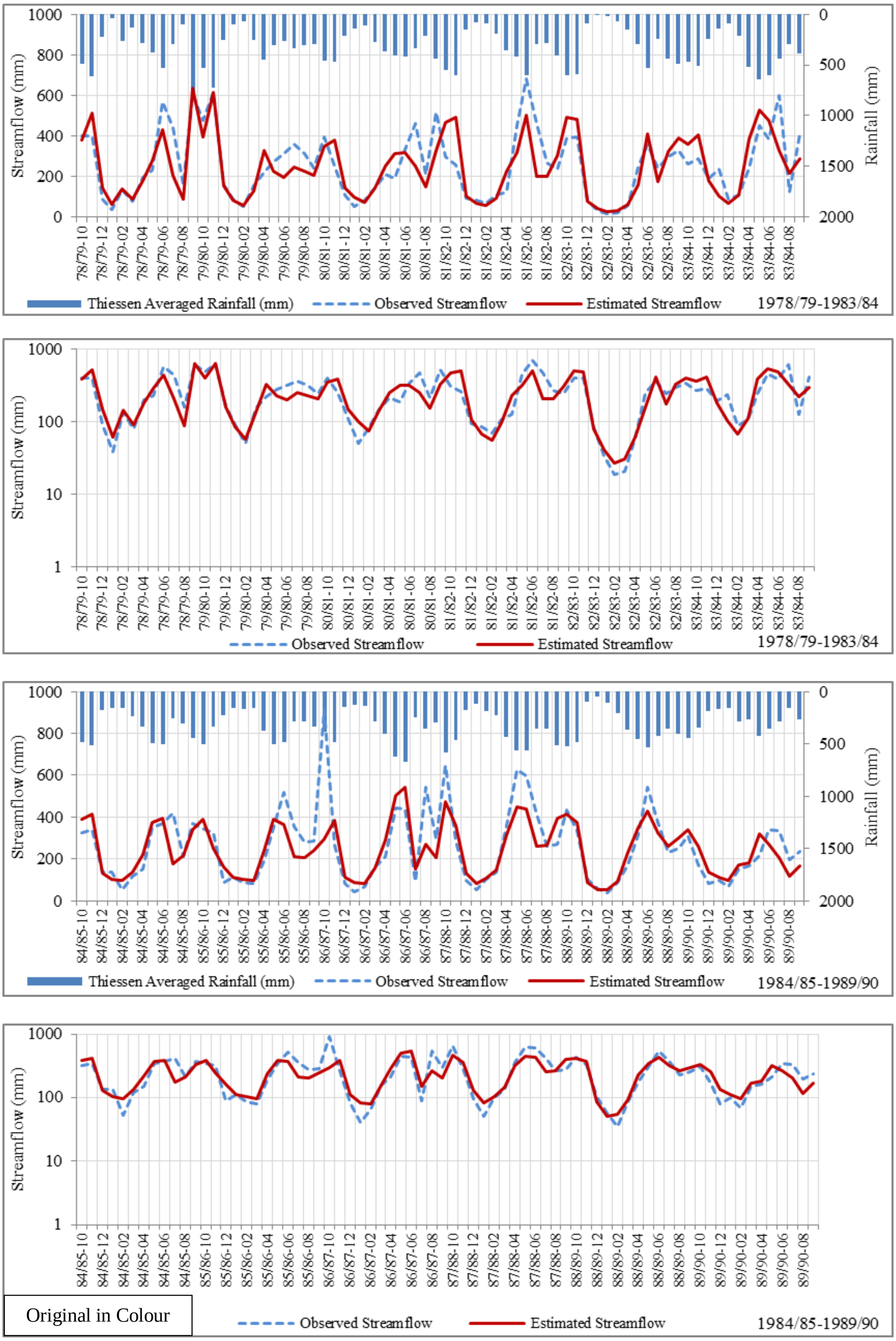


Figure E- 2: Outflow Hydrograph for Kelani Ganga 1978-1990 (Normal & Logarithmic Plot)

