CALIBRATION AND VERFICATION OF A-TWO PARAMETER MONTHLY WATER BALANCE MODEL AND ITS APPLICATION POTENTIAL FOR EVALUATION OF WATER RESOURCES -A CASE STUDY OF KALU AND MAHAWELI RIVERS OF SRI LANKA

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October 2015

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

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October 2015

DECLARATION

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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ABSTRACT

Water balance is a method by which we can account for the hydrological cycle of a specific area, with the emphasis on plants and soil moisture. One of the main purposes of a water balance study is to evaluate the net available water resources, both on the surface and in the subsurface. Understanding the behavior of a catchment from a hydrological point of view is necessary when planning and activities needed to be done in the watershed.

A-two parameter monthly water balance model for two basins was calibrated and verified using 30 years monthly rainfall, observedflow and pan evaporation data. Kalu Ganga at Ellagawa and Mahaweli Ganga at Morape were selected to estimate the streamflow. The model was calibrated and verified and a good performance was shown for both catchments. The C coefficient for Kalu Ganga at Ellagawa and Mahaweli Ganga at Morape were found as 1 and 1.1 respectively while the SC parameter was found as 800 and 1200 respectively.

The MRAE value for calibration period for Kalu Ganga at Ellagawa and Mahaweli Ganga at Morape showed a very good fitting with value of 0.145 and 0.152 respectively. The same for verification period was also very good with value of 0.153 and 0.157 respectively. During the calibration and verification periods value of the Nash–Sutcliffe efficiency for Kalu Ganga at Ellagawa was found as a 93.6% and 92.4% respectively. 93.6% and 94.1% were the Nash–Sutcliffe values for Mahaweli Ganga at Morape respectively. The two parameter monthly water balance model produced a better fitting of MRAE in annual and seasonal values when compared with monthly time series.

The two-parameter monthly water balance model with the simple structure and two parameters proved as a very efficient model when simulating the monthly, seasonal and annual runoff. Due to its simplicity and high efficiency in performance, this two-parameter monthly water balance model can be easily and efficiently used for the water resources planning and management.

ACKNOWLEDGEMENTS

Prima facea, I am grateful to the God for the good health and wellbeing that were necessary to complete this thesis.

I would like to express my sincere gratitude to my advisor Professor N.T.S.Wijesekera for the continuous support of my Postgraduate studies and related research, for his patience, motivation, and immense knowledge. His guidance helped me all the time of research and writing of this thesis. I could not have imagined having a better advisor and a mentor for my Postgraduate studies.

My sincere thanks also goes to Dr.R.L.H Lalith Rajapakse for his support and guidance provided both in terms of academic and logistic welfare during my stay.

I take this opportunity to express gratitude to all of the faculty members of the department of Civil Engineering for their help and support.

I place on record, my sincere thank you to Madanjeet Singh for providing scholarship to pursue a Masters degree in Water Resources Engineering and Management.

I would like to thank Mr. H.W. Kumarasinghe for his kind assistance during my stay in Sri Lanka.

Last but not the least; I would like to thank my family especially from my elder brother Engineer Abdullah Sharifi who acted as a father to me since childhood. He encouraged and supported me from school days to pursue a Postgraduate degree.

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1 INTRODUCTION

1.1 General

Water balance is a method by which the hydrological cycle of a specific area is accounted with emphasis on plants and soil moisture. Water balance models are simple mathematical representations of complex real world hydrologic processes and therefore they are prone to error and uncertainty in capturing reality (Nasseri, Zahraie, Ajami, & Solomatine, 2014). When the time steps used are large-these hydrologic models are called water balance models because the response time is much small when compared with time step (Mouelhi, Michel, Perrin, & Andréassian, 2006).

One of the main purposes of a water balance study is to evaluate the net available water resources, both on the surface and in the subsurface. Water balance models that simulate hydrographs of river flow on the basis of available meteorological data would be a valuable tool in the hands of the planners and designers of water resources systems (Xu, Seibert, & Halldin, 1996). Without an accurate water balance, it is not possible to manage water resource of a country especially when the water resources are becoming scarce with increasing population and the anticipated changes in the climate.

Water balance models have been developed at various time scales such as hourly, daily, monthly & yearly, and to a varying degree of complexity (Xu & Singh, 1998). Vandewiele, Xu, & Ni-Lar-Win, (1992) in their work on comparative study of monthly water balance models has expressed efforts required to model in the daily time scale when compared with monthly. Wang et al., (2011) indicated in their comparative study of monthly versus daily water balance models that monthly rainfall models are better because of their ability to speedily process a large number of simulations for parameter sensitivity and uncertainty analyses, ensemble predictions, and applications over a large number of catchments.

Mouelhi et al. (2006) in their study of stepwise development of a two-parameter monthly water balance model hade explained that monthly water balance models are valuable tools in water resources management, reservoir simulation, drought assessment or long-term forecasting of water resources implications. They have indicated that these models are also very useful because, due to their inherent parsimony, they lend themselves to regionalization, can be further used on ungauged basins, can be very simple and are easy to handle by water resources managers.

In case of Sri Lanka, peer reviewed research publications on monthly rainfall runoff modelings are limited. Wijesekera (2000) modeled Ginganga watershed of Sri Lanka with the Tank model using monthly rainfall, evaporation and streamflow data. In this work, the model had produced satisfactory hydrograph having Main Ratio of Absolute Error (MRAE) values between 0.39 & 0.31. Wijesekera (1999) also used a Tank model for monthly water balance analysis for efficient watershed management in two watersheds each in Thailand and Sri Lanka. A research on monthly water balance carried out by Wijesekera (2001) had identified Lunugamwehera reservoir management requirements using five years of monthly streamflow and daily pan evaporation data, for paddy cultivation from 1990 to 1994.

All over the world, different monthly water balance models with 2 to 12 parameters have been presented and studied intensively. Kim et al. (2015) carried out a comparative study with a simple two-parameter monthly water balance model and they Kajiyama formula for monthly runoff estimation in Han river of Korea. The water balance model which estimated two runoff parameters namely transformation of time scale (C) and field capacity (SC), had proved to be efficient in monthly simulations. Moreover, the same model could be used at the ungauged sites because the parameters can be estimated by using meteorological and geological conditions.

Rwasoka, Madamombe, Gumindoga, & Kabobah, (2014) calibrated and verified a two parameter monthly water balance model for water resource planning and management in two Zimbabwe catchments and reported that the two parameter monthly water balance model performed quite satisfactorily in simulating monthly flows. Guo, Wang & Yang (2001) applied a two-parameter monthly water balance model to study climate change impacts in a macro scale basin, and reported that the model efficiencies were above 90% while relative error in runoff estimations were less than 5%.Xiong & Guo (1999) developed a two parameter monthly water balance model, which consisted of soil moisture capacity and remaining surplus water fraction as parameters. Makhlouf & Michel (1994) developed a two-parameter monthly water balance model for water resources assessment in French watersheds with areas ranging from 315 to 5560 km² for water resource assessment and management.

Water is one of the most important natural resources. The supply of fresh water is limited. In recent years, the increasing imbalance between water supply and water demands has given rise to a greater attention from both the relevant authorities and the general public. Practicing engineers require tools to manage water resources. The most frequent problems in practice are the data availability and access to resources for easy modeling. In Sri Lanka, the available guidelines (ID 1991) facilitate monthly evaluation for water resources planning. Also In case of most watersheds, monthly data are available at an affordable cost. In literature, two parameter water balance models have performed satisfactorily in many other parts of the world. However, only limited applications had been carried out for Sri Lanka. Accordingly, it is suitable to evaluate the potential of applying a two parameter model for Sri Lankan watershed due to its easiness, lesser number of parameters and easy access to data.

In order to strengthen the research and application of watershed models for water resources management in Sri Lanka, a two parameter monthly water balance model is applied to the Kalu Ganga and Mahaweli Ganga watershed at Ellagawa and Morape gauging stations respectively.

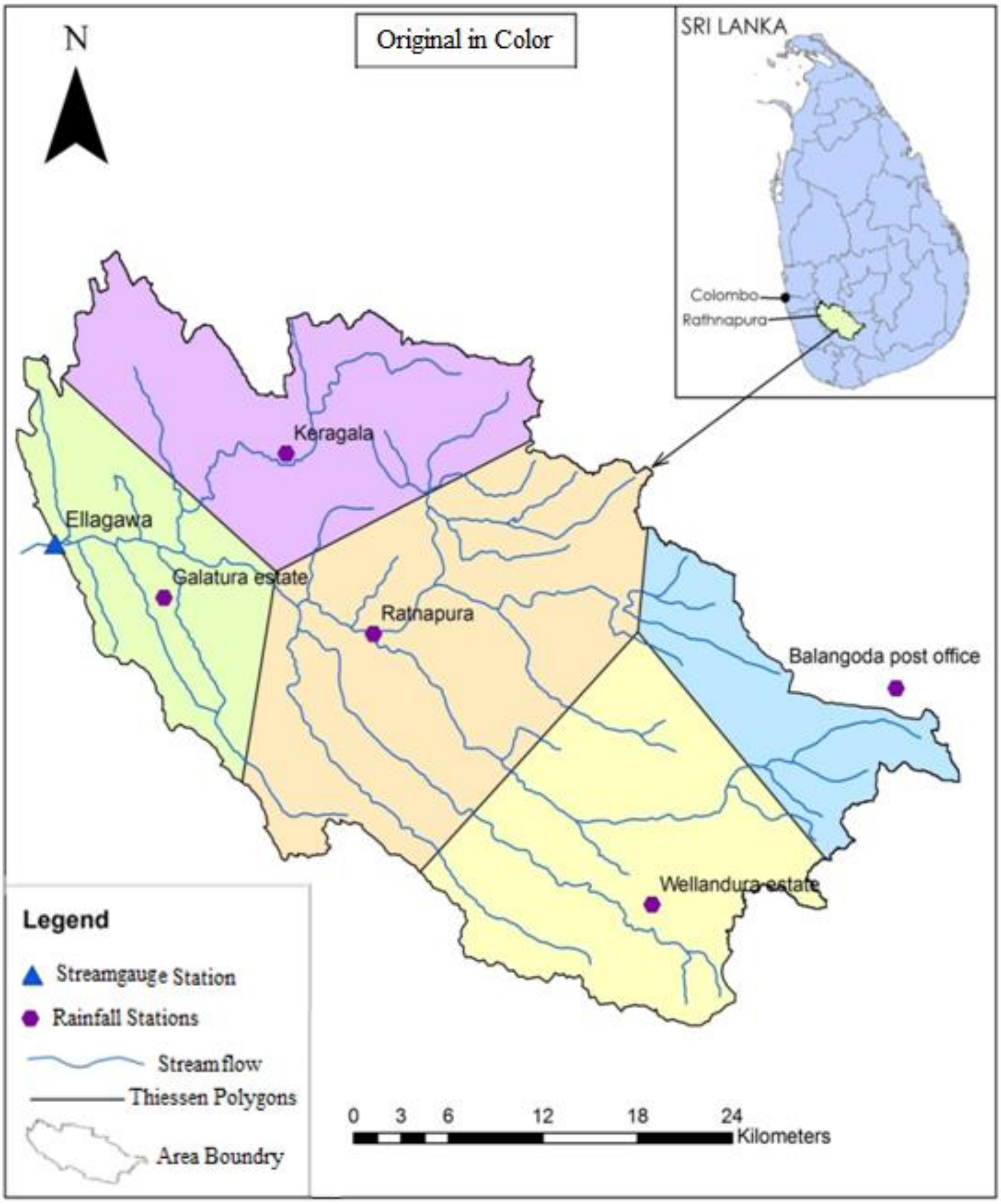


Figure 1-1: Catchment Area of Kalu Ganga at Ellagawa

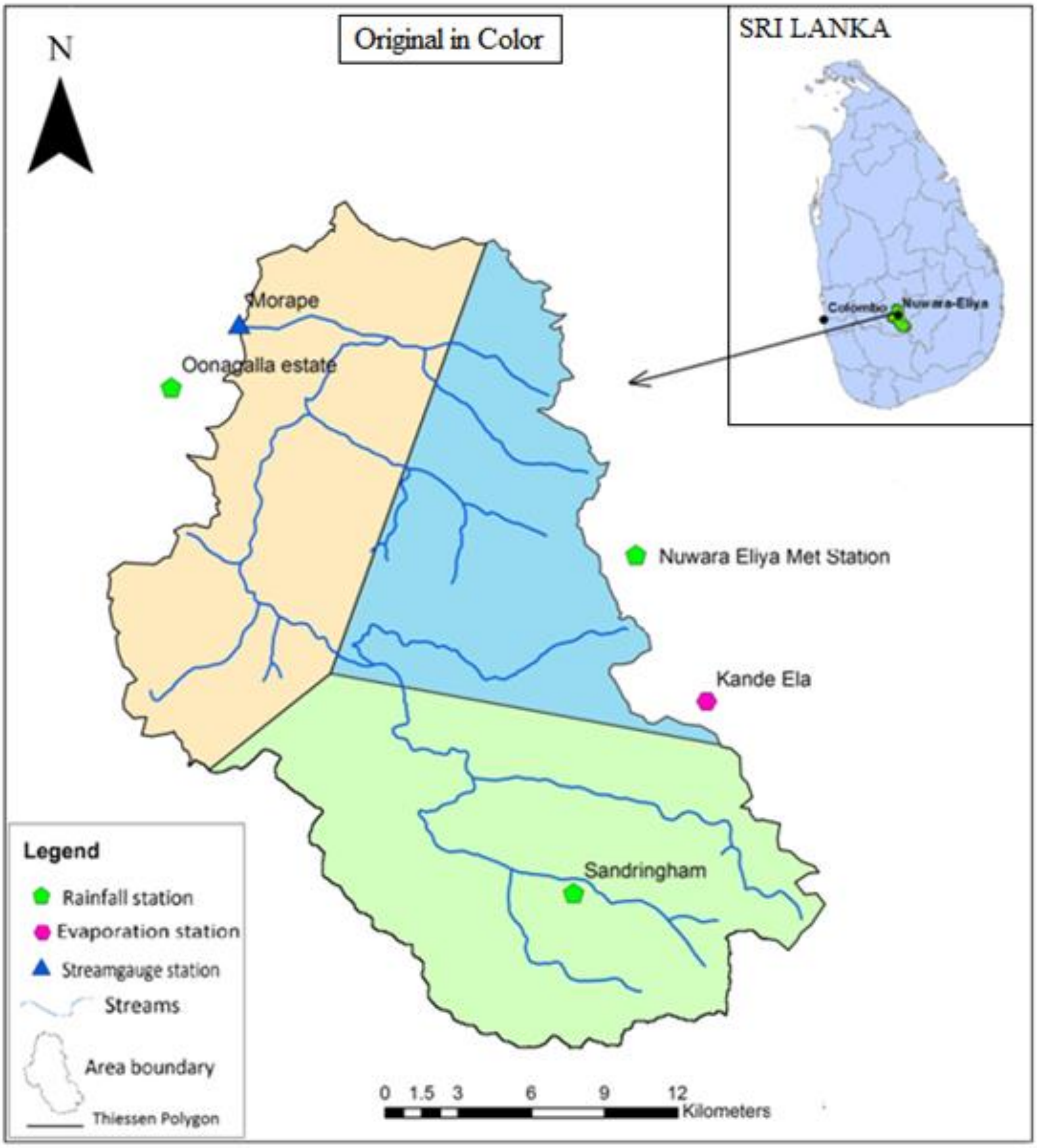


Figure 1-2: Catchment Area of Mehaweli at Morape

1.2 Objective of the Study

1.2.1 Overall Objective

Overall objective of the present study is to calibrate and verify a two parameter monthly water balance model and then to identify its application for water resource management.

1.2.2 Specific Objectives

The specific objectives of the study are:

i. Developing a two parameter monthly water balance model to estimate the streamflow hydrographs.
ii. Calibrate and verify the two parameter of monthly water balance model at Kalu Ganga and Mahaweli Ganga watersheds at Ellagawa and Morape respectively.
iii. Evaluate the streamflow estimates of the two parameter monthly water balance model to generate streamflow in the selected watersheds.
iv. Make recommendations for water resources management applications.

2 LITERATURE REVIEW

2.1 Types of Monthly Water Balance Models

Water balance models are essentially bookkeeping procedures which estimate the balance between the inflow of water from precipitation and the outflow of water by evapotranspiration, streamflow and groundwater recharge. These models have been used for predicting streamflow, lake levels, depths to groundwater and the hydrologic effects of weather modifications or changes in vegetation cover (Hydrological Annual, 1993/1994).

Monthly water balance models were first developed in the 1940s by Thornthwaite (1948) and later revised by Thornthwaite and Mather (1955, 1957). These models have since been adopted, modified, and applied to a wide spectrum of hydrological problems (Xu & Singh, 1998; (Xu et al., 1996); (Xiong & Guo, 1999); (Chen, Chen, & Xu, 2007).

Lu.Zhang, Walker & Dawes, (2002) in their work on water balance modeling concepts indicated that it is not the complexity that counts but the quality of output that depends mostly on clearly defined objectives and the appropriateness of selected model.

Water balance models have become an indispensable tool for the assessment, management, and use of water resources. They provide mechanisms to anticipate catchment behavior and evaluate the consequences of natural or human-induced changes. For hydrologists, such models are especially useful in the evaluation of assumptions and theories about the dominant hydrologic processes in a basin (Al-Lafta, Al-Tawash, & Al-Baldawi, 2013).

2.1.1 Monthly Water Balance Models Using Different Parameters

A variety of monthly water balance models with different number of parameter have been developed, ranging from relatively complex conceptual models with 12 parameters to very simple 2, 4 and 6 parameters. Mouelhi et al., (2006) applied GR2M model using 2 parameter; Xu et al., (1996) applied a monthly water balance model using 6 parameters; Martinez & Gupta, (2010) applied "abcd" model using 4 parameters; Hughes & Metzler, (1998) applied Pitman model using 12 parameters; Wang et al., (2011) applied Wapada model using 5 parameters; Vandewiele & Ni-Lar-Win, (1998) applied PE and P models using 3, 5 and 6, 5 parameters, respectively.

Xiong and Guo (1999) carried out a research in china using a two Parameter monthly water balance model to simulate the runoff in 70 sub-catchments ranging from 243-4660 km² and using 17 years of monthly rainfall, streamflow and evaporation data. In this study average values of R2 on the 8 sub-catchments from the Dongjiang Basin were 88.60% for calibration and 90.98% for verification; average values of R2 on the 21 sub-catchments from the Ganjiang Basin were 90.61% for calibration and 89.11% for verification; average values of R2 on the 41 sub-catchments from the Hanjiang Basin were 85.66% for calibration and 84.78% for verification; average values of R2 Ganjiang Basin were 84% for calibration and 71% for verification.

Al-Lafta et al., (2013) had applied a "abcd" monthly water balance model for three USA catchments with areas of 7940, 4369 and 290 km² using 17 years of monthly precipitation and potential evapotranspiration data. In this study the difference between the simulated outputs and observed outputs were measured by the Mean Square Error (MSE). The calibrated parameters a, b, c and d were 0.944, 700, 0.1 and 0.03 respectively with a mean square error of 8.25.

Huges & Metzler, (1998) applied three monthly rainfall runoff models (Pitman, Nam Pit and Namrom), for 5 semiarid catchments in Namibia with area ranging from 212 to 5463 km² and using 20 years of rainfall and streamflow data. In this the Pitman model had 12 parameters while the Nam Pit had 13 parameters and the Namrom had only 5 parameters.

2.1.2 Precipitation as Input

Rainfall or Precipitation constitutes one of the largest and essential components in the water balance equation. Rainfall is the most essential component in water balance estimations. It is a key forcing variable in hydrologic models and hence spatially and temporally correct rainfall measurements are critical for hydrologic modeling processes and for the management of water resources (Deus, Gloaguen, & Krause, 2013).

A common feature of monthly water balance models using rainfall as input is that evapotranspiration is calculated as a fraction of the rainfall and the rest of the rainfall is considered empirically as either infiltration and or direct runoff. Estimation of evapotranspiration as a fraction of rainfall is, clearly, not reliable on a monthly time scale, since it is not unusual for evapotranspiration to be greater than precipitation, especially during those months that follow immediate end of the rainy season, and the fact that rainfall is highly variable in most parts of the world. Hence, these models can be used as approximate tools for water resources planning in those regions where no other meteorological data are available (Xu & Singh, 1998).

Snyder (1963) developed the Tennessee Valley Authority (TVA) model for prediction of monthly water yield to analyze past records of streamflow and to predict yield from the watershed under varying patterns of rainfall. The tested area ranged from 3.7 to 426880 acres and computation had used a 32 month monthly rainfall data. This model by partitioning runoff into three components as (1) immediate runoff, (2) delayed runoff, calculated using a linear reservoir concept, (3) time function had carried out the computations.

2.1.3 Temperature as Input

In these models temperature is used as the driving force to estimate potential evapotranspiration for use with monthly rainfall as input data. These models differ in their treatment of the relationship between actual and potential evapotranspiration, soil moisture accounting and aquifer recharge (Xu & Singh, 1998; Calvo, 1986).

In Calvo, (1986), Thornthwaite water balance technique is used to predict monthly streamflow, with 15 years of monthly rainfall and temperature data as input. This work had been carried out in Rio Macho basin (47.4 km²) of Costa Rica. This study had affirmed that most of the mean estimated values fall between the 90% confidence intervals for the measured streamflow indicating the suitability for predicting monthly and annual streamflow for ungauged basins.

2.1.4 Rainfall & Potential Evapotranspiration as Input

Monthly areal precipitation and potential evapotranspiration are used as the sole inputs to most monthly rainfall-runoff models. These models have been developed in a wide range of climatic regions for an extensive range of applications and they vary considerably in their complexity.

Vandewiele & Elias, (1995) carried out a study of monthly water balance in 75 ungauged basins in Belgium with catchments ranging from 19 to 1597 km^2 and using monthly rainfall and potential evapotranspiration of 4 to 35 years. Kriging was used to compute the rainfall input. This had given good results in 72% of the basins.

A research on Stepwise development of a two-parameter (GR2M) monthly water balance model was carried out by Mouelhi et al., (2006) in order to compare with the different well-known water balance model results. This had been carried out for reservoir management and long-term drought forecasting in 410 basins (1-50600 km^2) while using 34 years monthly rainfall and potential evapotranspiration data. It had been revealed that the GR2M model performs very satisfactorily when compared with other models.

2.1.5 Monthly Water Balance Models Using Daily Data

Conceptual daily rainfall-runoff models are common in hydrology. They typically represent a drainage basin as a number of soil moisture stores, with mathematical functions symbolizing the hydrological processes. They are designed to closely simulate the basin hydrological response, with the primary intention of generating sequences of synthetic flow data from rainfall data (H. A. Houghton-Carr, 1999).

Wang et al., (2011) compared monthly versus daily water balance models in simulating monthly runoff over 331 catchments (ranging from 51 to 1979 km^2) using daily rainfall and monthly evaporation data to study the water supply demand alternatives in Australian catchments. In this study Wadapada monthly water balance model was compared with two daily SimHyd& AWMB models. In this work it had been found that, the model aggregate skill of Wapaba is better than that of AWBM in 59% of catchments, and better than that of SimHydin 47% of catchments.

Wijesekera, Musiake & Herath (1995) estimated the actual evapotranspiration of the three sub-catchments, using Tank model at monthly time scale, with respective extents of 4609 km², 515 km² and 4340 km² in the Chao Pharya river basin of Thailand. Rainfall, streamflow and evapotranspiration in daily timescale were used. The water balance of all three catchments showed that the topmost layer of each catchment does not become quite wet for more than three months of a year. The model had demonstrated a good matching of outflow hydrographs, realistic tank storages and annual water balance values of good agreement.

Monthly water balance models are used in the translation of catchment climatic characteristics such as rainfall, evapotranspiration and soil moisture into streamflow. A monthly timescale reflects that the models may need only a small number of parameters to represent hydrological behavior of catchments which in turn makes the model easier to calibrate for regionalized results to use in ungauged catchments. In principle, monthly water balance models take a simpler form and use a smaller number of parameters than the corresponding daily hydrological models (Wang et al., 2011).

2.2 Actual Evapotranspiration

Actual evapotranspiration (ET) is a critical component of water balance at plot, field, farm, catchment, basin or global level (Ketema Tilahun Zeleke, 2012). Compared with precipitation and streamflow, the magnitude of actual evaporation over the long term is more difficult to estimate (McMahon, Peel, Lowe, Srikanthan, & McVicar, 2013). Accurate spatial and temporal predictions of ET are required for water balance models (Xu & Singh, 1998) (Cao, Han, & Song, 2014). The estimations of groundwater storage and its feedback to ET are also important when assessing groundwater budget to develop sustainable groundwater management plans (Cao et al., 2014). Transpiration which is estimated as a fraction of the potential evapotranspiration, draws water first from the unsaturated store, and then from the saturated store in order to fulfill the aqauota (Robbie M. Andrew, 2007).

Many formulae are available for the calculation of the actual evapotranspiration of a catchment. The choice of a suitable formula depends on the availability of data and convenience. In the conversion of the pan evaporation to the actual evapotranspiration, one widely used method is to multiply pan evaporation value by a reduction factor. An interesting way to get the actual evapotranspiration from the pan evaporation is by using the ‘‘complimentary relationship between pan evaporation and actual evaporation’’ (Morton, 1983, (Xiong & Guo, 1999).

2.3 Model Evaluation and Parameter Optimization

Model testing includes two essential steps, i.e. Calibration and verification. Correspondingly, the whole dataset is divided into two parts, i.e. the calibration period and the verification period. Calibration refers to the process of using apart of dataset to find the optimum values of the model parameters. Verification is the process of using an independent dataset to justify the parameter values obtained with the calibration. Only when the performance of a model is satisfactory, in both calibration and verification periods, then the model could be used with confidence to achieve the objectives (Xiong & Guo, 1999).

Tekleab et al. (2011), carried out water balance modeling for 20 Ethiopian catchments with area ranging from 10 to 1000 km² and using 9 years rainfall and streamflow dataset to obtain better understanding of water balance dynamics. During the calibration period (1995–2000) the Nash- Sutcliffe efficiency (ENS) for monthly flow prediction had varied between 0.52 to 0.93, while the ENS varied between 0.32 to 0.90 using logarithms of flow series. Al-Lafta et al. (2013) in the “abcd” Monthly Water Balance model simulated and observed outputs were measured by the Mean Square Error (MSE) which produced a value of 8.25 for the best fitting. In Pakistan (Abulohom, Shah, & Ghumman, 2001) used monthly rainfall and evaporation data to model four catchments. Five parameters used in the model were estimated using the Downhill Simplex method. When the model was calibrated and tested, the statistical results showed a correlation coefficient between 77% and 93%.

2.3.1 Model efficiency criteria

The process of model performance evaluation is of primary importance, not only in the model development and calibration process, but also when communicating the results to other researchers and to stakeholders. The basic ‘rule’ is that every modeling result should be put into context, for example, by indicating the model performance using appropriate indicators, and by highlighting potential sources of uncertainty, and this practice has found its entry into the large majority of papers and Conference presentations (Bettina, Schaefli & Gupta, 2007).

Efficiency (E) proposed by Nash and Sutcliffe (1970) is the measurement that is used to evaluate the hydrograph matching in most literature (Tekleab et al., 2011). The range of E lies between 1.0 and $-\infty$. An efficiency of lower than zero indicates that the mean value of the observed time series would have been a better predictor than the model. 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(Krause, Boyle, & Bäse, 2005).

Chen et al., (2007) carried out a research on developing a monthly hydrological model for integrating spatial variations of basin topography and rainfall using monthly rainfall and streamflow in two watersheds in China with areas 78595 and 25325 km2. The model had produced good results for Nash–Sutcliffe efficiency coefficient. The Nash–Sutcliffe efficiency coefficient for Yuanjiang watershed and its nested basins were found in between 0.75 and 0.90.

2.3.2 Parameter Optimization and Selection of Objective function

Parameter optimization for the mathematical models in hydrology is difficult because these models are multi-dimensional, nonlinear, multimodal, lacking a convex response surface, with interdependent and complementary parameters (Zhang, Wang, & Meng, 2015). Deterministic rainfall-runoff models require parameter calibration with the aim of matching the modeled streamflow record to an observed record as closely as possible (Cohen, Ollington & Linga, 2013).

The objective functions are to help with the calibration of parameters and for assessing verification. Their formulations to fulfill a particular influence on the shape and values of the series calculated with the use of model. One objective function may have an important effect on low levels of flow, while another would influence the flood peak. The objective functions are the indicators of the suitability of model estimations. As a result, the value of any objective function enable some solutions to be eliminated or rejected, enabling the evaluation of model output quality as a whole (Servat & Dezetter, 1991).

M. H. Diskin (1977) indicated in his study of a Procedure for the selection of objective functions for hydrologic models, that the choice of data and the objective function is a subjective decision which influences the values of model parameters on the performance of the model. In this paper a procedure for the selection of objective function is outlined.

Madsen (2000) in a study of automatic calibration of a conceptual rainfall–runoff model using multiple objectives had indicated following reasons for using an objective function in a hydrologic module. 1) A good agreement between the averages of simulated and observed catchment runoff volume. 2) A good overall agreement of the shape of the hydrograph. 3) A good agreement of the peak flows with respect to timing, rate and volume and.4) A good agreement of low flows.

Mata-Lima (2011) using different options in his study of evaluating the objective functions to improve the matching performance revealed that a suitable approach requires the adoption of an objective function that combines lag time with deviation-based-statistic (SSR), to enhance the history of matching process. Moreover, it had revealed that use of some statistical indicators as objective functions can lead to incorrect selection of the best realization from a series of candidate realizations.

In the present study, Nash–Sutcliffe criterion which is proposed by Nash and Sutcliffe (1970), and the Mean Ratio of Absolute Error (MRAE), which is suggested by World Meteorological Organization (WMO, 1975) have been computed to evaluate the model efficiency and to match each and every point of the two hydrographs relative to the observed value at that particular time point (Perera & Wijesekera, 2011).

$$MRAE = \frac{1}{n} \sum \frac{|Qc - Qo|}{Q_O} \qquad \textbf{(1)}$$

In equations (1), Qo is the observed streamflow and Qc is the calculated streamflow and n is the number of observations used for comparison.

Wannirachchi (2013) in his study of mathematical modeling of watershed runoff coefficient for reliable estimation to met the future challenges of water resource development has found good model performance through estimation of MRAE which gives 0.39 and 0.35 for calibration and verification period respectively.

Wijesekera & Rajapaske (2013) derived a Mathematical Modeling of watershed wetland crossings for flood mitigation and groundwater on Attanagalu Oya River Basin with an area of 790 km² using 4 years daily rainfall and streamflow data. An Eco friendly distributed watershed model was developed, calibrated and verified. The Mean Ratio of Absolute Error (MRAE) during calibration was 0.66 while the same at validation was 0.70.

3 METHODOLOGY

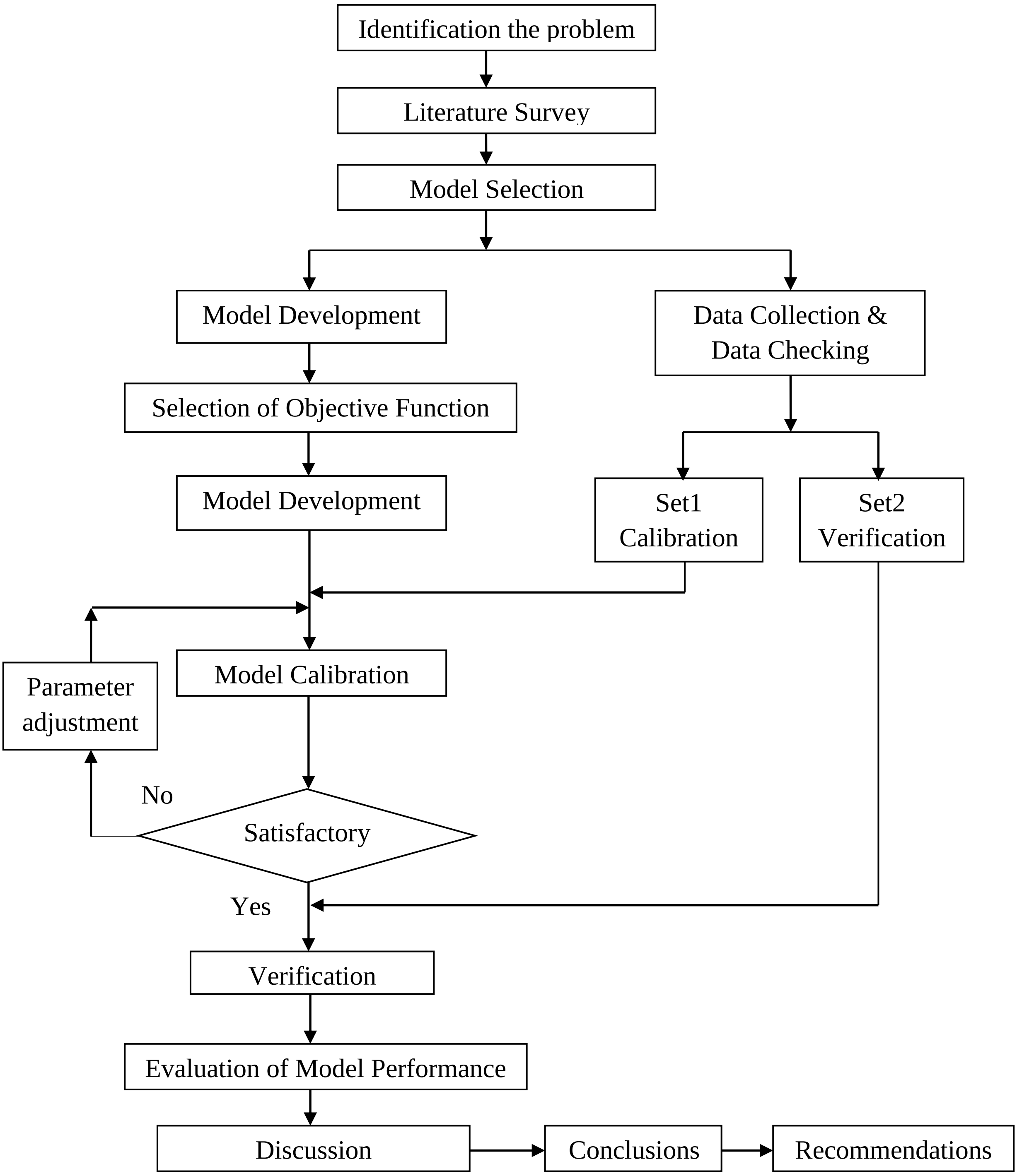


Figure 3-1: Methodology Flow chart

4 DATA AND DATA CHECKING

4.1 Study Area

Two sub watersheds at two major basins of Sri Lanka were selected for this study. They are Kalu Ganaga at Ellagawa (Figure 1.1) and Mahaweli at Morape (Figure1.2).

4.1.1 Kalu Ganga at Ellagawa

Kalu Ganga basin is one of the most important river basins in Sri Lanka which receives a very high rainfall and has high discharges. The Ellagawa watershed is a sub watershed of Kalu Ganga in Rathnapura district of Sri Lanka. Kalu Gnaga river basin lies in between Kelani Ganga and Gin Ganga river basins. Drainage area of the Ellagawa watershed is approximately 1490 km2. Ellagawa watershed has five rain gauging stations which are Galatura estate, Balangoda Post office, Wellandura estate, Ratnapura and Keragala. Rathnapura was selected as the evaporation station for this study (Figure 1.1).

4.1.2 Mahaweli at Morape

Mahaweli river is 335 km long and is the longest river in Sri Lanka. Its drainage basin is the largest in the country, and covers almost one-fifth of the total area of the island. Mahaweli Ganga catchment at Morape streamgauge station has a drainage area of 541.6 km2. Morape streamgauge station data and data from three rainfall stations which are Nuwara Eliya Met Station, Oonagalla Estate and Sandrigham were selected for this study. Pan evaporation data for the study was collected from Kande Ela station (Figure1.2).

Table 4-1: Land use Distribution of Kalu Ganga Watershed at Ellagawa

Land Use Type	Area (km2)	Percentage of Area
Cultivation (paddy, tea, coconut, rubber & chena)	874.87	61%
Forest & Scurb land	239.49	17.23%
Homesteads/Garden	250.65	18.03%
Marsh land/other	26.98	1.94%
Rock, stream and Tank	25	1.8%

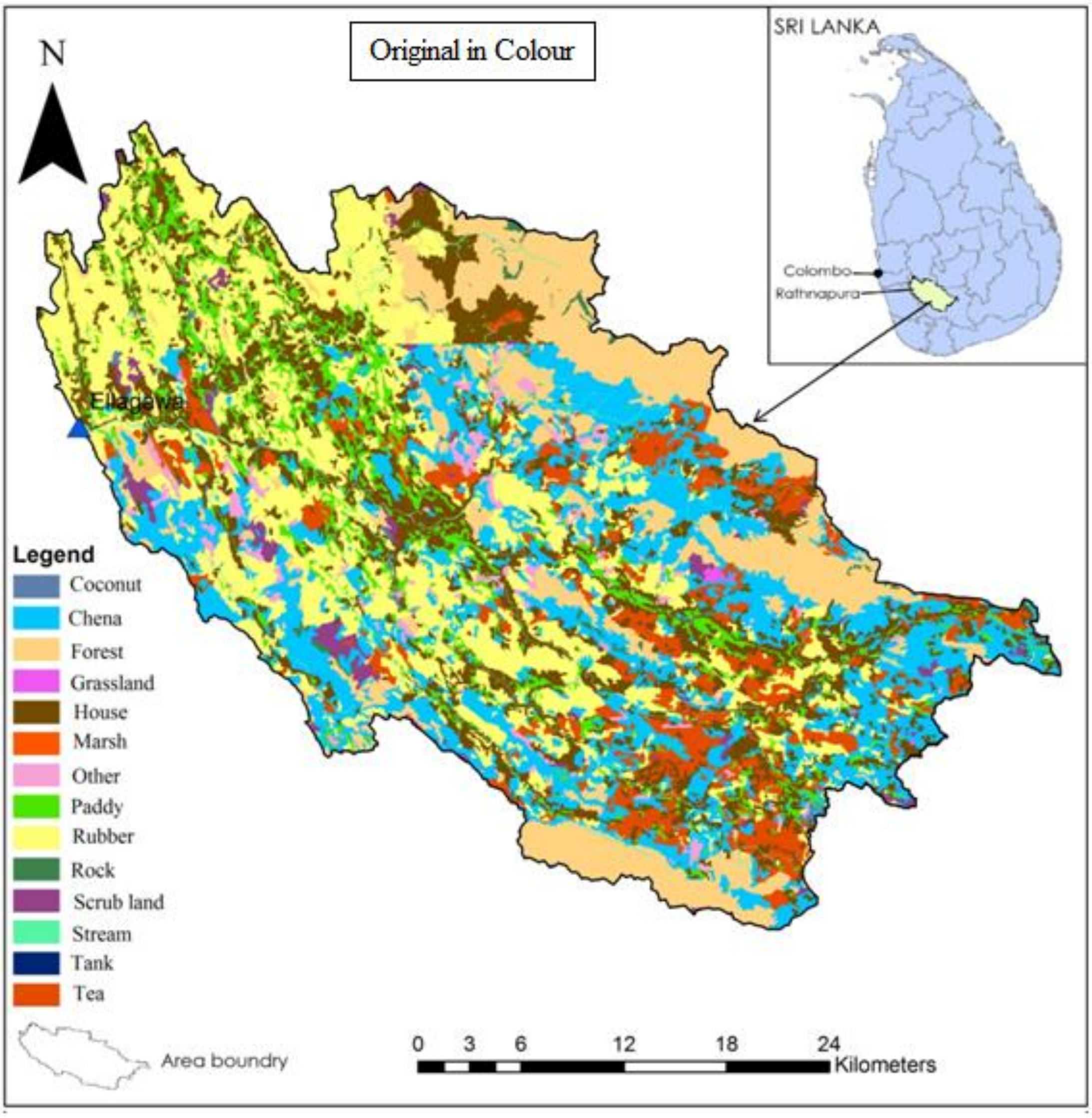


Figure 4-1: Landuse Map of Kalu Ganga Watershed at Ellagawa

Table 4-2: Land use Distribution of Mahaweli Watershed at Morape

Land Use Type	Area (km^2)	Percentage of Area
Cultivation (paddy, tea)	299.11	55.19%
Forest, Marsh & other	179.89	33.19%
Reservoir, Stream, Water & Tank	9.29	1.71%
Home sleads	28.36	5.23%
Rock, Scrb, Cmtya	25.29	4.66%