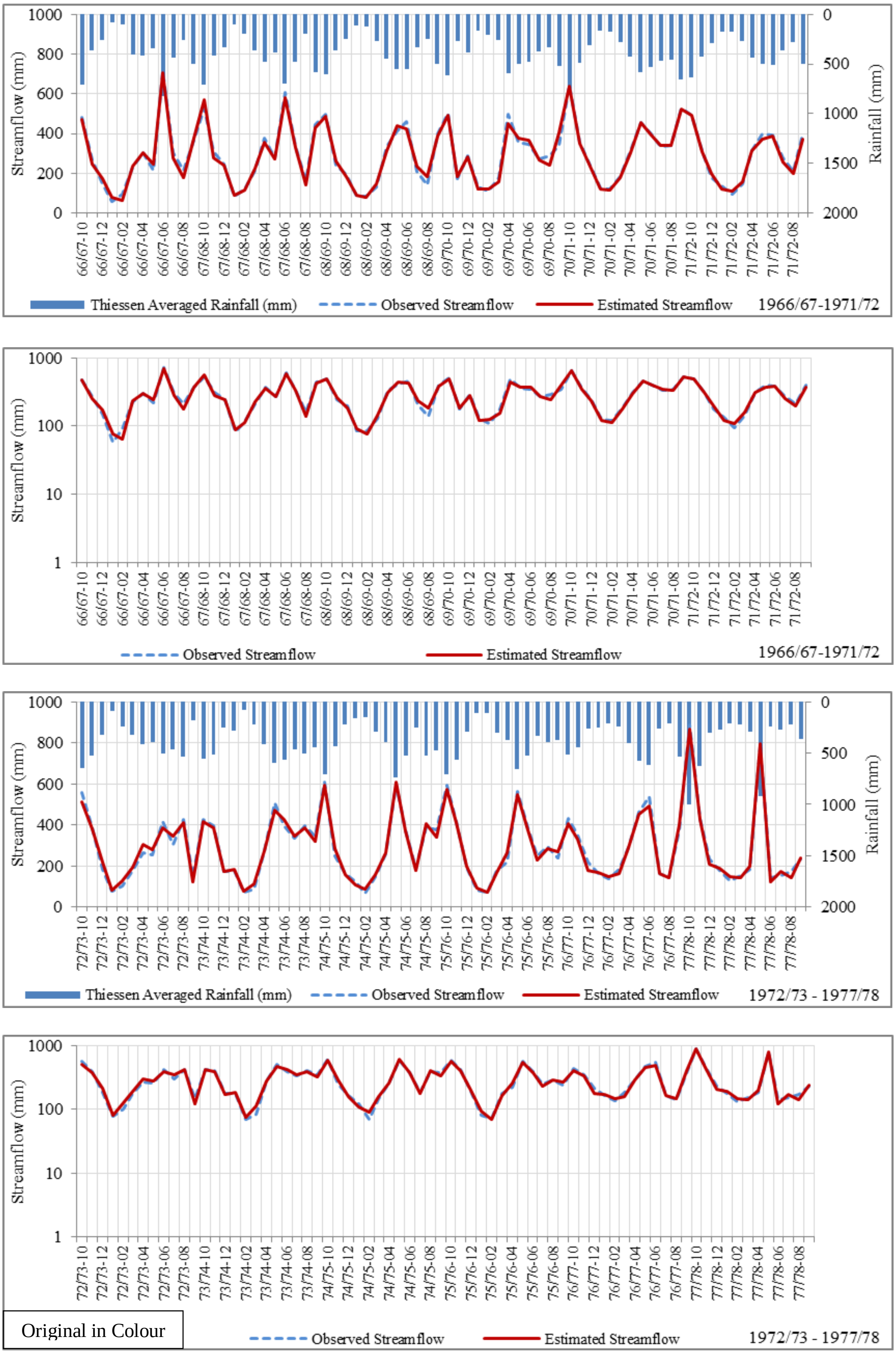


Figure E- 3: Outflow Hydrograph for Kelani Ganga 1966-1978 (Normal & Logarithmic Plot)

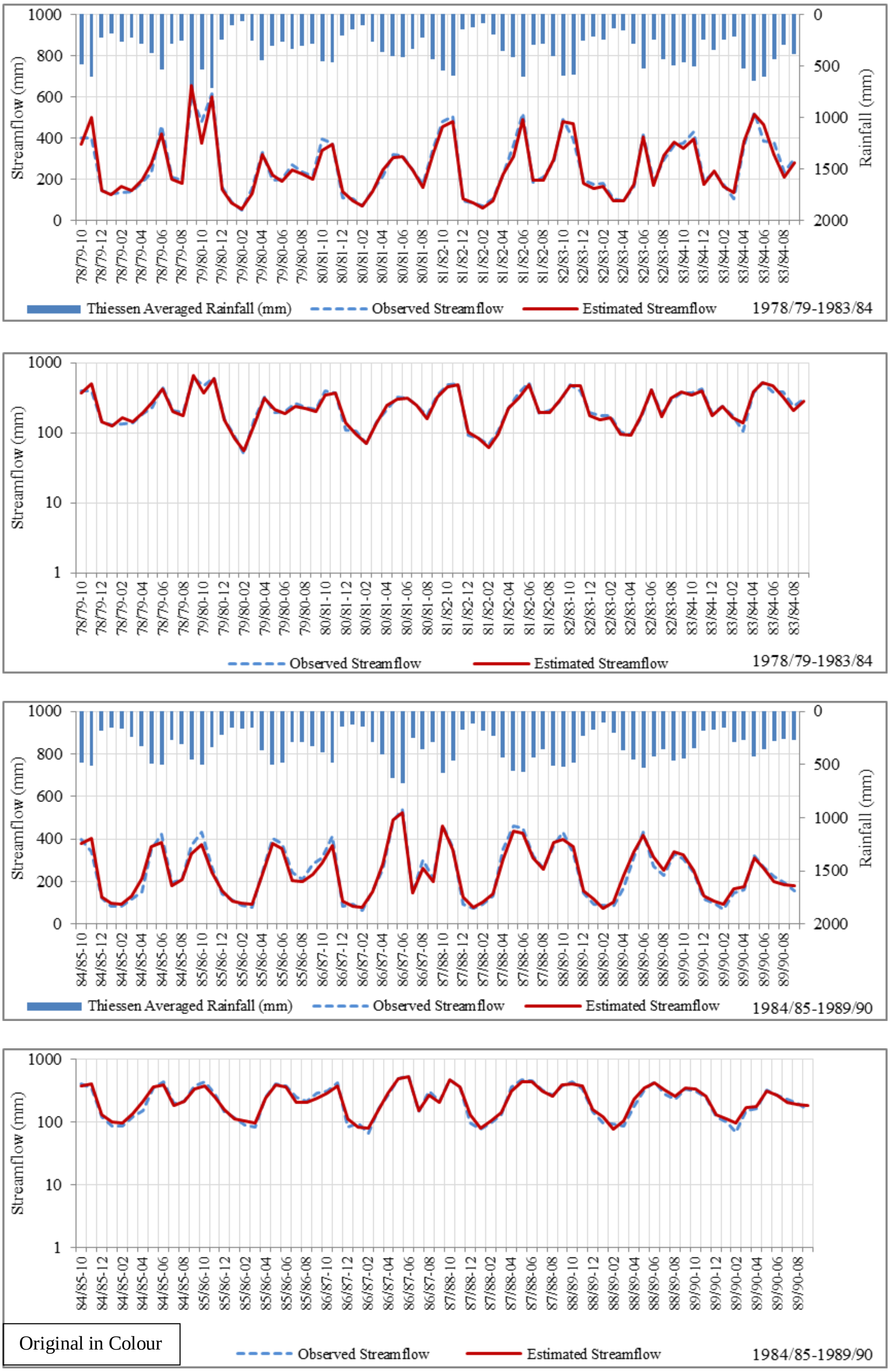


Figure E- 4: Outflow Hydrograph for Kelani Ganga 1978-1990 (Normal & Logarithmic Plot)

APPENDIX-F

RESULTSGIN GANGA

(CALIBRATION)