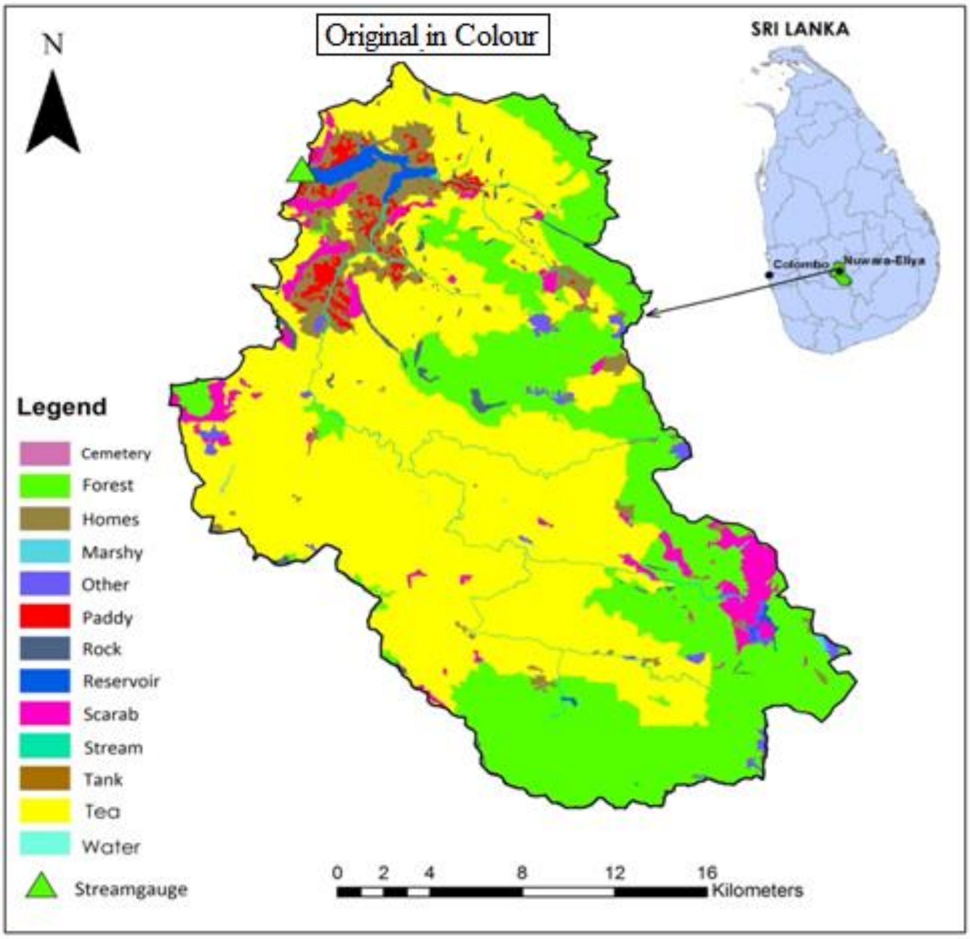


Figure 4-2: Land use Map of Mahaweli Watershed at Morape

4.2 Data

Rainfall, stramfllow, pan evaporation and topographic data are the main data used in this study.

Stramfllow data for the selected basin were collected from the Department of Irrigation and from the Masterplan of the Electricity Supply of Sri Lank respectively. Rainfall and evaporation data for Kalu Gang at Ellagawa and Mahaweli at Morape were collected from Meteorology Department of Sri Lanka and Masterplan of the Electricity Supply of Sri Lanka respectively. The data sources and resolutions are indicated in the Table 4-3 and Table 4-4 for Kalu Ganga at Ellagawa and Mehaweli at Morape respectively.

Comparison of rainfall, streamflow and pan evaporation data are in Appendix A.

Table 4-3: Data source and Data availability of Kalu Ganga at Ellagawa

Data types	Spatial Resolution	Station Name	Data Period	Source
Rainfall	Monthly	Galatura estate	1984-2013	Department of Meteorology
		Balangoda Post office	1984-2013	
		Wellandura estate	1984-2013	
		Ratnapura	1984-2013	
		Keragala	1984-2013	
Streamflow	Monthly	Ellagawa	1984-2013	Department of Irrigation
Pan evaporation	Monthly	Rathnapura	1984-2013	Department of Meteorology
Land use map	1:50,000		Updated	Department of Survey
Topographic	1:50,000		Updated	Department of Survey

Table 4-4: Data source and Data availability of Mahaweli Ganga at Morape

Data types	Spatial Resolution	Station Name	Data Period	Source
Rainfall	Monthly	Nuwara Eliya Met	1949-1979	Masterplan of the Electricity Supply of Sri Lanka
		Oonagalla Estate	1949-1979	
		Sandrigham	1949-1979	
Streamflow	Monthly	Morape	1949-1979	Masterplan of the Electricity Supply of Sri Lanka
Pan evaporation	Monthly	Kande Ela	1949-1979	Masterplan of the Electricity Supply of Sri Lanka
Land use map	1:50,000		2001	Department of Survey
Topographic	1:50,000		2001	Department of Survey

4.2.1 Rainfall and Streamflow

Monthly rainfall and streamflow data were used for the analysis of both Kalu Ganga and Mahaweli Ganga catchments. Locations of the stations are indicated in Table 4-5 and Table 4-6.

Table 4-5: Gauging Station Details of Kalu Ganga at Ellagawa

Rain Gauging Station	**Location Details**		
	Co-ordinates		**Location Relative to the Catchment Boundary**
	Latitude	Longitude	
Ellagawa	6.9 N	8.44 E	At the boundary
Galatura estate	6.70 N	80.28 E	Inside the boundary
Balangoda Post office	6.65N	80.70 E	Outside the boundary
Wellandura estate	6.53 N	80.57 E	Inside the boundary
Ratnapura	6.68 N	80.40 E	Inside the boundary

Table 4-6: Gauging Station Details of Mahaweli Ganga at Morape

Rain Gauging Station	**Location Details**		
	Co-ordinates		**Location Relative to the Catchment Boundary**
	Latitude	**Longitude**	
Morape (SF)	40N	20E	At the boundary
NuwaraEliya Met	6.90 N	81.12 E	Outside the boundary
Oonagalla Estate	6.78 N	81.02 E	Outside the boundary
Sandrigham	6.73 N	81.10 E	Inside the boundary

4.3 Data Checking

Spatial distribution of streamflow and rainfall stations were checked and compared as per the guideline of World Meteorological Organization (WMO, 1975).

Table 4-7: Distribution of Gauging Stations in Kalu Ganga at Ellagawa

Gauging Station	**Number of Stations**	**Station Density (km^2/station)**	**WMO Standards (km^2/station)**
Rainfall	6	278	575
Streamflow	1	1390	1875

Table 4-8: Distribution of Mahaweli Ganga at Morape

Gauging Station	**Number of Stations**	**Station Density (km^2/station)**	**WMO Standards (km^2/station)**
Rainfall	3	180	575
Streamflow	1	542	1875

Results of Kalu Ganga at Ellagawa (278 km2) and Mahaweli Ganga at Morape (180 km2) showed satisfactory outputs. Data were checked for missing periods. Regression analysis was done, after single mass curve analysis, to find the rainfall missing data. In the selected data period for streamflow no missing data was found for both Kalu Ganga and Mahaweli Ganga. Statistical checking of mean and standard deviation was done to check and verify the higher and lower outliers.

4.3.1 Consistency Checking

Prior to use, all rainfall records of all stations were checked for continuity and consistency. Station wise consistency checking of the data is indicated in Appendix-A Figures A1 to A4 (a-h). The correlation studies of monthly streamflow and monthly rainfall and same in seasonal context are indicated in Appendix-A figure A5 to A8 (i-m).

Prior to fill the missing rainfall data, single mass curve of rainfall stations were plotted to find out the correlation between them. Figure 4-3 & 4-4 indicate the correlation of rainfall data in both Kalu Ganga and Mahaweli Ganga respectively.

4.3.2 Graphical Checking

Graphical methods provide details about the outliers, data errors, missing period etc., of a hydrologic time series that may not be easily identified with statistical methods.

Hence, monthly, yearly and seasonal comparison of rainfall, streamflow and pan evaporation were plotted to check the patterns, shift from patterns or out of range values.

For both catchments, the graphical plots of monthly (Figure 4-5 to 4-8 & 4-11 to 4-13), Seasonal (Appendix A, Figure A6 & A8 and Figure A9, A10 & A11) and Annual (Figure 4-9 to 4-10 & 4-14 to 4-15) showed the expected behavior of rainfall and observedflow.

Figure (4-5) to Figure (4-8) indicate the graphical plot of Kalu Ganga Thiessen rainfall with observedflow. All five selected rainfall stations were checked. The maximum monthly Thiessen averaged rainfall was found as 771.18 mm while the minimum monthly rainfall was found as a 10 mm. Thiessen polygons are shown in Figure 1-1.

Figure (4-11) to Figure (4-13) indicate the graphical plot of Mahaweli Ganga Thiessen rainfall with observedflow. All three selected rainfall stations of Mahaweli Ganga were checked. The maximum Thiessen averaged monthly rainfall was found as 709.05 mm while the minimum rainfall was found as 9.89 mm. Thiessen polygons are shown in Figure 1-2.

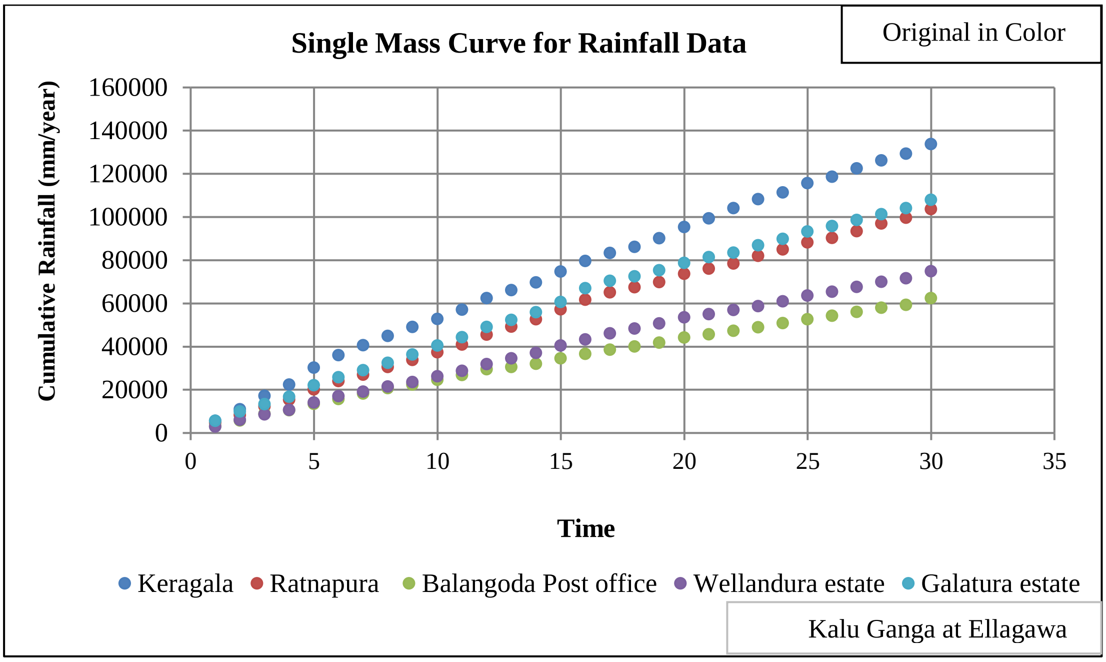


Figure 4-3: Single Mass curve Analysis for Rainfall Stations in Kalu Ganga

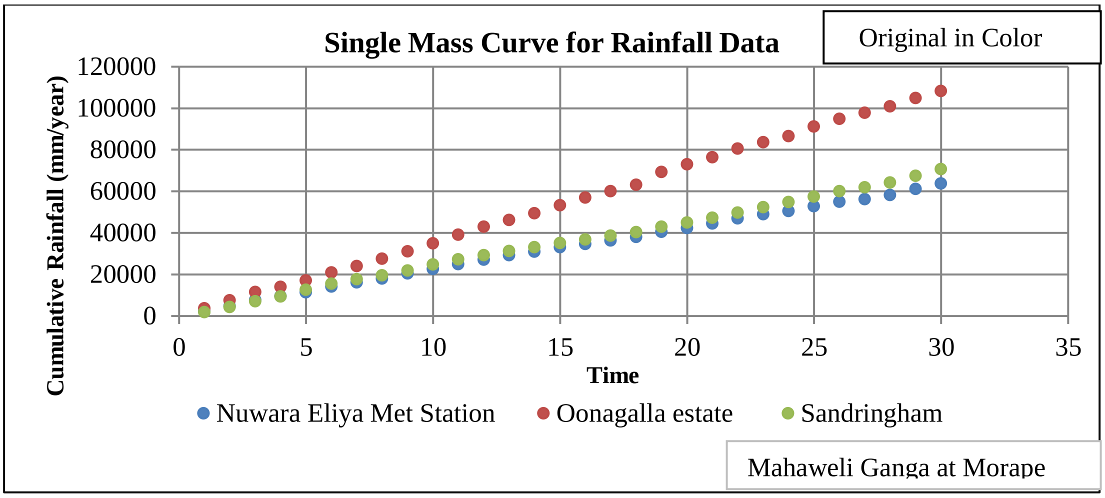


Figure 4-4: Single Mass curve Analysis for Rainfall stations in Mahaweli Ganga

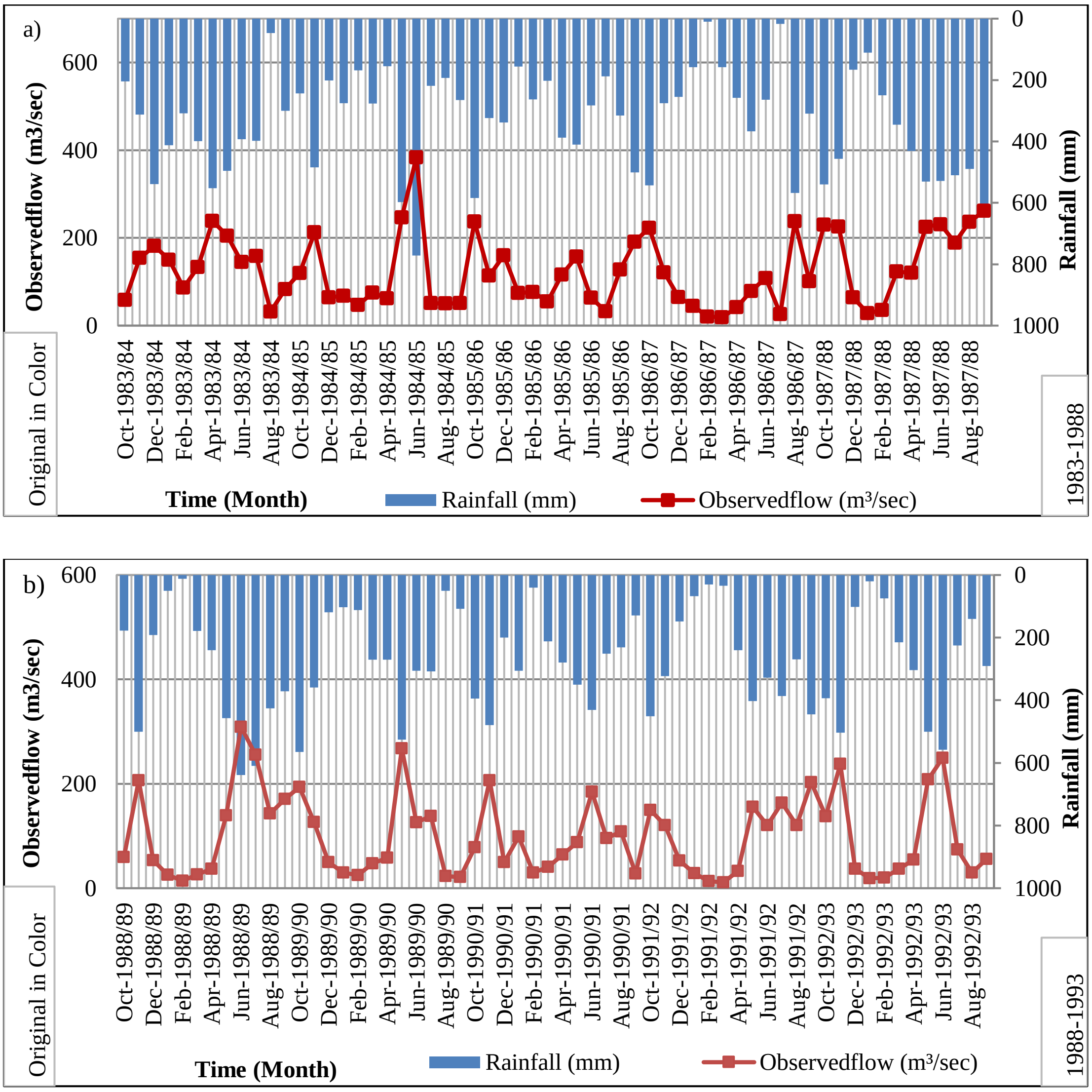


Figure:4-5: Thiessen Rainfall Corresponding to Observedflow in Kalu Ganga (a-b)

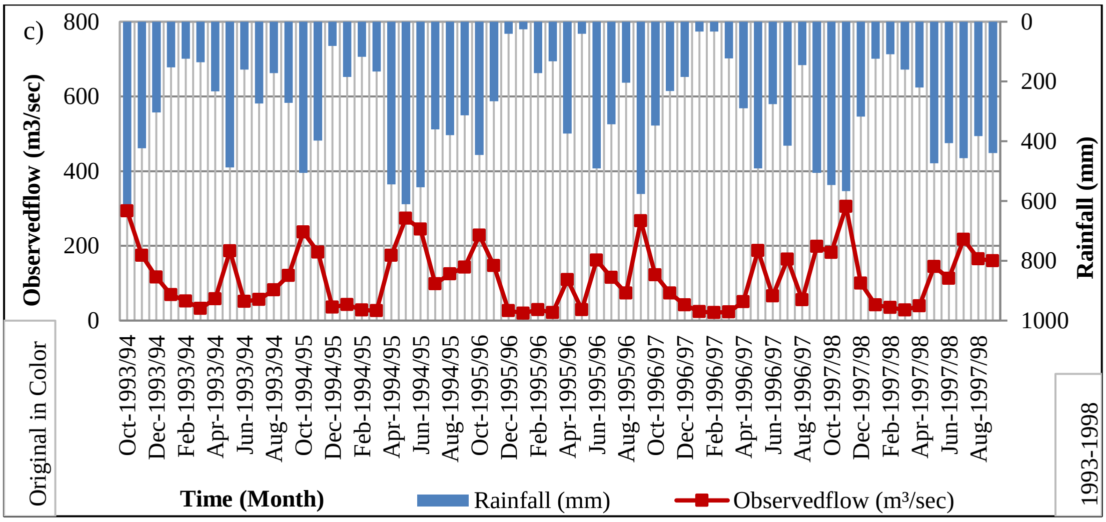


Figure:4-6: Thiessen Rainfall Corresponding to Observedflow in Kalu Ganga (a-c)