APPENDIX-F: CALIBRATION RESULTS GIN GANGA

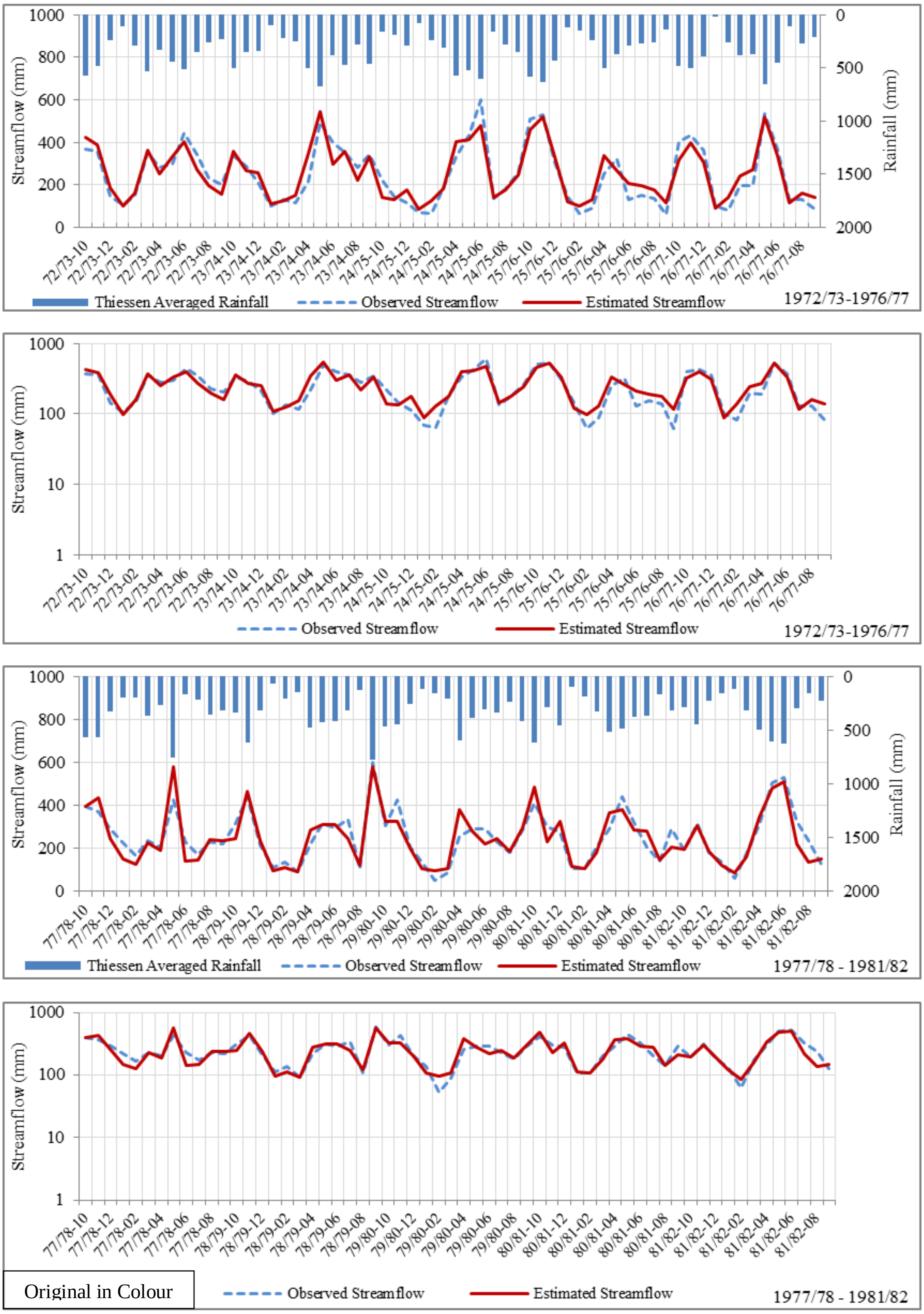


Figure E- 5: Outflow Hydrograph for Gin Ganga 1972-1982 (Normal & Logarithmic Plot)

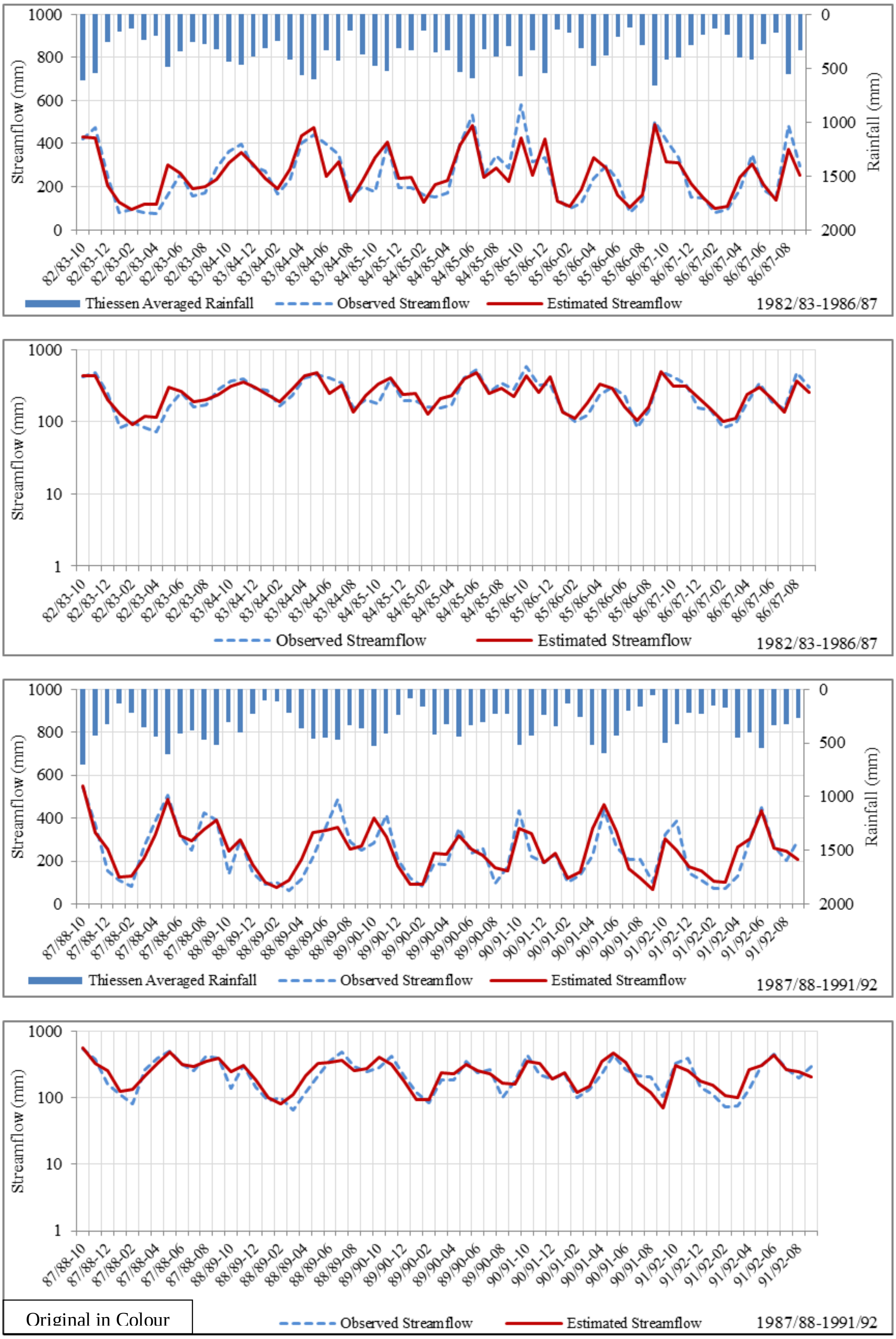


Figure E- 6: Outflow Hydrograph for Gin Ganga 1972-1992 (Normal & Logarithmic Plot)

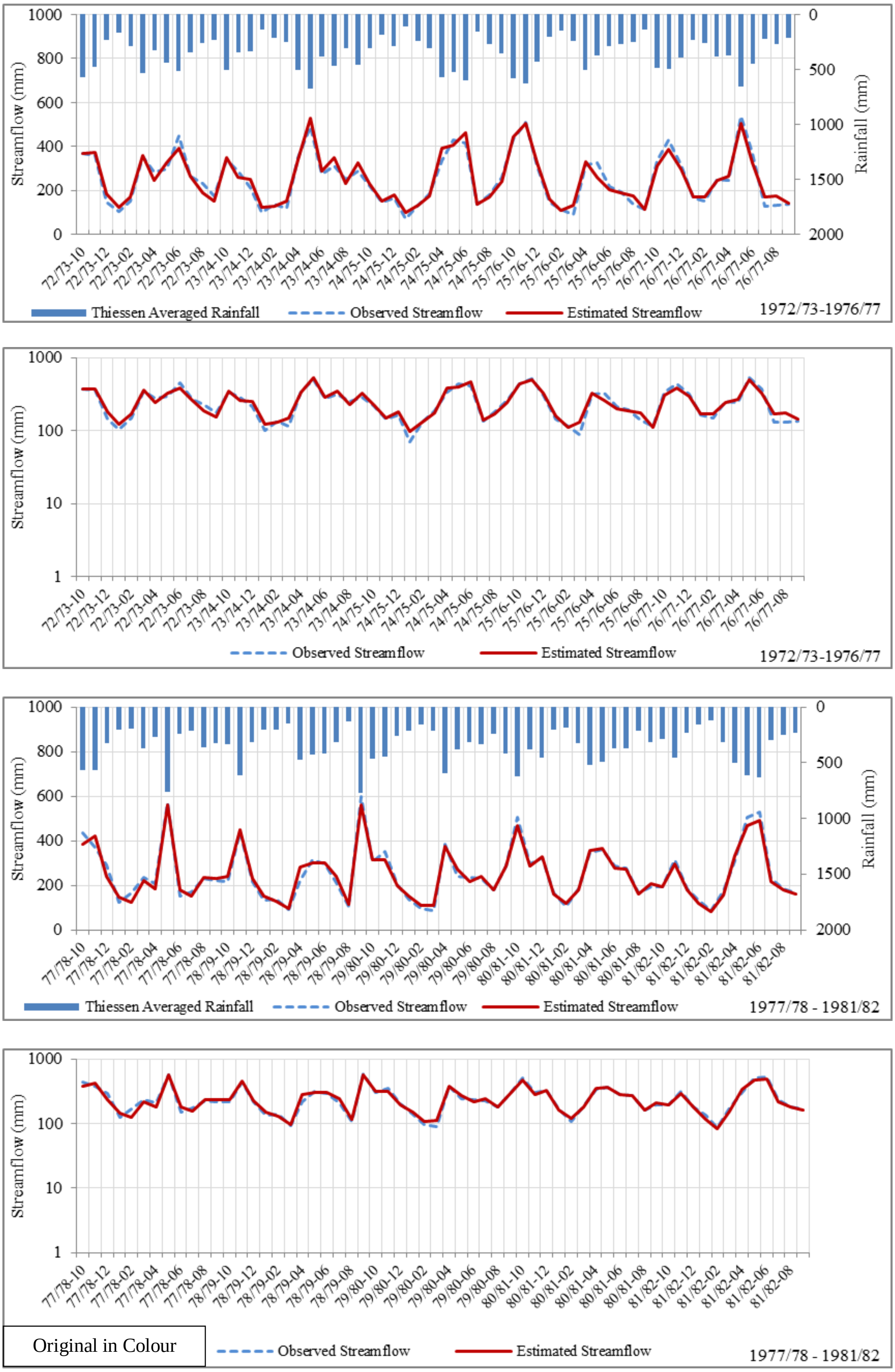


Figure F- 1: Outflow Hydrograph for Gin Ganga 1972-1982 (Normal & Logarithmic Plot)