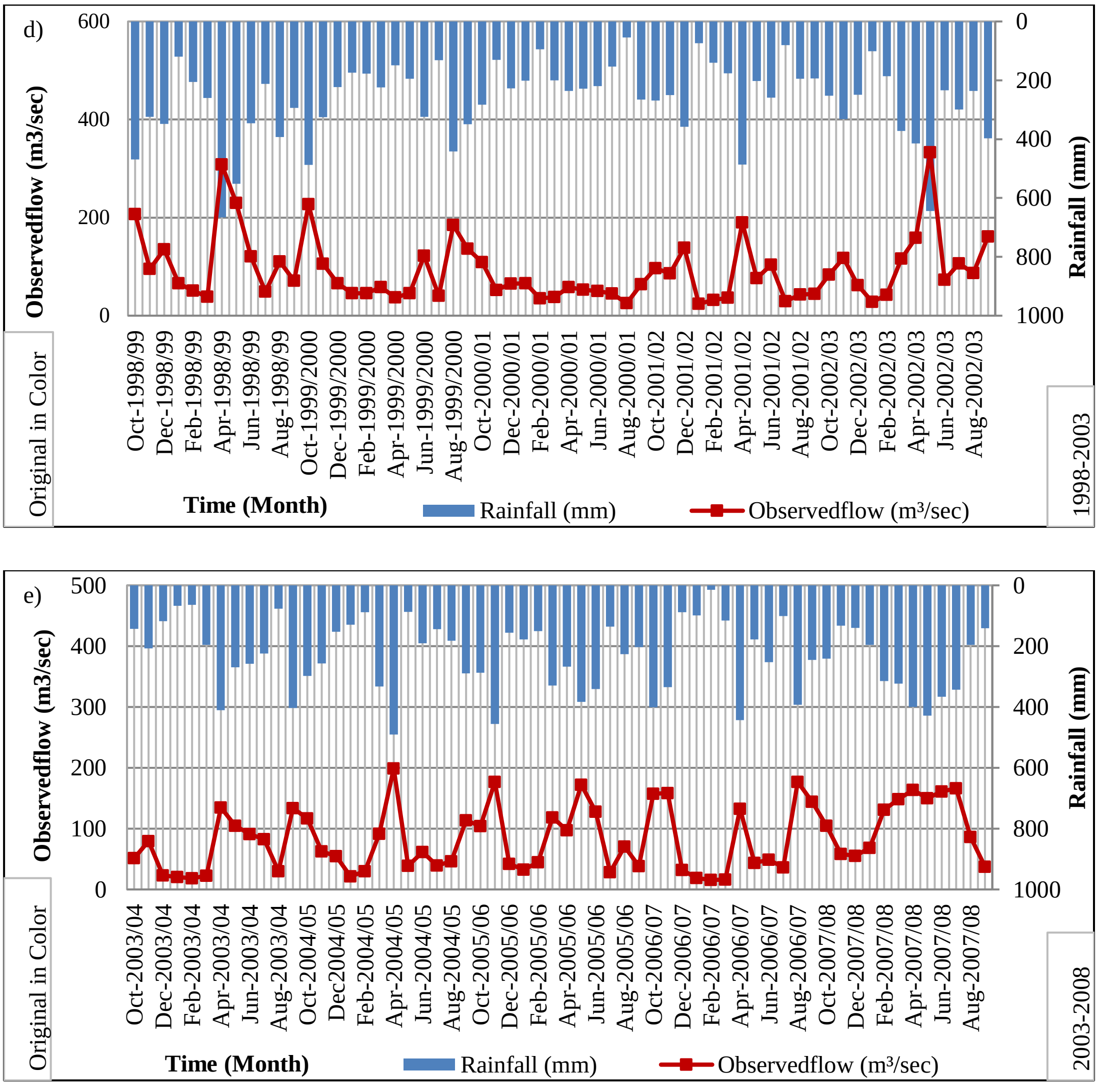


Figure:4-7: Thiessen Rainfall Corresponding to Observedflow in Kalu Ganga (c-e)

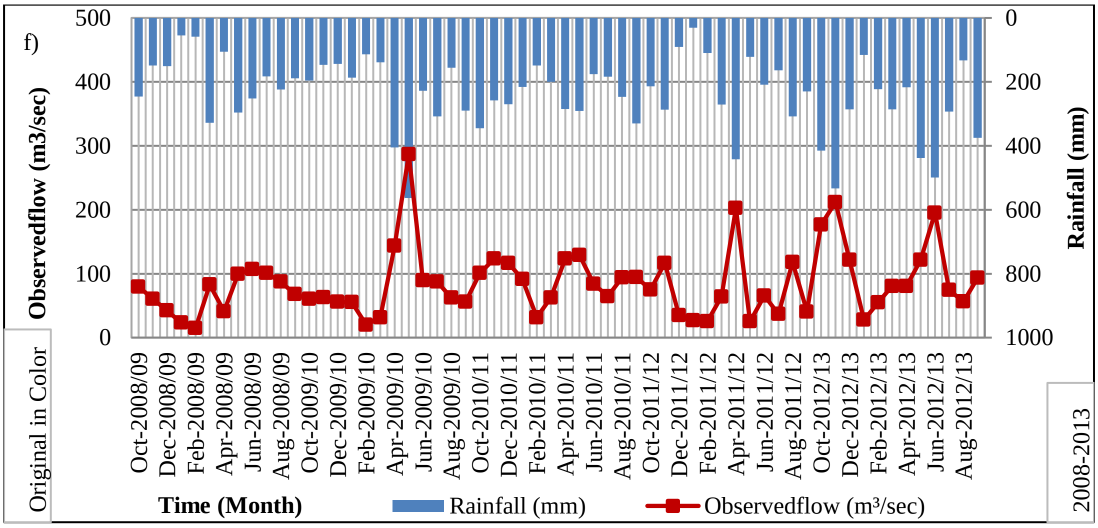


Figure 4-8: Thiessen Rainfall Corresponding to Observedflow in Kalu Ganga (f)

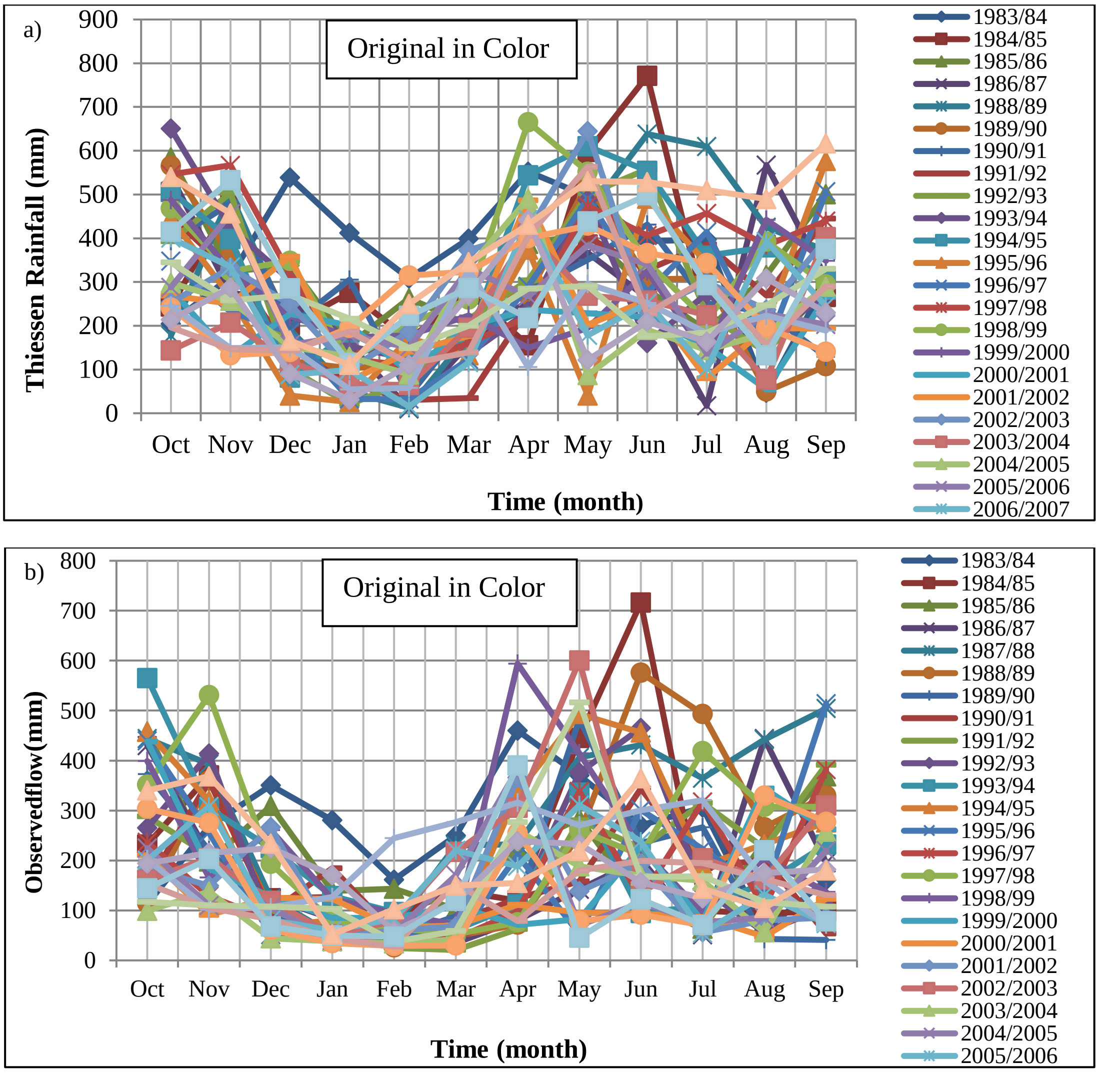


Figure 4-9: Variation of Thiessen Rainfall & Observedflow in Kalu Ganga (a-b)

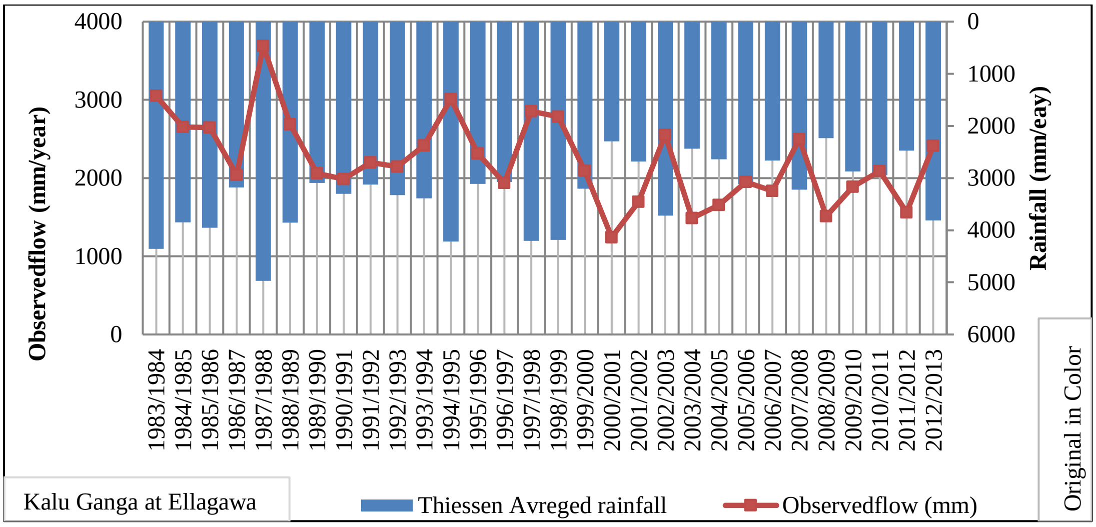


Figure 4-10: Annual Rainfall Corresponding to Observedflow in Kalu Ganga

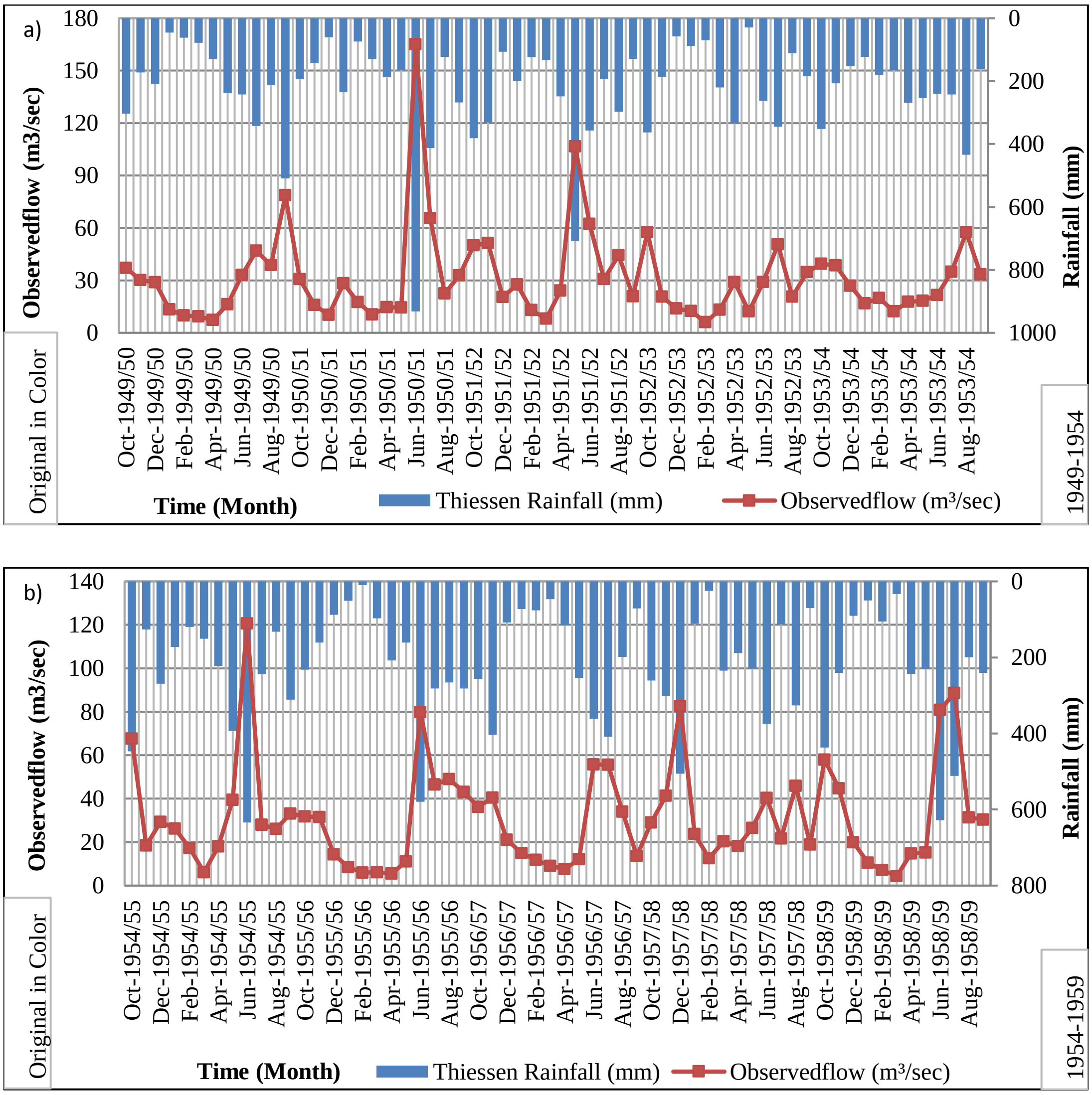


Figure 4-11: Thiessen Rainfall Corresponding to Observedflow in Mahaweli (a-b)

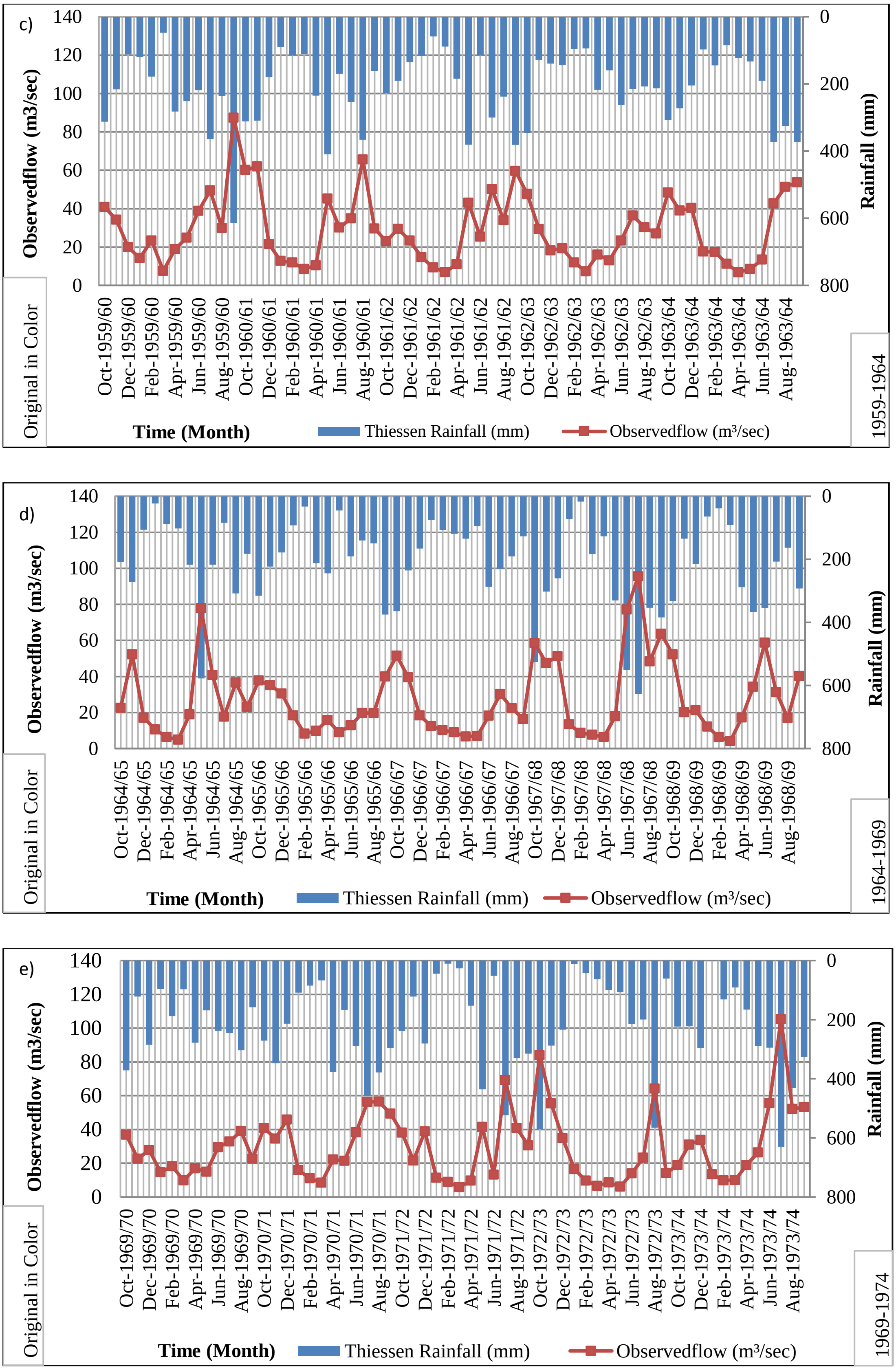


Figure 4-12: Thiessen Rainfall Corresponding to Observedflow in Mahaweli Ganga (c-e)