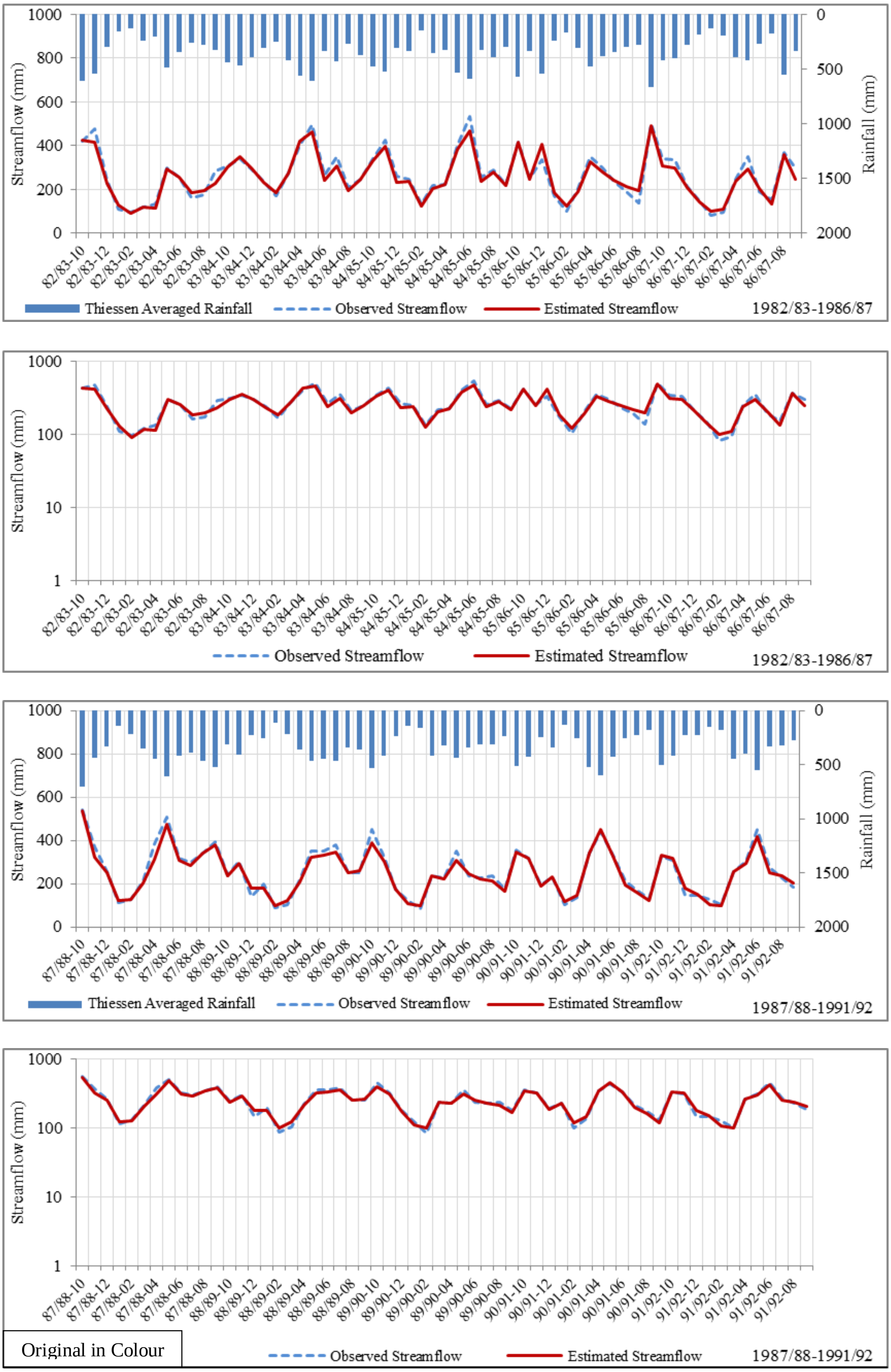


Figure F- 2: Outflow Hydrograph for Gin Ganga1982-1992 (Normal & Logarithmic Plot)

APPENDIX-G

RESULTS KELANI GANGA

(VERIFICAITON)

Figure G- 1: Outflow Hydrograph for Kelani Ganga 1990-2002 (Normal & Logarithmic Plot)

Figure G- 2: Outflow Hydrograph for Kelani Ganga 2002-2014 (Normal & Logarithmic Plot)

APPENDIX-G: VERIFICATION RESULTS KELANI GANGA

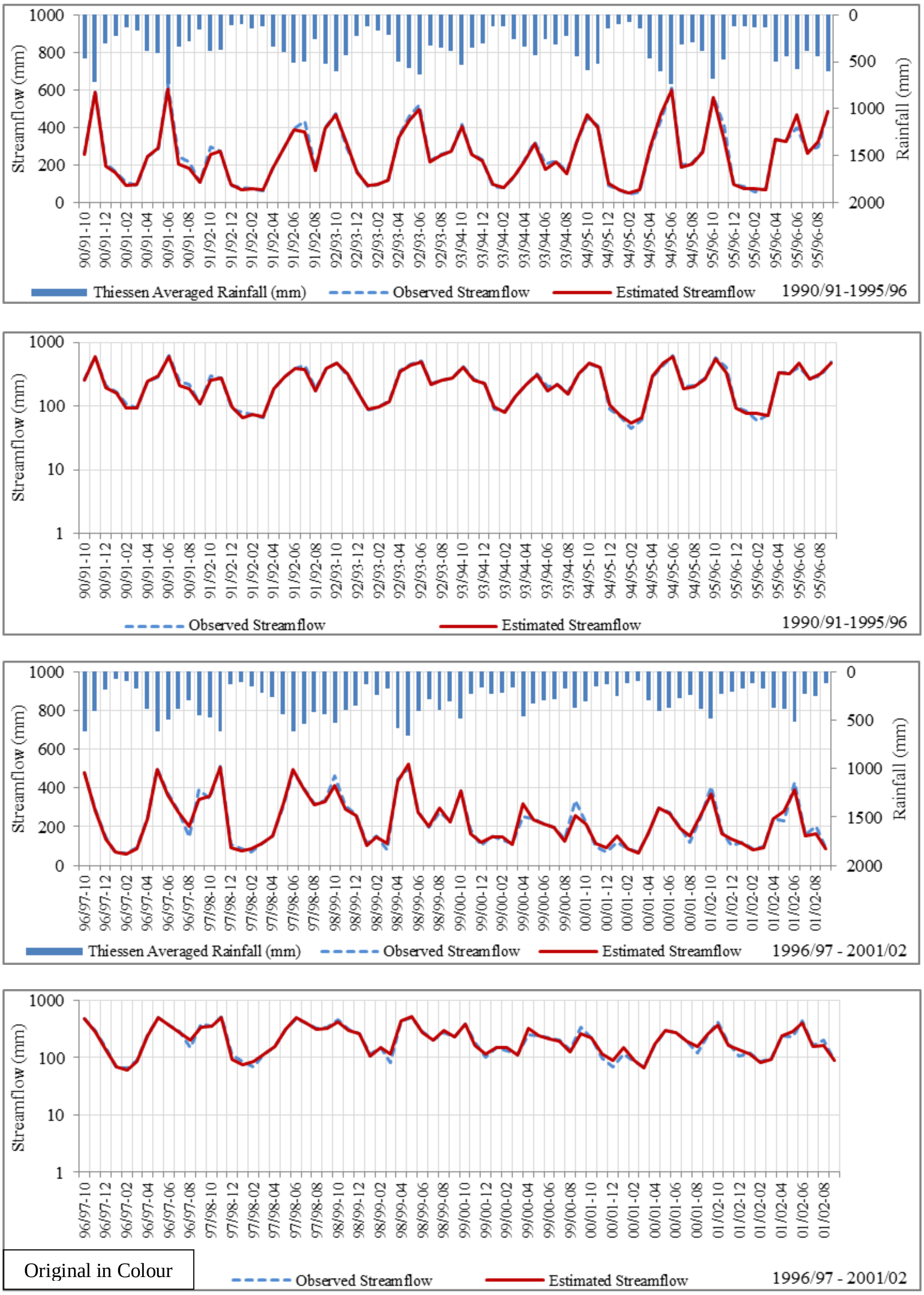


Figure G- 1: Outflow Hydrograph for Kelani Ganga 1990-2002 (Normal & Logarithmic Plot)