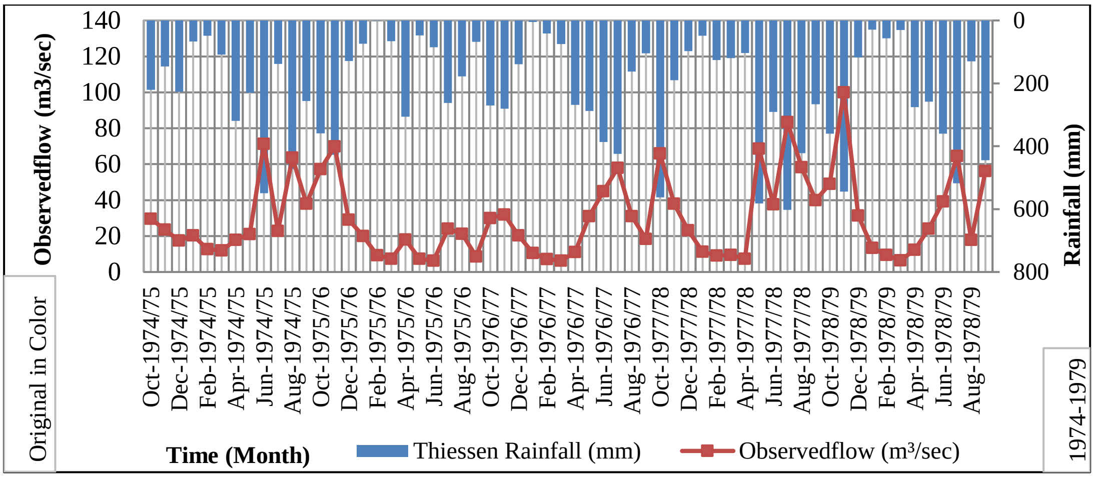


Figure 4-13: Thiessen Rainfall Corresponding to Observedflow in Mahaweli Ganga

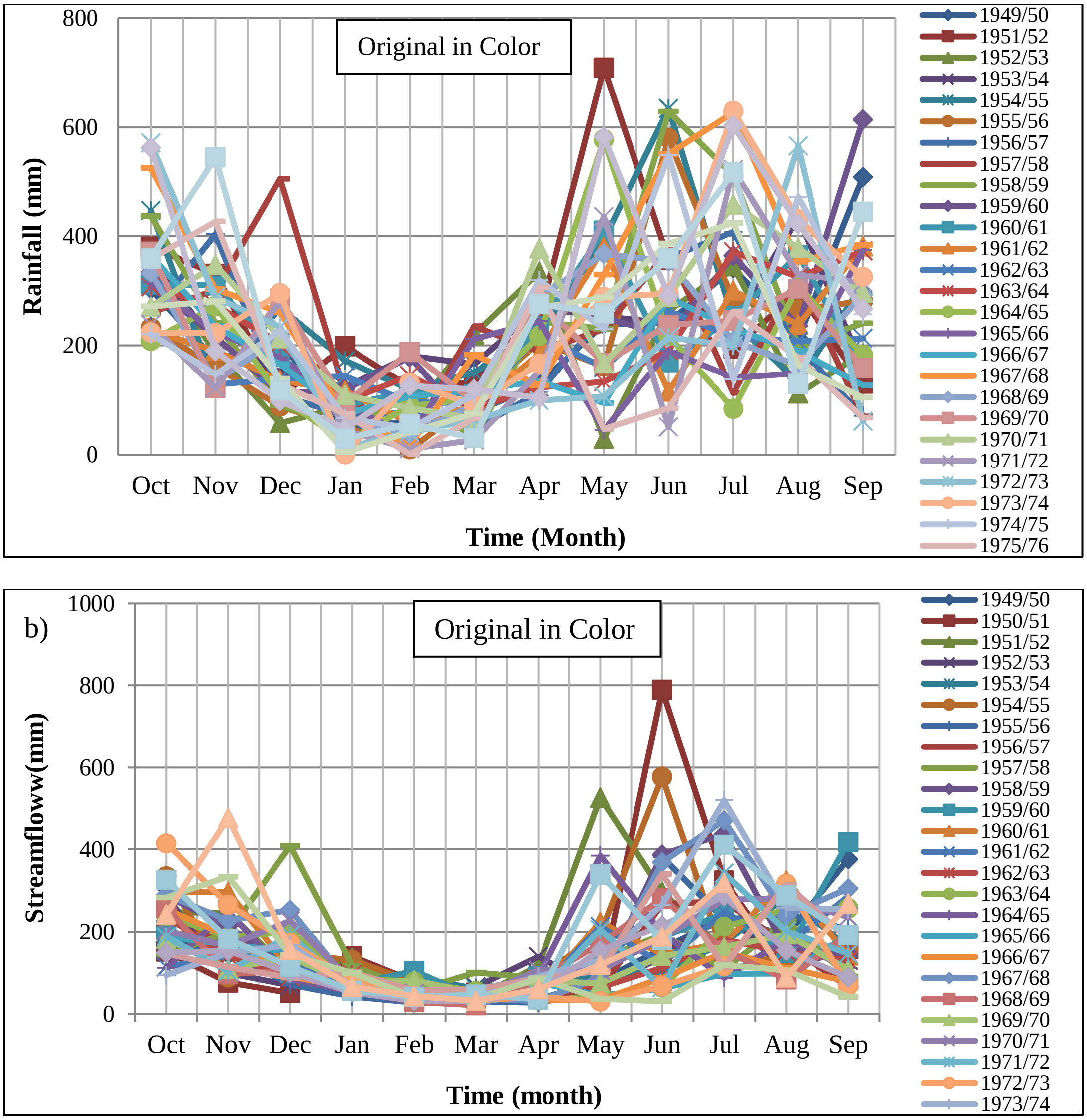


Figure 4-14: Variation of Thiessen Rainfall and Observedflow in Mahaweli Ganga (a-b)

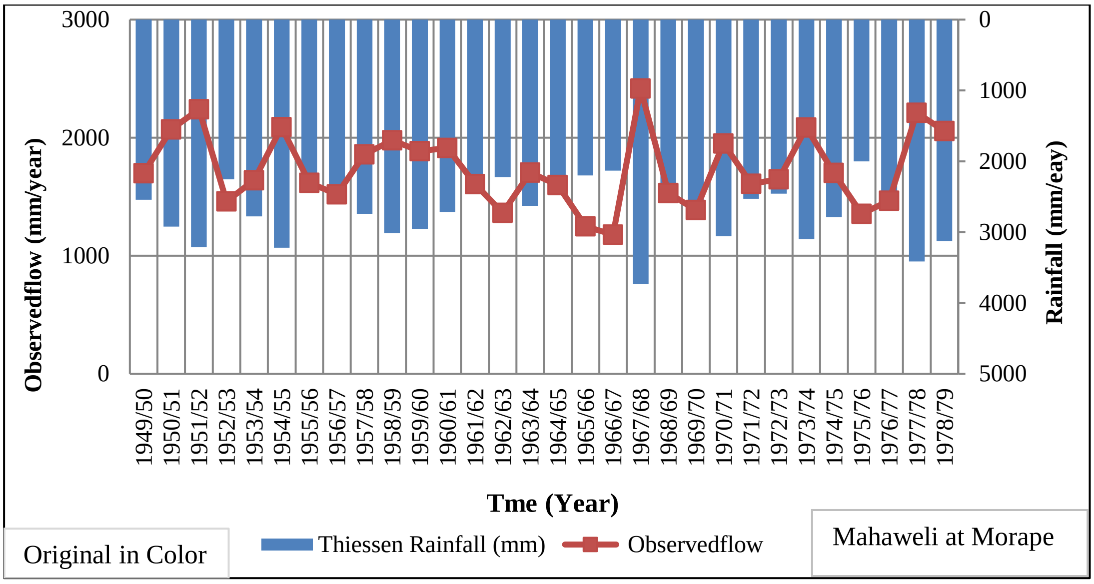


Figure 4-15: Annual Rainfall Corresponding to Observedflow of Mahaweli Ganga

5 ANALYSIS AND RESULTS

5.1 Thiessen Averaged Rainfall

ArcGIS software was used for the estimation of Thiessen averaged rainfall for the selected catchments. Corresponding Thiessen polygon areas and weights are in Table 5-1 and 5-2 respectively.

Table 5-1: Thiessen Areas and Weights of Rainfall Stations in Kalu Ganga

Rain Gauging Stations	**Thiessen Area (km 2)**	**Thiessen Weight (%)**
Galatura estate	194.59	14
Keragala	290.09	21
Ratnapura	436.31	31
Balangoda Post office	137.95	10
Wellandura estate	330.93	24

Table 5-2: Thiessen Areas and Weights of Rainfall Stations in Mahaweli Ganga

Rain Gauging Stations	**Thiessen Area (km)2**	**Thiessen Weight (%)**
Sandringham	226.7	42
Nuwara Eliya Met Station	139.91	26
Oonagalla estate	175.35	32

Comparison of Thiessen averaged monthly rainfall and arithmetic average rainfalls are shown in Appendix A, Figure A-12 and Figure A-13 and values are shown in Appendix B, Table B-10 and Table B-18.

5.2 Classification of high intermediate and low flows

Determination of high, medium and low flows was carried out by using the flow duration curve. Flow duration curve provides information about the percentage of time that a particular streamflow had exceeded over a particular historical period. Generally it is represented on a log- normal scale with exceedence probability on the x-axis and discharge on the y-axis. The following steps were followed to determine High, Intermediate and low flow thresholds for both selected catchments.

a) Yearly flow duration curves were generated to obtain the behavior of high, medium and low flows, and to approximate the thresholds.

Yearly flow duration curves for Kalu Ganga at Ellagawa and Mahaweli Ganga at Morape are in Figure 5-1 (a-b) respectively.

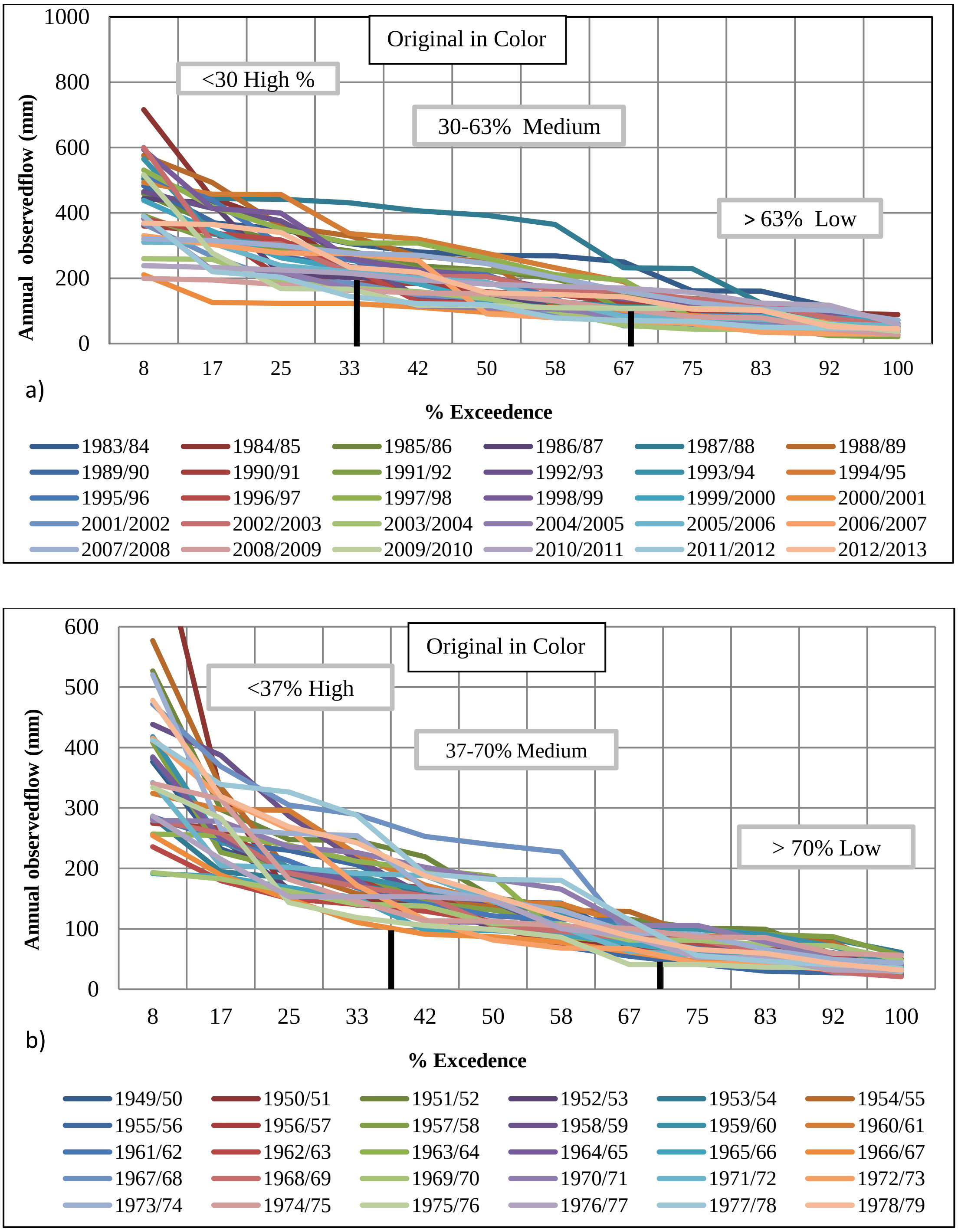


Figure 5-1: Annual flow Duration Curves in Kalu Ganga and Mahaweli Ganga (a-b)

b) Annual meanflow duration curve was plotted to confirm the thresholds for high, medium and low flows. The annual mean flow duration curve with its log plot for the selected two catchments with respective threshold values are shown in Figure 5-2, Figure 5-3 and Figure 5-4.

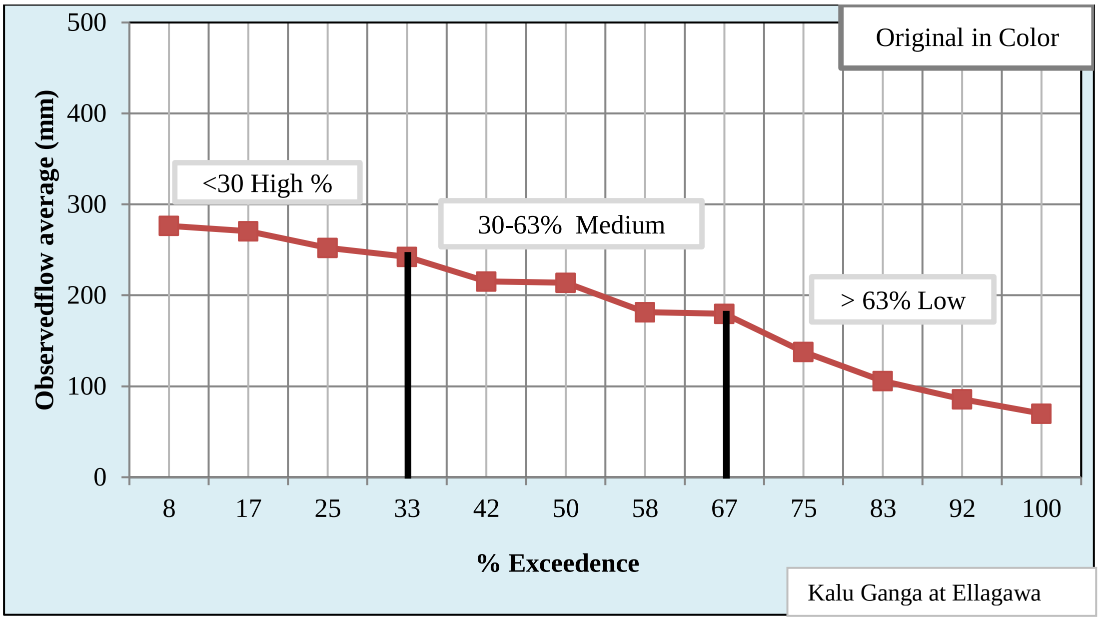


Figure: 5-2: Annual Mean Flow Duration curve in Kalu Ganga at Ellagawa

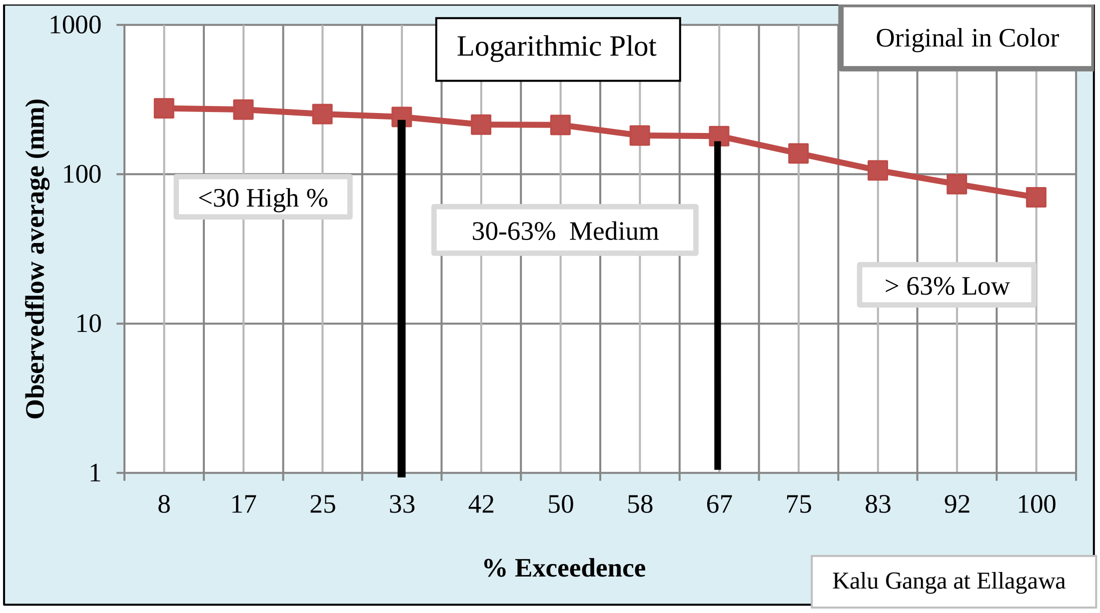


Figure 5-3: Log Plot of Annual Mean Flow Duration Curve in Kalu Ganga

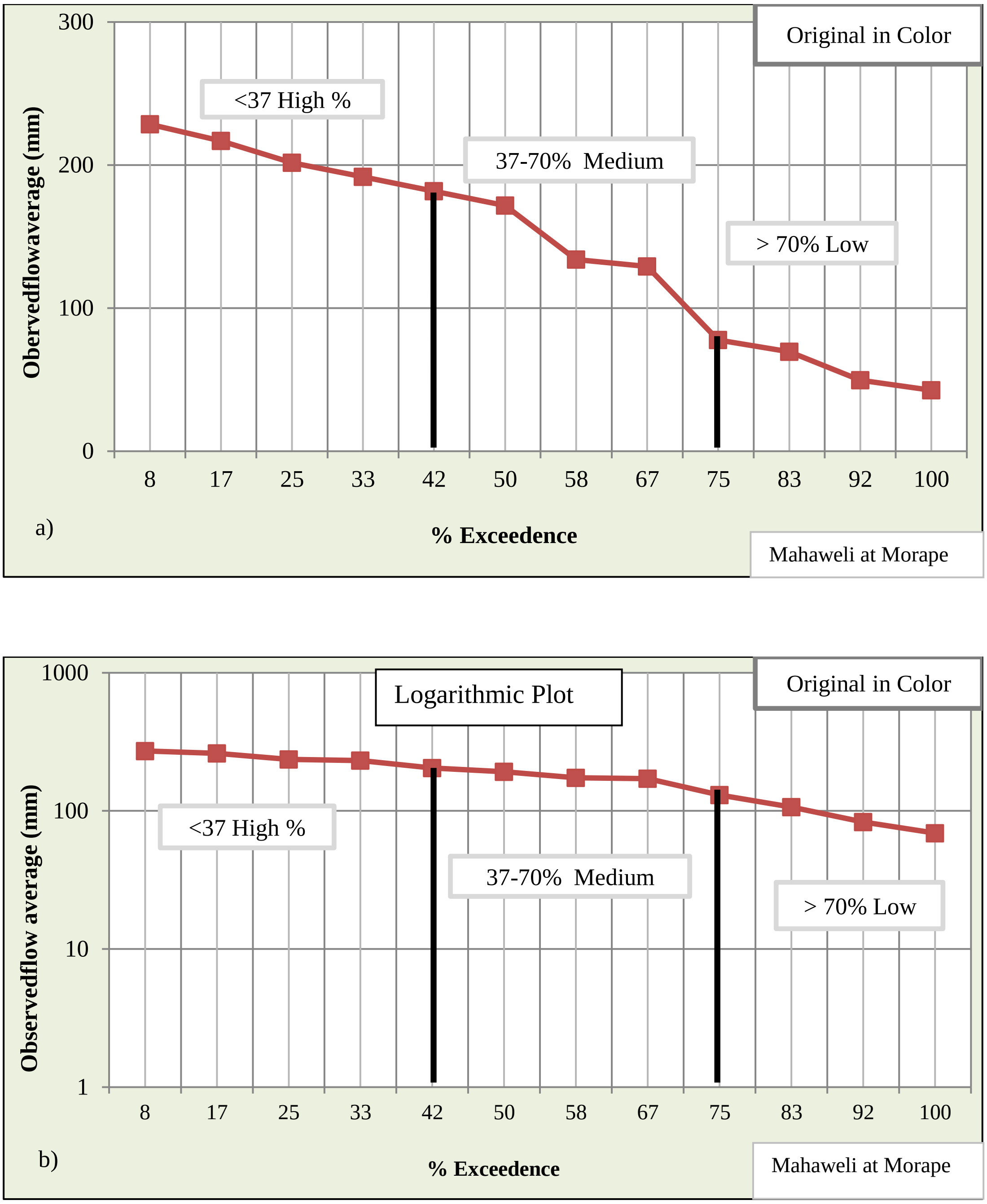


Figure 5-4: Flow Duration Curve of Mean and its log Plot in Mahaweli Ganga (a-b)

c) Monthly flow duration curve was plotted to observe the flow types in monthly time scale and to confirm the thresholds for high, medium and low flow. The monthly flow duration for the selected two catchments with respective threshold values in monthly time scale are shown from Figure 5-5 to Figure 5-7.