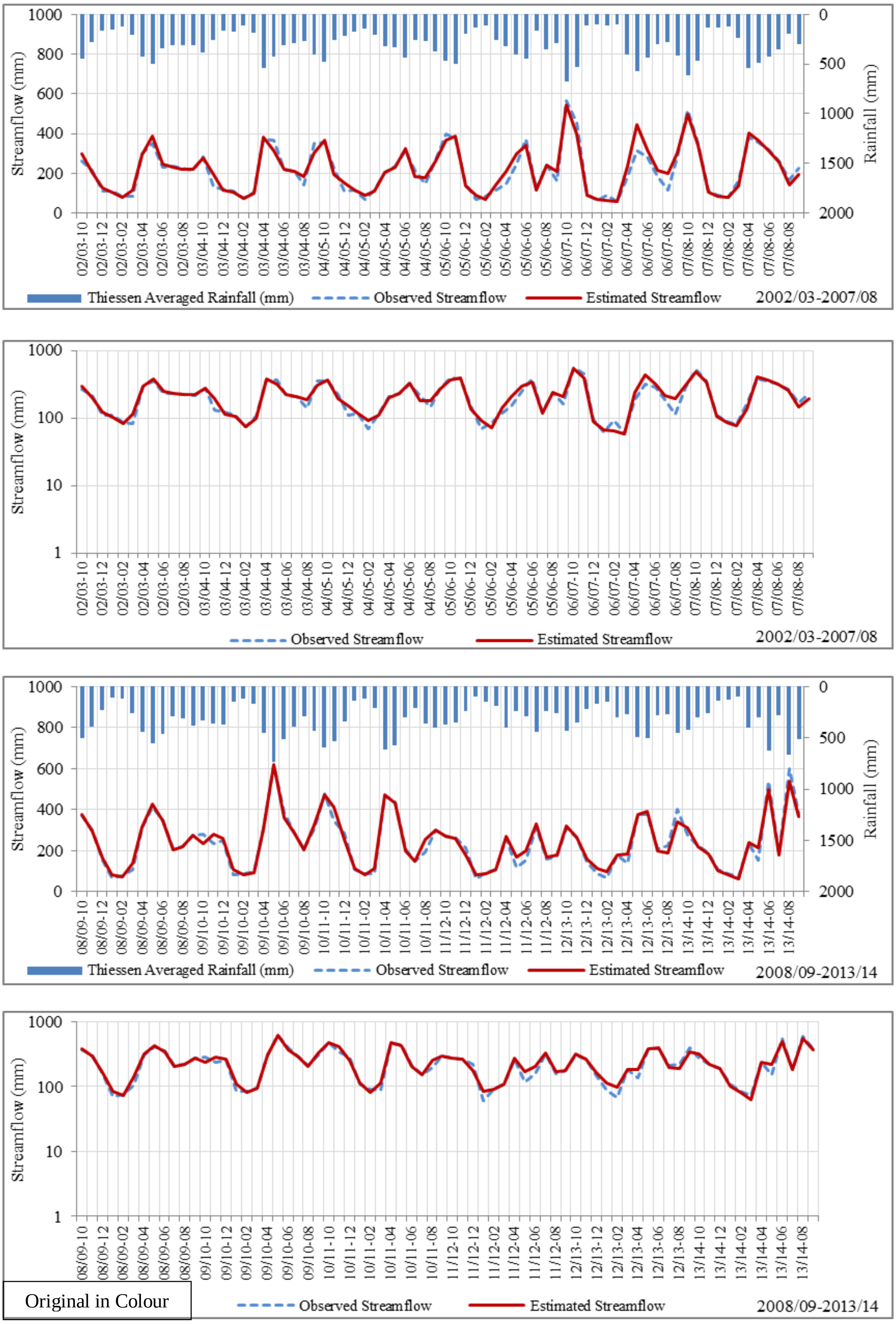


Figure G- 2: Outflow Hydrograph for Kelani Ganga 2002-2014 (Normal & Logarithmic Plot)

APPENDIX-H

RESULTS GIN GANGA

(VERIFICATION)