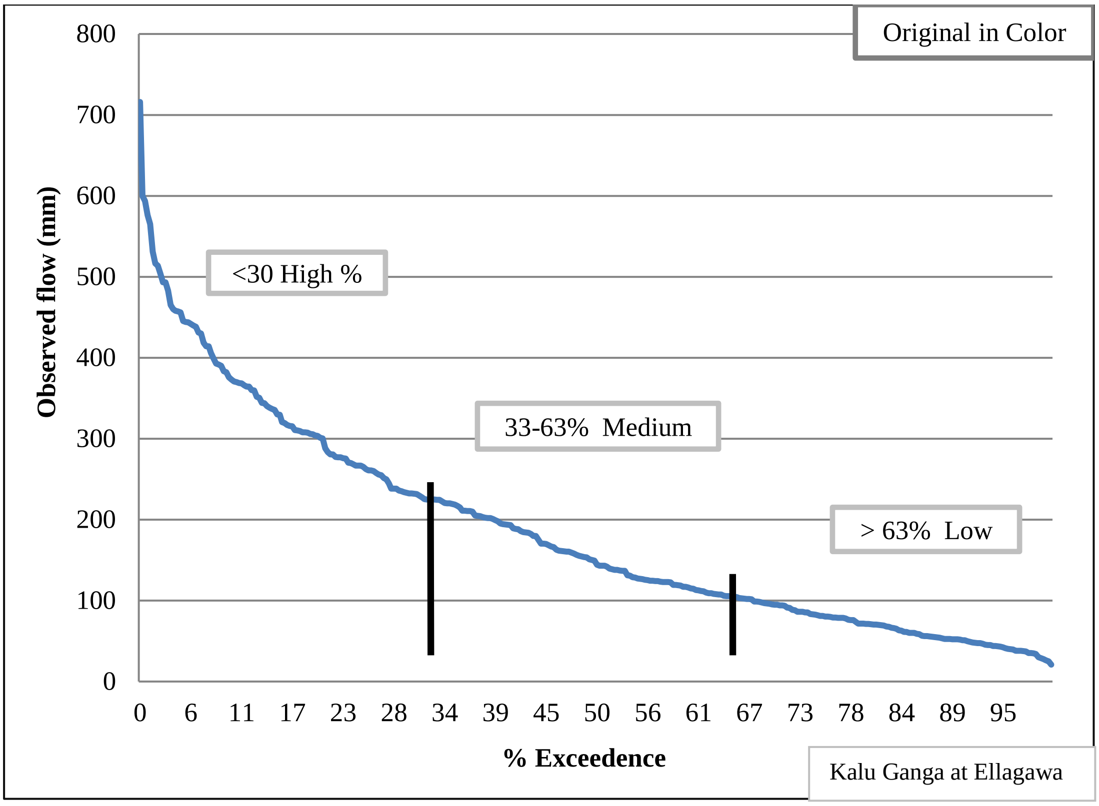


Figure 5-5: Monthly Flow Duration Curve for Kalu Ganga

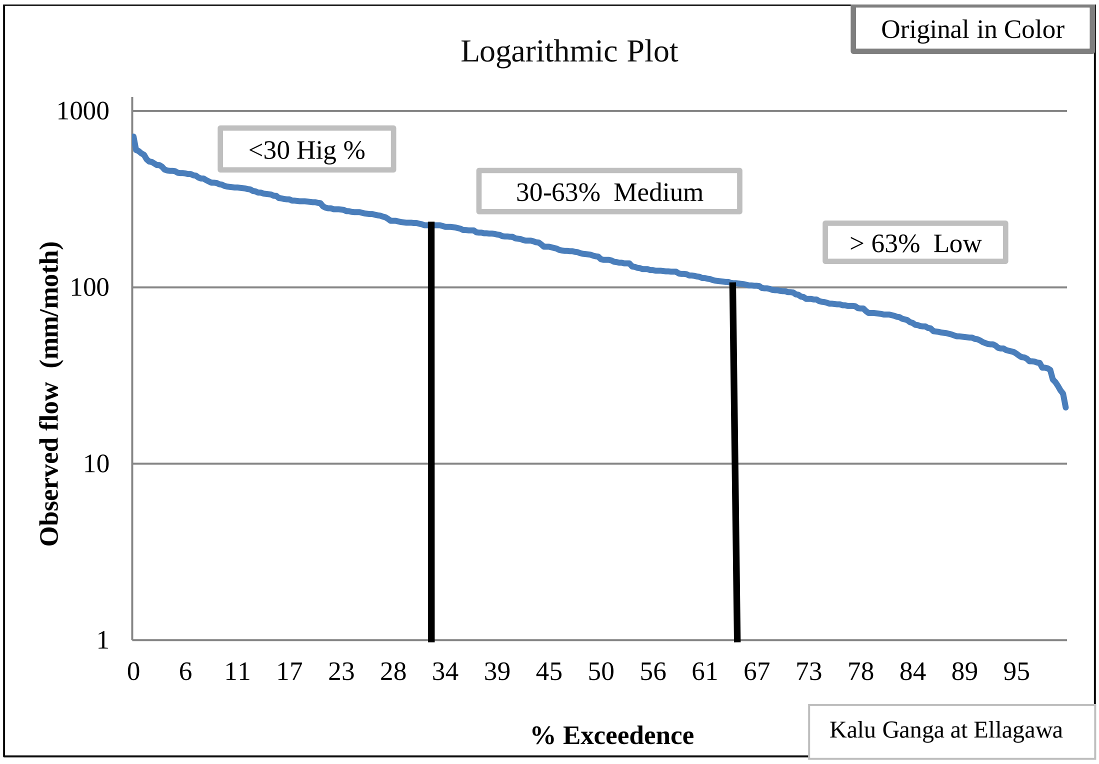


Figure 5-6: Log Plot of Monthly Flow Duration Curve for Kalu Ganga

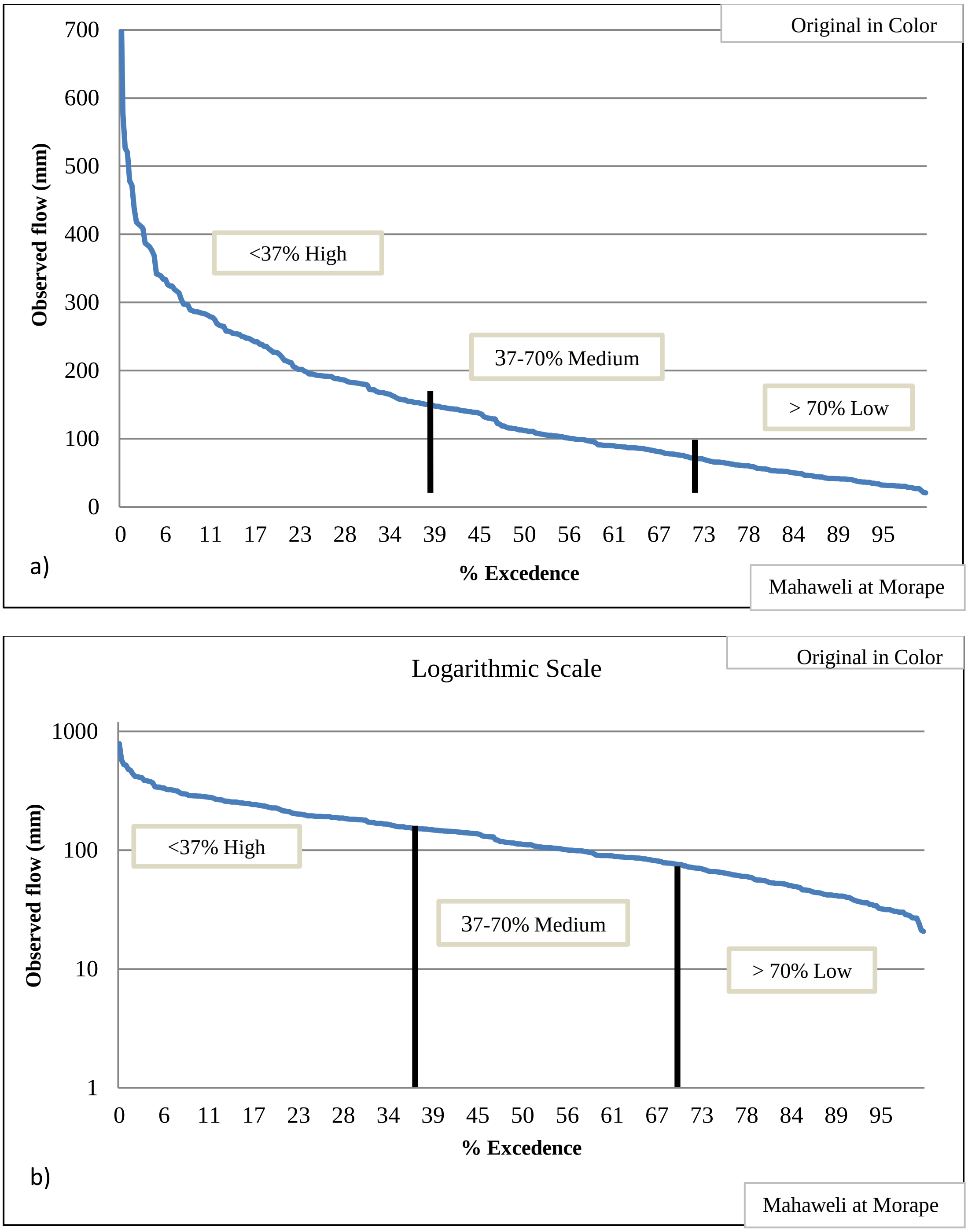


Figure 5-7: Monthly Flow Duration Curve with its Log Plot for Mahaweli Ganga (a-b)

After the computation of flow duration curves for both Kalu Ganga and Mahaweli Ganga in yearly and monthly time scales, the flow in Kalu Ganga was classified, to reflect <30% as high, 30-63% as medium and >63% as low. In Mahaweli Gang flow was classified to reflect <37% as high, 37-70% as medium and >70% as low.

5.3 Selected monthly water balance model

5.3.1 Model structure and parameters

After a careful survey of the available options to model water resources, the monthly water balance model Xiong and Guo (1998) was selected to model runoff in each watershed. The inter-relation between rainfall and evapotranspiration and runoff, on a monthly scale, appears to be very close because of the mutual effects and continuous feedback of all kinds of water movements in the soil–plant–atmosphere continuum.

A two parameter monthly water balance model has been used for generation of monthly runoff for evaluation of water resources in both Kalu Ganga and Mahaweli Ganga.

The following are the formula applied for calculation of streamflow in the model.

$$E(t) = EP(t) \times \tanh [P(t)/ EP(t)] \qquad \textbf{(2)}$$

Eq. (2) has been used for calculation of actual evapotranspiration of catchments. In this equation E(t) represents the actual annual evapotranspiration, EP(t) is the annual pan evaporation value, P(t) is the annual rainfall, and tanh is the hyperbolic tangent function.

$$E(t)/EP(t) = \tanh [P(t)/ EP(t)] \qquad \textbf{(3)}$$

Eq. (3) 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 E(t) approaches to EP(t).

After many numerical experiments, the authors had suggested that Eq. (2) can be used to calculate the actual monthly evapotranspiration if its right side is multiplied with a new coefficient. The adapted formula is given in Eq. (4).

$$E(t) = c \times EP(t) \times \tanh [P(t)/ EP(t)] \qquad \textbf{(4)}$$

In Eq. (4).E(t) represents the actual monthly evapotranspiration, EP(t) is the monthly pan evaporation value, P(t) is the monthly rainfall. C is the new coefficient which is the first model parameter and is linked to evapotranspiration. This parameter C is used to take an account of the change of time scale, i.e. from year to month, on the relationship expressed by Eq. (2).

The monthly runoff (Q) is closely related to the soil water content (S). In this model, the runoff Q is assumed as a hyperbolic tangent function of the soil water content S, which is given by,

$$Q(t) = S(t) \times \tanh[S(t)/SC] \qquad \textbf{(5)}$$

Where Q(t) is the monthly runoff, S(t) is the water content in soil, and SC is used to represent flied capacity of catchment.

In availability of both observation corresponding to of both the monthly rainfall P(t) and the monthly pan evaporation EP(t), the actual monthly evapotranspiration E(t) can be determined by Eq. (6). The quantity of remaining water in the soil will be [S(t - 1) + P(t) - E(t)], after the abstraction of evapotrasporation E(t), with S(t - 1) being the water content at the end of the (t - 1)th month and at the beginning of the tth month. Eq. (5) is then used to calculate the tth monthly runoff Q(t) as follows:

$$Q(t) = [S(t-1) + P(t) – E(t)] \times \tanh\{[S(t-1) + P(t) – P(t) – E(t)]/SC\} \qquad \textbf{(6)}$$

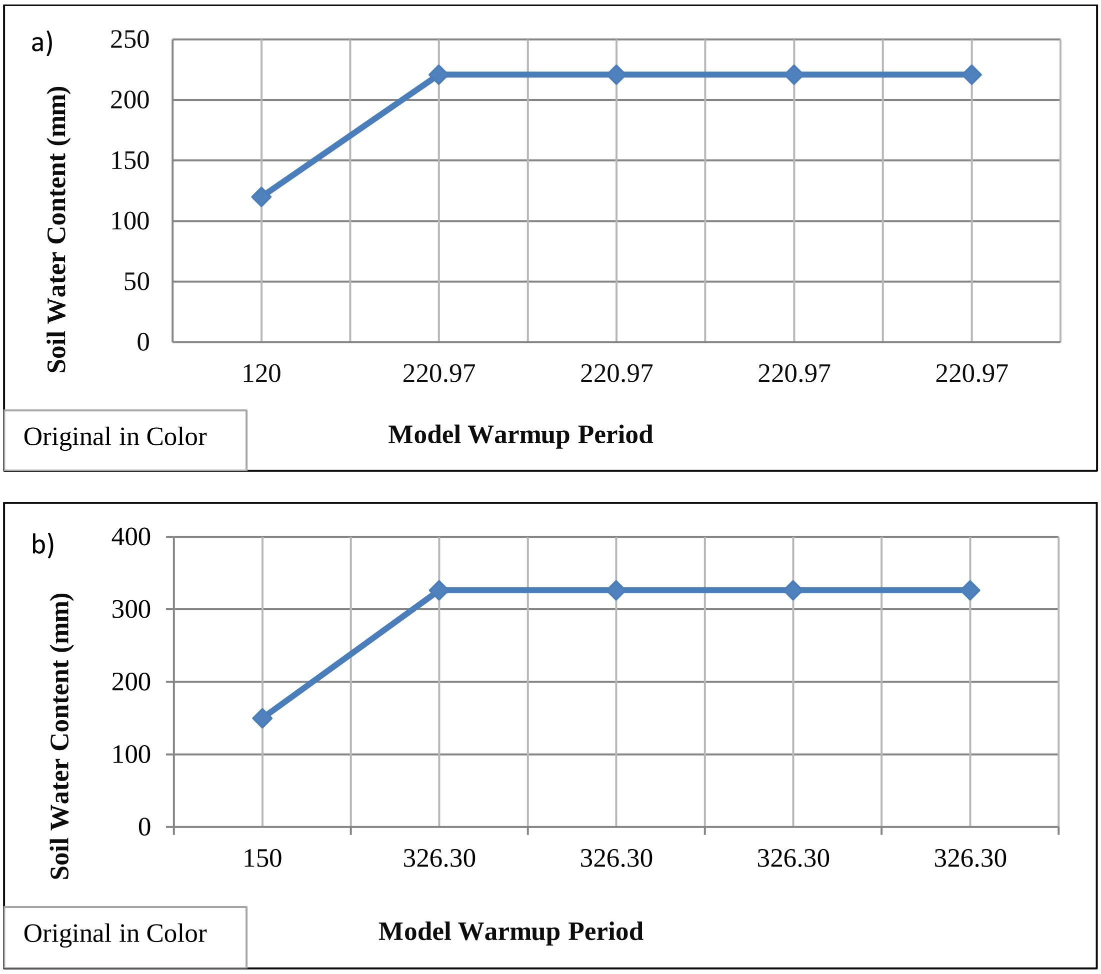
Finally, the water content at the end of the tth month, i.e. S(t), is calculated according to the water conservation law:

$$S(t) = S(t-1) + P(t) – Q(t) \qquad (7)$$

In this model there are only two parameters. Namely, C which takes an account of the effect of the change of time scale and SC which is the field capacity of the catchment. However the model also requires estimation of the initial soil moisture status.

5.4 Determination of initial soil water content

The initial value of soil water content, S(0*)* has its own effect on monthly runoff, Q(t), especially for limited observation data. Accuracy of the initial value of soil water content S(0) has an effect on the model performance, especially in the case when the used data series is not sufficiently long. In this study, for both catchments, the selection of initial soil water content was determined after five complete model runs over the calibration dataset as time warm-up period of model. The warm-up period soil water content values for both catchments are indicated in Figure (5-8).



Original in Color

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Figure 5-8: Model Warm-up Period for Initial Soil Water Content in Kalu Ganga and Mahaweli Ganga (a-b)

The initial soil moisture storage values for calibration dataset of Kalu Ganga at Ellagwa and Mahaweli at Morape were 220.97 mm and 326.3 mm respectively.

5.5 Selection of Objective Function and Parameter Optimization

5.5.1 Model Calibration and Model Verification

For Calibration and Verification, the entire dataset was divided into two parts. Calibration period of 15 years and the verification period 15 years. The calibration and verification data set for Kalu Ganga at Ellagawa are from 1983-1997 and from 1998-2013 respectively. The data used for Mahaweli Ganga at Morape for calibration and verification periods are from 1949-1963 and from 1963-1979 respectively.

The parameter C and SC were optimised for calibration period by selecting the MRAE as the primary objective function and Nash-Sutcliffe as the secondary objective function, for both catchments Kalu Ganga at Ellagwa and Mahaweli at Morape.

5.5.2 Selection of Objective function

A two parameter monthly water balance model was developed for both catchments, Kalu Ganga at Ellagawa and Mahaweli at Morape. Two objective functions that are MRAE and Nash-Sutcliffe are used as primary and secondary objective functions respectively. Mean ratio of absolute error (MRAE), which matches each and every point of the two hydrographs relative to the observed value at that particular time point, is used as an error criterion between the observed and simulated runoffs. Nash-Sutcliffe Efficiency is used to observe the peak matching between the observed and simulated runoff hydrographs.

The MRAE value for calibration period in Kalu Gnga at Ellagawa for overall flow, high flow, medium flow and low flow were obtained as 0.145, 0.083, 0.196, and 0.149 respectively, while these values were 0.153, 0.082, 0.124 and 0.234 respectively during verification. For Mahaweli at Morape, the MRAE value during calibration for overall flow, high flow, medium flow and low flow were 0.152, 0.117, 0.157 and 0.192 respectively. The verification showed that for same flow types the values were 0.157, 0.099, 0.195 and 0.184 respectively.

Nash-Sutcliffe is used, as a secondary objective function, to match the peaks between the observed and simulated hydrographs. The Nash-Sutcliffe efficiency for calibration period in Kalu Gnga at Ellagawa for over all flow, high flow, medium flow and low flow were 93.6%, 77.6%, 58.0% and 75.6% respectively, while these value during the verification period and for the same flows were 92.4%, 87.4%, 60.0% and 64.8% respectively. In the calibration period for Mahaweli at Morape, the Nash-Sutcliffe values for overall flow, high flow, medium flow and low flow were estimated as 93.6%, 87.6%, 38.8% and 60.8% respectively. In the verification period for the same flows, the Nash-Sutcliffe values were obtained as 94.1%, 86.5%, 30.7% and 64.7% respectively.

5.5.3 Parameter Optimization

Parameter optimization was done to find out the optimum values of C and SC for both catchments, Kalu Ganga at Ellagawa and Mahaweli at Morape. The optimization was at two different resolutions. They were coarse and fine search ranges. Optimum values of C and SC were optimised using a trial and error method. The optimization procedure includes the following two steps. At first, the parameter C and SC were optimized according to the criterion MRAE to achieve good simulation of the total runoff volume at a coarse search range. Secondly, after finding the coarse range values of C and SC with respect to minimum MRAE value, the optimization was done in the near minimum area to find the final optimum values of C and SC with the minimum MRAE value. Parameter optimization was done for both catchments, Kalu Ganga at Ellagawa and Mahaweli at Morape, at monthly yearly and seasonal time scales. It was found that the two parameter monthly water balance model produced less MRAE error at yearly and seasonally time scales when compared with monthly time scale. During the parameter optimization, it was revealed that the optimum value of the parameter SC is robust and very insensitive to the initial values of the parameters. The SC values appear to have a link to the location of catchments.

After parameter optimization of monthly model, the final values of C, SC, MRAE and Nash-Sutcliffe coefficient for Kalu Ganga at Ellagwa were found as 1, 800, 0.145 and 93.6% respectively. The optimum values of C and SC for Mahaweli at Morape were 1.1 and 1200 respectively. Optimised MRAE and Nash-Sutcliffe values were computed 0.152 & 93.6% respectively. The results of parameter optimization in two steps each Coarser and Finer regions for Kalu Ganga at Ellagawa and Mahaweli at Morape are tabled in Appendix-C, Table C1 to C4.

In Appendix-C, Figure C1 indicates the coarser resolution surface of parameter C, SC and MRAE for Kalu Ganga at Ellagawa. Coarser resolution optimizations of parameter C and SC for Kalu Ganga at Ellagawa are indicated in the same Appendix in Figure C2 and Figure C3 respectively. The finer resolution of parameter optimization for parameter C and SC are indicated in Figure C4 and C5 for Kalu Ganga at Ellagawa respectively. The annual and seasonal optimisation of parameter C and SC for Kalu Ganga at Ellagawa are indicated in the same appendix in Figure C11 and Figure C12.

The parameter optimization for Mahaweli at Morape is also shown in Appendix-C from Figure 6 to Figure 10. Figure 6 indicates the coarser resolution surface of parameter C, SC and MRAE. In the same Appendix Figure 7 and Figure 8 indicates the coarser resolution optimization of parameter C and SC and Figure 9 and Figure 10 indicates the finer resolution of the same parameter respectively. The annual and seasonal optimisation of parameter C and SC for Mahaweli Ganga are indicated in the same Appendix in Figure C13 and Figure C14.

The parameter optimization for both catchments was done to optimise the values at both coarser and finer regions to find out the most optimum values to calibrate and verify the two parameter monthly water balance model. Table 5-3 & 5-4 indicates the results of parameter optimization for both catchment outputs in monthly, annual and seasonal time scales.

Table 5-3: Parameter Optimization Results for Kalu Ganga at Ellagawa

MRAE	C Optimum	SC Optimum	MRAE Minimum
Monthly	1	800	0.145
Annual	1	600	0.042
Maha	0.9	600	0.069
Yala	1	1000	0.054

Table 5-4: Parameter Optimization Results for Mahaweli Ganga at Morape

MRAE	C Optimum	SC Optimum	MRAE Minimum
Monthly	1.1	1200	0.152
Annual	1	1400	0.056
Maha	1.1	1300	0.077
Yala	1	1600	0.067

The Parameter optimization detailed results are maintained in Appendix-C.

5.6 Evaluation of Calibration Results

5.6.1 Kalu Ganga at Ellagawa

Monthly rainfall evaporation and streamflow from 1983 to 1998 were used for calibration period. At first, flow duration curve was plotted to identify high flow, medium flow and low flow of the observedflow. Flow duration curve identified that Kalu Ganga at Ellagawa for less than 30% of time produced high flow, between 30% of time to 63% of time medium flow and more than 63% of time low flow. Secondly, the initial soil moisture content was found as a 220.97 mm, after five complete model runs over the calibration dataset as the warm-up period. Then, with parameter optimization the optimum values for S and Sc parameters were identified. Optimum C and SC were determined as 1 and 800 respectively. The calibration period showed that the MRAE for total flow was 0.145 while, for high medium and low flow the same value were 0.083, 0.196 and 0.149 respectively. Model efficiency was computed with Nash-Sutcliffe coefficient produced good matching with results of 93.6% for total flow and 77.6%, 58.0% and 75.6% for high medium and low flows respectively. The estimated parameters and errors in the calibration period are in Table (5-5).

Table 5-5: Estimated Parameters & Errors for Calibration period of Kalu Ganga

C	**Sc**		**Total flow**	**High flow**	**Medium flow**	**Low flow**
1	800	**MRAE**	0.145	0.083	0.196	0.149
		NASH-Sutcliffe	0.936	0.776	0.580	0.756

The hydrographs of observed and calculated flow were plotted in normal and logarithmic scale to present the variation and to evaluate their matching in each and every observation. The hydrograph of observed and calculated flow in normal and semi-log plots are shown in Figure 5-9 to Figure 5-14. Flow duration curve (Figure 5-16) in normal and logarithmic scale demonstrate the matching of high flow, medium flow and low flow of the hydrographs. Accordingly, the results for calibration period showed that the low flow periods produced a better matching when compared with high and medium flow periods. The water balance comparison for calibration period of Kalu Ganga at Ellagawa is in Table 5-6 and Figure 5-15. Figure 5-15 illustrates that a highly accurate balance for calibration period has been achieved. Monthly, annual and seasonal scatter plot comparisons in Figure 5-17, Figure 5-18 and Figure 5-19 shows their behaviour in terms of water balance is very satisfactory. The annual and seasonal value of estimated and observedflow of Kalu Ganga at Ellagawa are Tabled in Appendix-D (Table D1). The simulated soil water content is also shown in the same Appendix in Figure D1 and Figure D6.

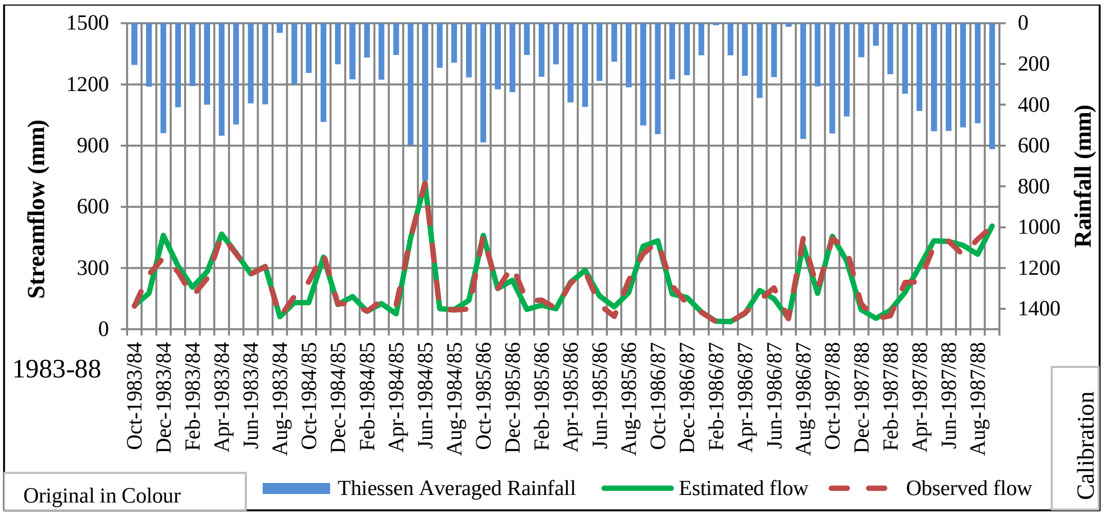


Figure 5-9: Calculated & Observed Monthly Flow hydrograph of Kalu Ganga (1983-1988)

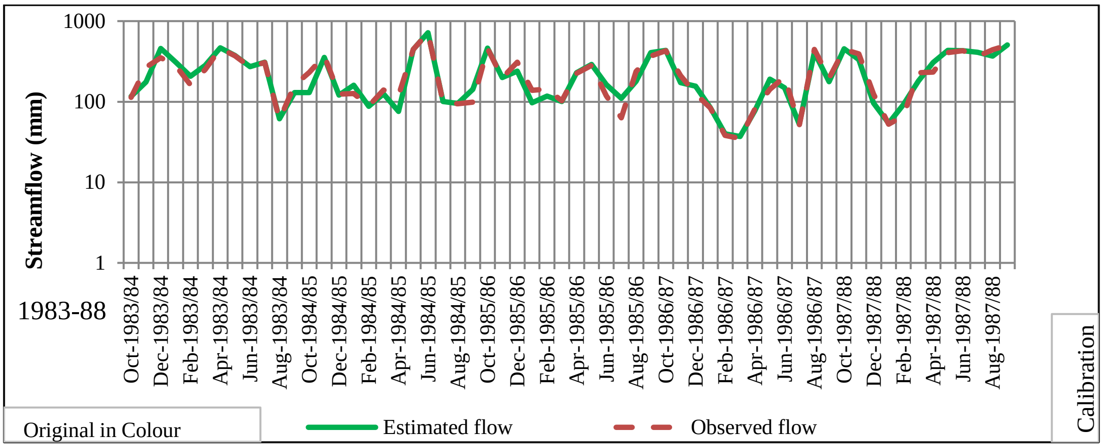


Figure 5-10: Logarithmic scale of Monthly Flow hydrograph of Kalu Ganga (1983-1988)

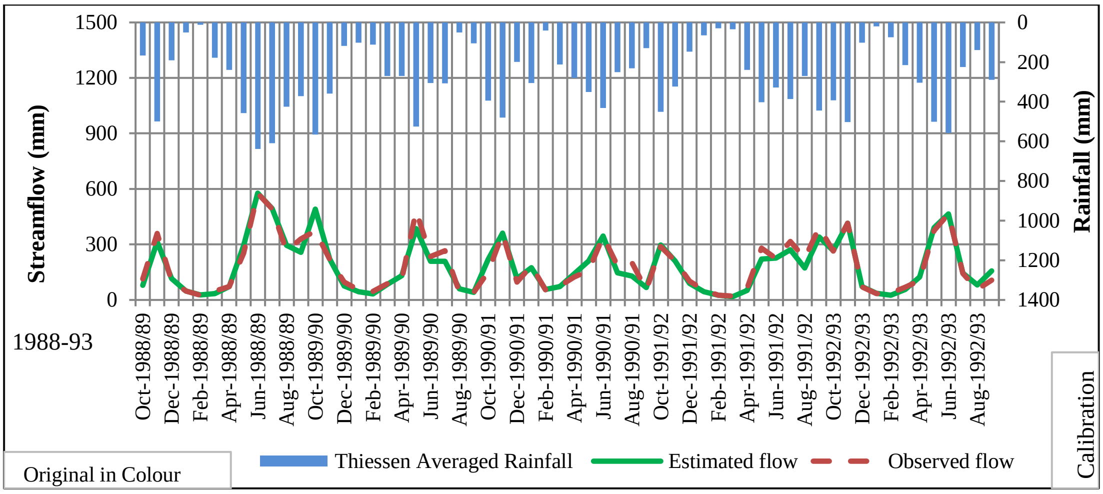


Figure 5-11: Calculated & Observed Monthly Flow hydrograph of Kalu Ganga (1988-1993)

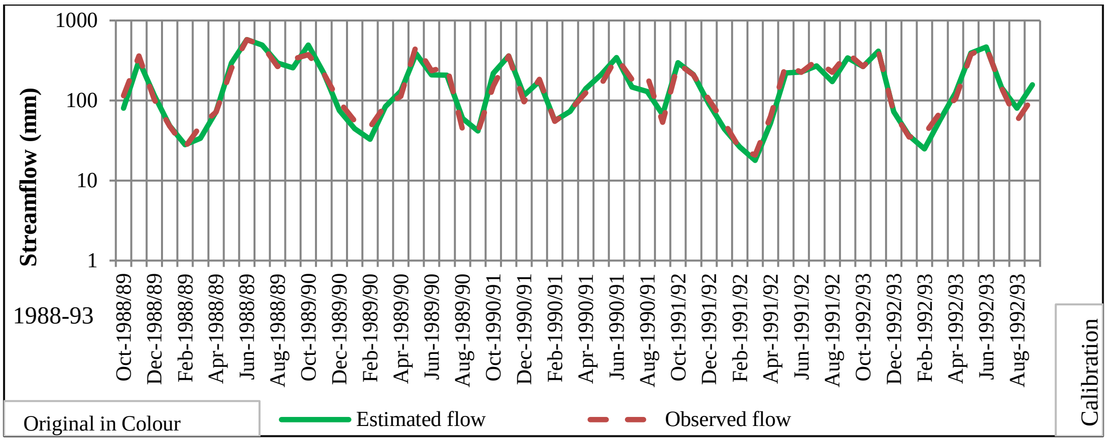


Figure 5-12: Logarithmic scale of Monthly Flow hydrograph of Kalu Ganga (1988-1993)

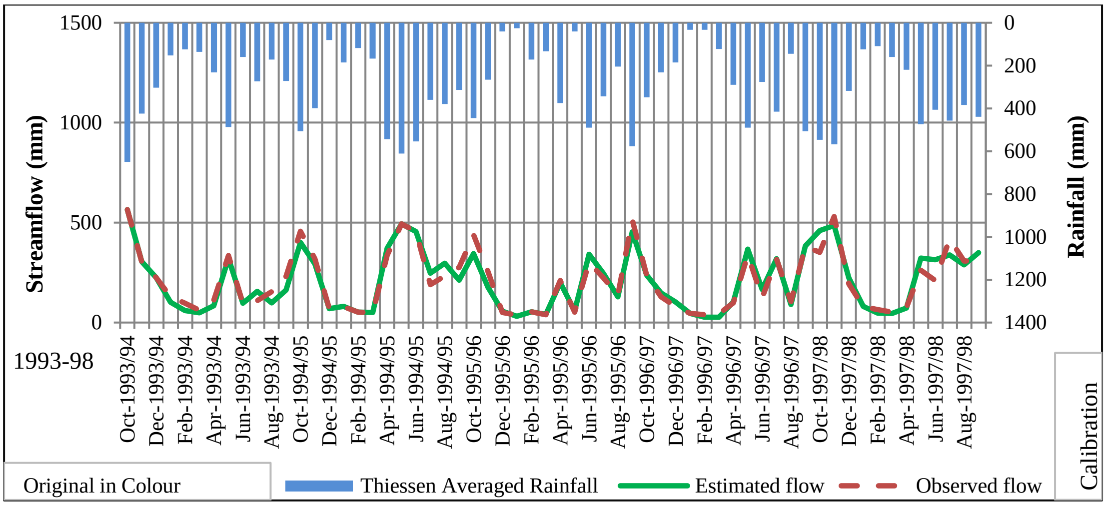


Figure 5-13: Calculated & Observed Monthly Flow hydrograph of Kalu Ganga (1993-1998)

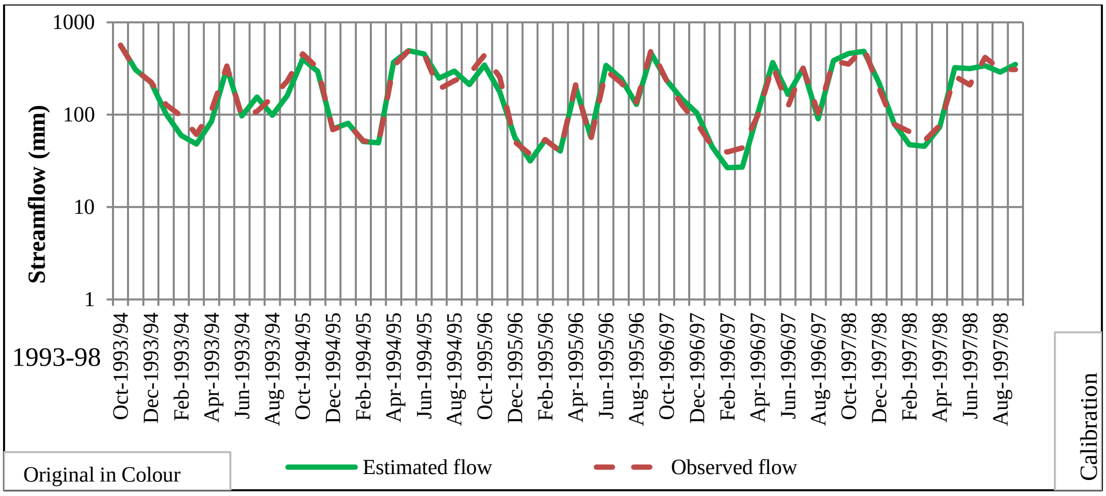


Figure 5-14: Logarithmic scale of Monthly Flow hydrograph of Kalu Ganga (1993-1998)

Table 5-6: Water Balance Estimation for Calibration Period of Kalu Ganga

Water Years	Rainfall (mm)	Estimated flow (mm)	Observed flow (mm)	Water Balance Estimated flow (mm)	Water Balance Observed flow (mm)
1983/84	4359.8	3162.2	3049.6	1197.6	1310.2
1984/85	3850.2	2554.5	2653.7	1295.7	1196.4
1985/86	3952.3	2592.6	2646.1	1359.6	1306.2
1986/87	3181.8	1980.6	2038.2	1201.2	1143.6
1987/88	4975.0	3664.5	3689.0	1310.5	1286.0
1988/89	3842.1	2609.1	2687.8	1233.0	1154.4
1989/90	3093.9	1983.8	2060.9	1110.1	1033.0
1990/91	3303.5	2040.5	1988.6	1263.0	1314.9
1991/92	3123.3	1972.8	2198.7	1150.5	924.6
1992/93	3324.6	2232.5	2144.6	1092.1	1180.1
1993/94	3385.9	2222.1	2417.5	1163.8	968.4
1994/95	4215.2	3025.3	3009.7	1189.9	1205.4
1995/96	3110.3	2131.5	2315.8	978.8	794.5
1996/97	3073.8	2017.8	1936.3	1055.9	1137.5
1997/98	4202.7	3030.2	2854.1	1172.5	1348.6