APPENDIX-H: VERIFICATION RESULTS GIN GANGA

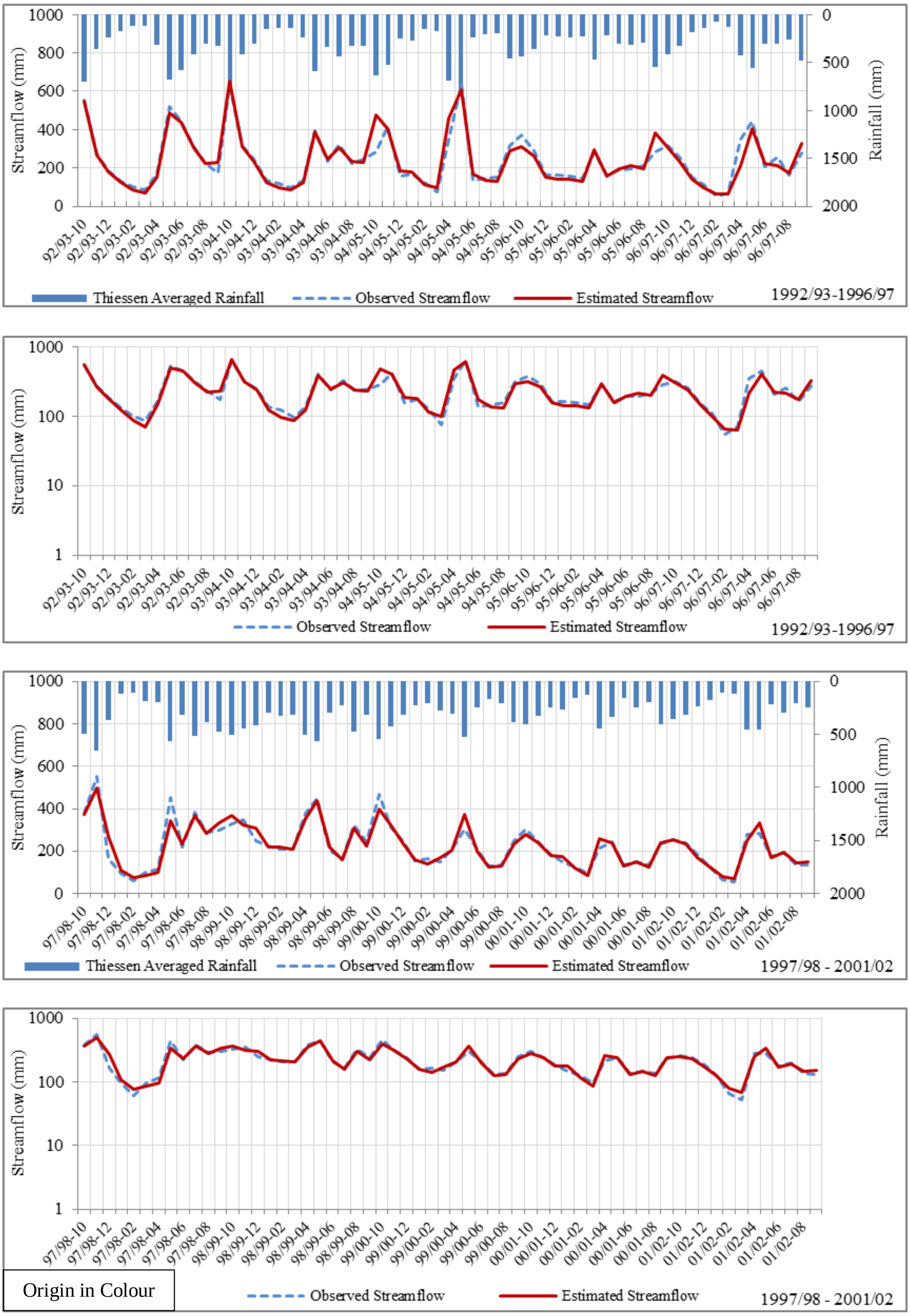


Figure H- 1: Outflow Hydrograph for Gin Ganga 1992-2002 (Normal & Logarithmic Plot)

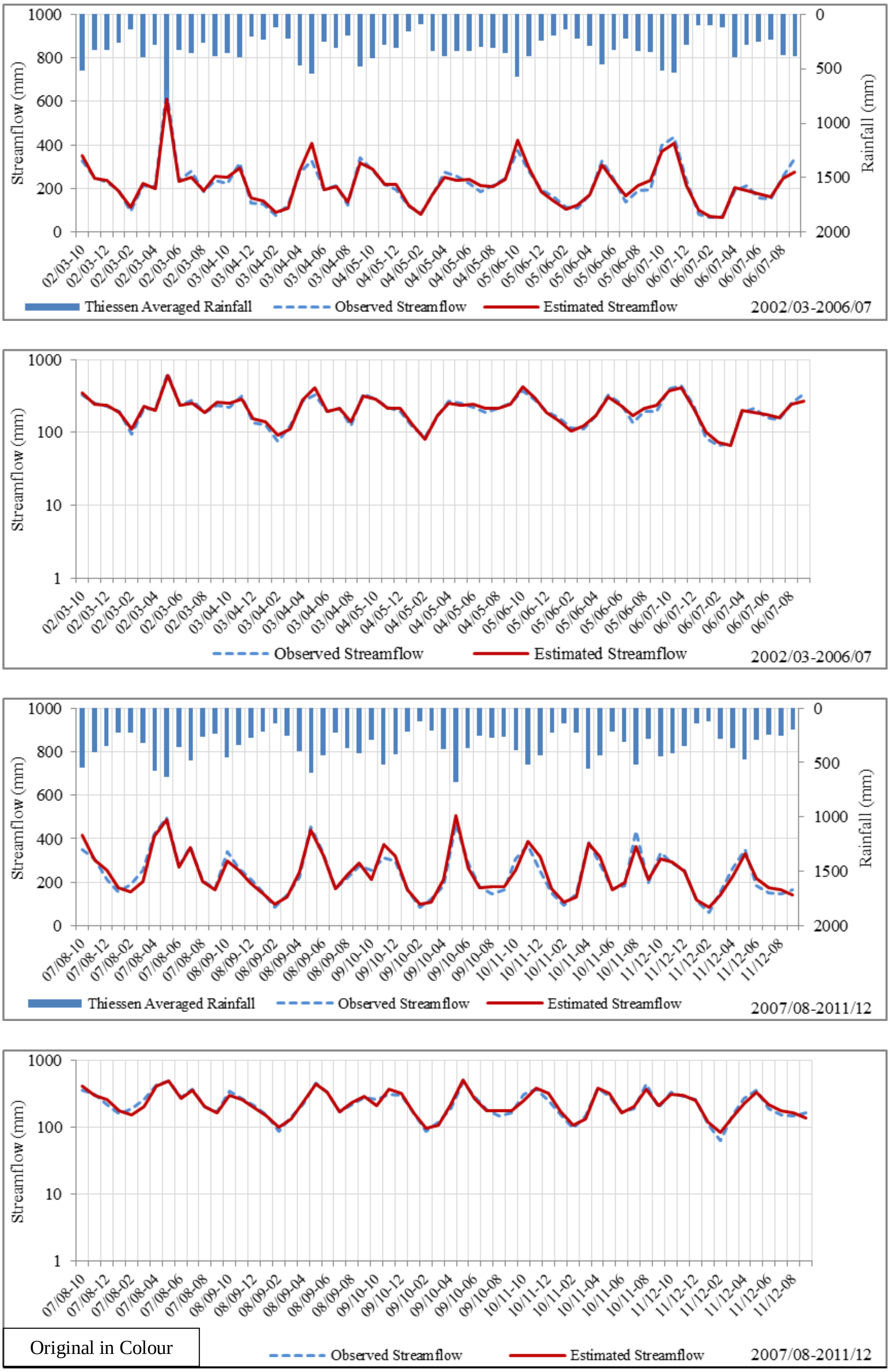


Figure H- 2: Outflow Hydrograph for Gin Ganga 2002-2012 (Normal & Logarithmic Plot)

APPENDIX-I

SPECIMEN CALCULATIONS

APPENDIX-I: SPECIMEN CALCULATIONS

Specimen Calculation for Kelani Ganga

Consider Year 1966/67-10 (First Row)

Model Input Data

Monthly Thiessen Averaged Rainfall P(t) = 707.02 mm

Monthly Pan Evaporation EP(t) = 114.39 mm

Model Parameter (Optimized)

Monthly Evaporation Coefficient c = 0.46

Field Capacity of Catchment SC = 899.48 mm

Actual Evapotranspiration is given by:

$$E(t) = c \times EP(t) \times \tanh\left(\frac{P(t)}{EP(t)}\right)$$

E(t) = 52.619 mm

Condition Applied:

Actual Evaporation should not be less than Zero

If (E(t)<0,0,E(t))

Actual Evaporation should not be more than Pan Evaporation

If (E(t)<EP(t),E(t),EP(t))

The water content at the end of the (t-1)-th Month is given by S(t-1)

Initial S(t-1) is obtained from 5-Hydrologic Cycle and next month S(t-1) value is equal to S(t) of the first month.

S(t-1) = 138.88 mm

Monthly Runoff can be calculated by

$$Q(t) = (S(t-1) + P(t) - E(t)) \times \tanh\left[\frac{(S(t-1) + P(t) - E(t))}{SC}\right]$$

Q(t) = 561.156 mm

Condition Applied:

Runoff should not be less than Zero

If (Q(t)<0,0,Q(t))

The water content at the end of the t-th Month can be computed by

$$S(t) = S(t-1) + P(t) - E(t) - Q(t)$$

S(t) = 232.125 mm

This can be used as the initial storage in the following month 1966/67-11

Condition Applied:

Soil Moisture Content should not be less than Zero.

If (S(t)<0,0,S(t))

Runoff Coefficient C can be calculated as;

$$C = \frac{Q(t)}{P(t)}$$

C = 0.794

The Average runoff coefficient in the calibration period is the average value in calibration data set

Cavg = 0.84

Catchment Area = 182.54 km^2

Estimated Streamflow can be computed by;

$$Q = Q(t) \times Cavg \times A \times \frac{10^6}{(1000 \times 31 \times 24 \times 60 \times 60)}$$

Q = 32.125 m^3/s or 472.87 mm

Error Estimation& Optimization

1. Nash Sutcliffe Efficiency (E)

Mean flow during calibration period Qc = 272.88 mm

Observed Streamflow Qo = 479.35 mm

Simulated Streamflow Qs = 472.87 mm

$F = (Qo - Qs)^2$

$F = (479.53 - 472.87)^2 = 41.99$ mm

$Fo = (Qo - Qc)^2$

$Fo = (479.53 - 272.88)^2 = 42629.81$ mm

But sum of Fo and F is

Fo = 6348208.15 mm

F = 172348.74 mm

$$E = \frac{(Fo - F)}{Fo}$$

$$E = \frac{(6348208.15 - 172348.74)}{6348208.15}$$

E = 0.973

2. Mean Ratio of Absolute Error (MRAE)

$$MRAE = \left(\frac{1}{n}\right) \times \left[\sum_{i}\left(\frac{Abs(Qo - Qs)}{Qo}\right)\right]$$

Sum of (Qo-Qs)/Qo = 24.31 mm

MRAE = (1/288)*(24.31) = 0.0843

Specimen Calculation for Gin Ganga

Consider Year 1972/73-10 (First Row)

Model Input Data

Monthly Thiessen Averaged Rainfall P(t) = 574.70mm

Monthly Pan Evaporation EP(t) = 104.37mm

Model Parameter (Optimized)

Monthly Evaporation Coefficient c = 0.51

Field Capacity of Catchment SC = 1322mm

Actual Evapotranspiration is given by:

$$E(t) = c \times EP(t) \times \tanh\left(\frac{P(t)}{EP(t)}\right)$$

E(t) = 53.23mm

Condition Applied:

Actual Evaporation should not be less than Zero

If (E(t)<0,0,E(t))

Actual Evaporation should not be more than Pan Evaporation

If (E(t)<EP(t),E(t),EP(t))

The water content at the end of the (t-1)-th Month is given by S(t-1)

Initial S(t-1) is obtained from 5-Hydrologic Cycle and next month S(t-1) value is equal to S(t) of the first month.

S(t-1) = 280mm

Monthly Runoff can be calculated by

$$Q(t) = (S(t-1) + P(t) - E(t)) \times \tanh\left[\frac{(S(t-1) + P(t) - E(t))}{SC}\right]$$

Q(t) = 434.05mm

Condition Applied:

Runoff should not be less than Zero

If (Q(t)<0,0,Q(t))

The water content at the end of the t-th Month can be computed by

$$S(t) = S(t-1) + P(t) - E(t) - Q(t)$$

S(t) = 367.42mm

This can be used as the initial storage in the following month 1972/73-11

Condition Applied:

Soil Moisture Content should not be less than Zero.

If (S(t)<0,0,S(t))

Runoff Coefficient C can be calculated as;

$$C = \frac{Q(t)}{P(t)}$$

C = 0.755

The Average runoff coefficient in the calibration period is the average value in calibration data set

Cavg = 0.84

Catchment Area = 368.75km^2

Estimated Streamflow can be computed by;

$$Q = Q(t) \times Cavg \times A \times \frac{10^6}{(1000 \times 31 \times 24 \times 60 \times 60)}$$

Q = 50.36m^3/s or 365.76mm

Error Estimation & Optimization

1. Nash Sutcliffe Efficiency (E)

Mean flow during calibration period Qc = 256.07mm

Observed Streamflow Qo = 368.27mm

Simulated Streamflow Qs = 365.76mm

$F = (Qo - Qs)^2$

$F = (368.27 - 365.76)^2 = 6.30mm$

$Fo = (Qo - Qc)^2$

$Fo = (368.27 - 256.07)^2 = 12588.764mm$

But sum of Fo and F is

Fo = 3143183.115mm

F = 141473.6304 mm

$$E = \frac{(Fo - F)}{Fo}$$

$$E = \frac{(3143183.115 - 141473.6304)}{3143183.115}$$

E = 0.955

2. Mean Ratio of Absolute Error (MRAE)

$$MRAE = \left(\frac{1}{n}\right) \times \left[\sum_{i} \left(\frac{Abs(Qo - Qs)}{Qo}\right)\right]$$

Sum of (Qo-Qs)/Qo = 19.711mm

MRAE = (1/240)*(19.711) = 0.082