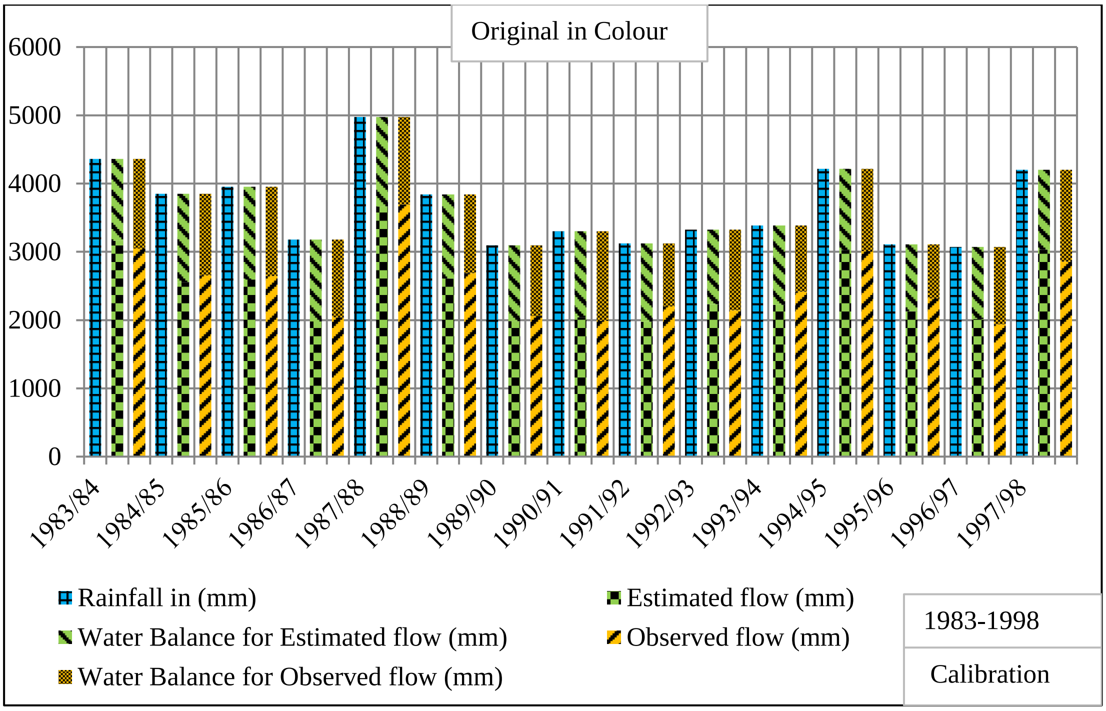


Figure 5-15: Water Balance for Calibration Period of Kalu Ganga at Ellagawa

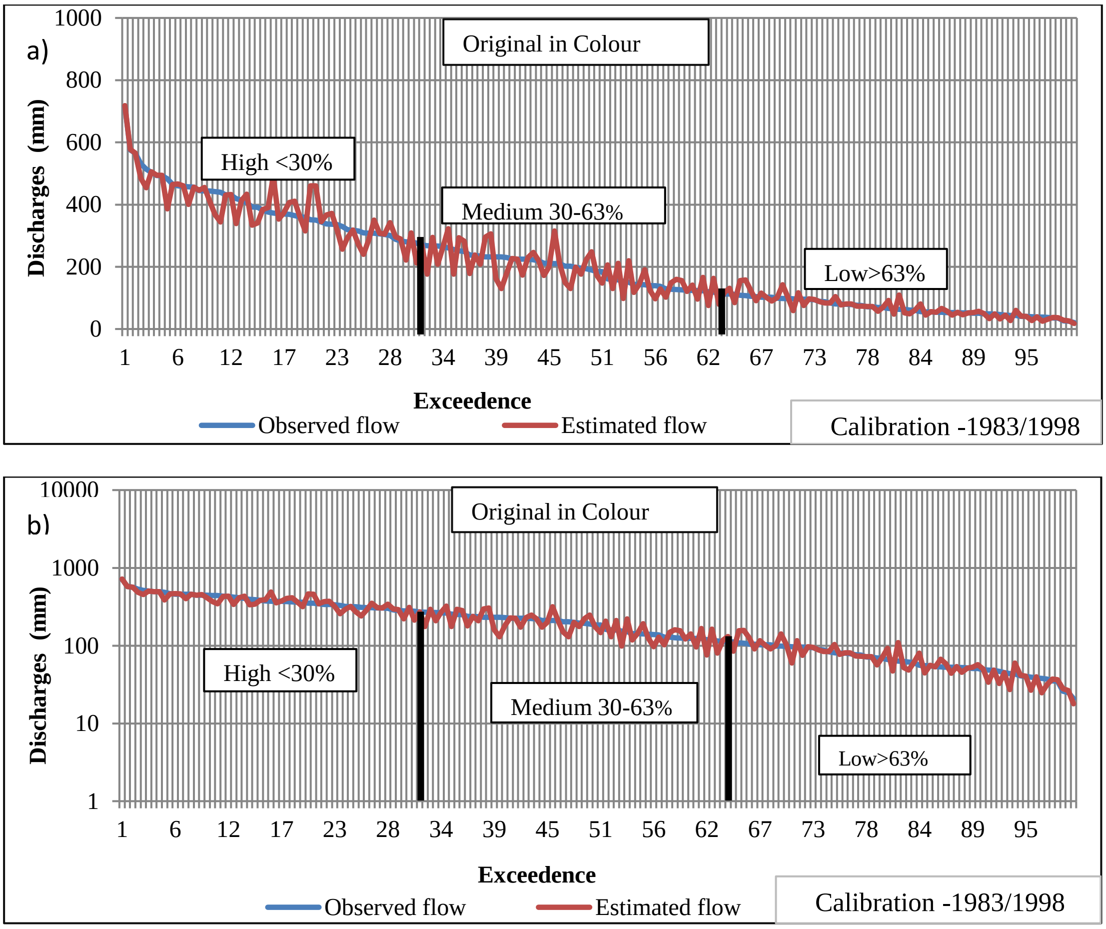


Figure 5-16: Normal and log plot of Flow Duration Curve of Kalu Ganga (a -b)

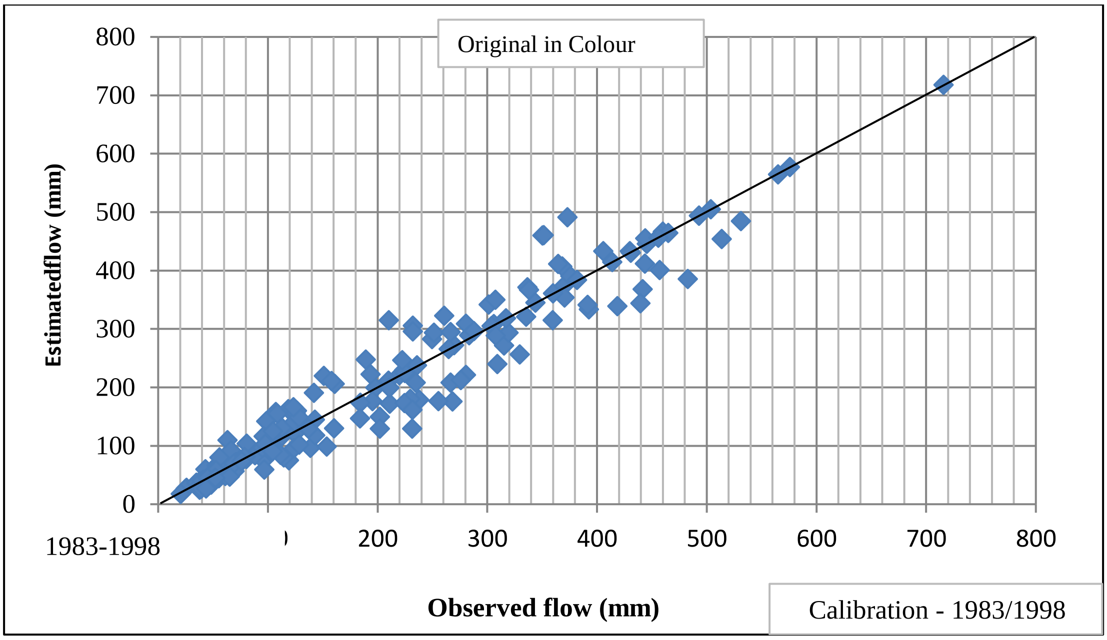


Figure 5-17: Monthly Comparison of Observed and Estimated Flow of Kalu Ganga

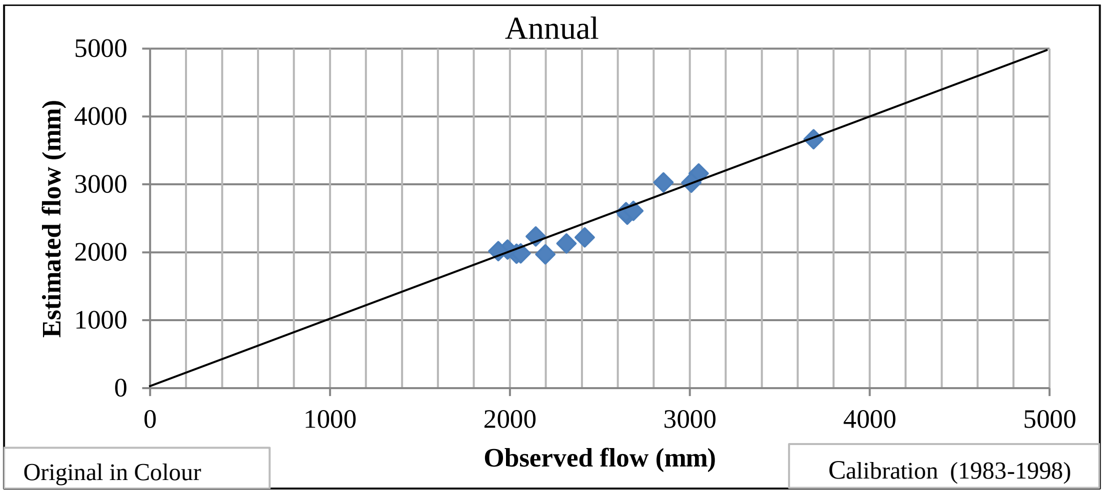


Figure 5-18: Annual Comparison of Estimated & Observedflow of Kalu Ganga

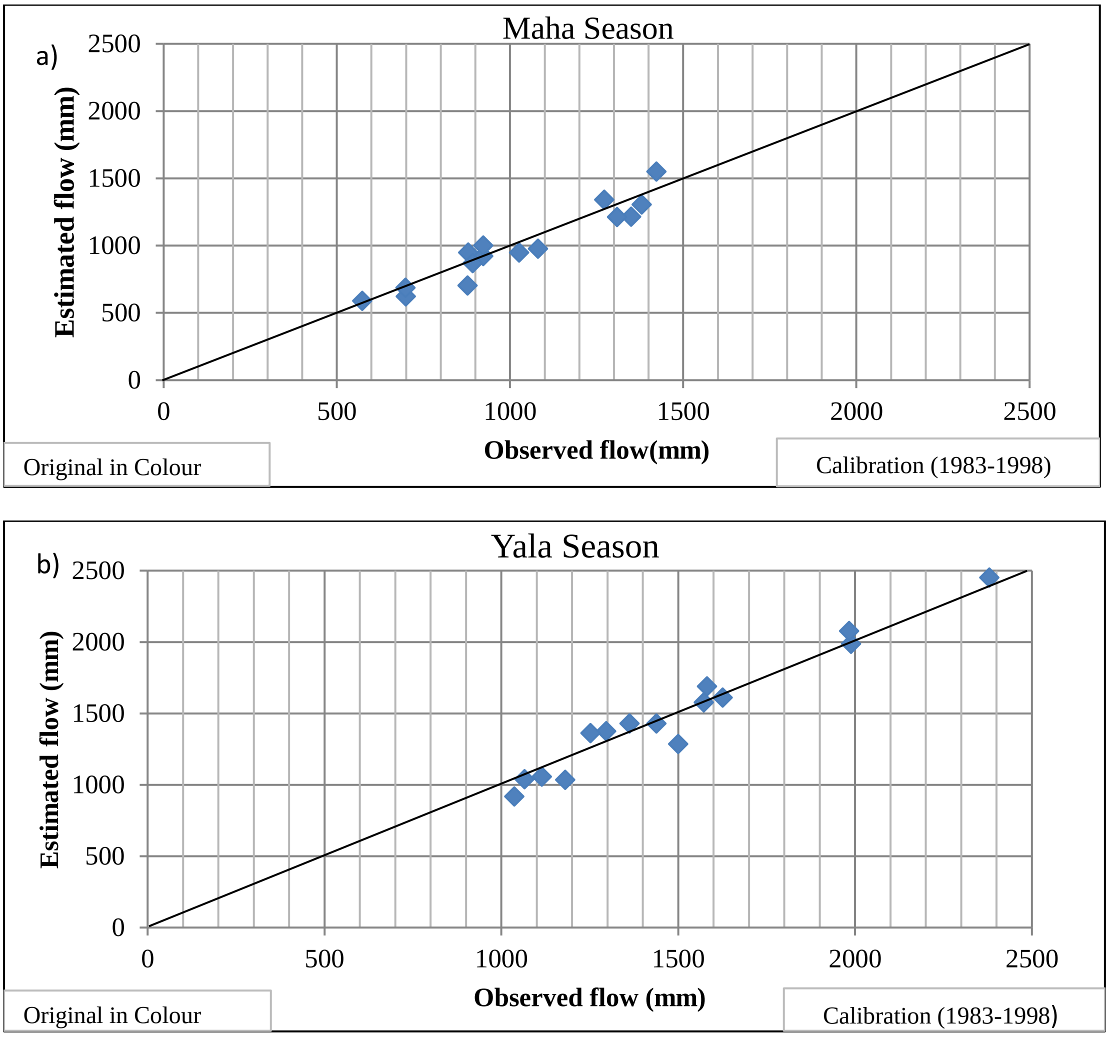


Figure 5-19: Seasonal Comparison of Estimated & Observed Flow of Kalu Ganga (a-b)

5.6.2 Mahaweli at Morape

From 1949 to 1964, the monthly rainfall, streamflow and evaporation data were used for calibration period. At first, flow duration curve was plotted to identify the high flow, medium flow and low flow of the observedflow. The flow duration curve indicated that Mahaweli at Morape for less than 37% of the time produced high flow, between 37%-70% of the time medium flow and more than 70% of the time low flow. After flow analysis, the initial moisture content was determined as 326.3 mm, after the warm-up period of five data cycles. Optimum values for S and Sc parameters were as 1.1 and 1200 respectively. For the calibration period MRAE for total flow was 0.152 while for high, medium and low flow the MRAE values were 0.117, 0.157 and 0.192 respectively. Model efficiency shown by Nash-Sutcliffe coefficient was 93.6% for total flow and 87.6%, 38.8% and 60.8% for high, medium and low flows respectively. The estimated parameters and errors for calibration period are maintained in Table 5-7.

Table 5-7: Estimated Parameters & Errors for Calibration period of Mahaweli Ganga

C	**Sc**	**MRAE**	**Total flow**	**High flow**	**Medium flow**	**Low flow**
1.1	1200		0.152	0.177	0.157	0.192
		NASH-Sutcliffe	0.936	0.876	0.388	0.608

Observed and estimated flow hydrographs are plotted in normal and log scale (Figure 5-20 to 5-25). Flow duration curve in normal and log scale shown the matching of high flow, medium flow and low flow (Figure 5-27). The calibration results showed that the high flow fits better when compared to low flow and medium flow respectively. Water balance estimations for calibration period shown in Table 5-8 and Figure 5-26, shows a very good matches between estimated flow and observedflow. The scatter plots of monthly, annual and seasonal in Figures 5-28, 5-29 and 5-30 also demonstrate the goodness of fit. The values are tabled in Appendix-D (Table D2). In the same Appendix, Figure D3 and Figure D8 indicate the behavior of calculated soil water content.

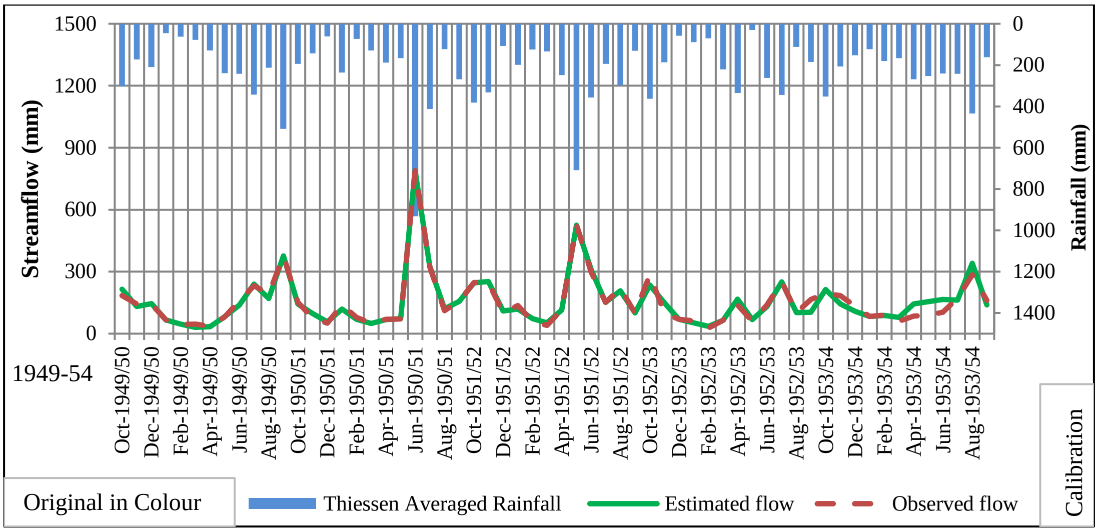


Figure 5-20: Calculated & Observed Monthly Flow hydrograph of Mahaweli Ganga

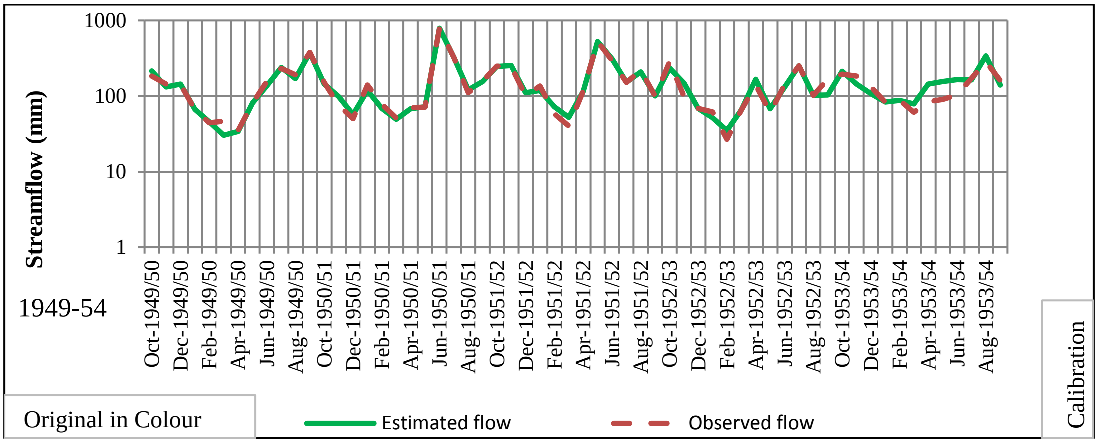


Figure 5-21: Logarithmic scale of Monthly Flow hydrograph of Mahaweli Ganga

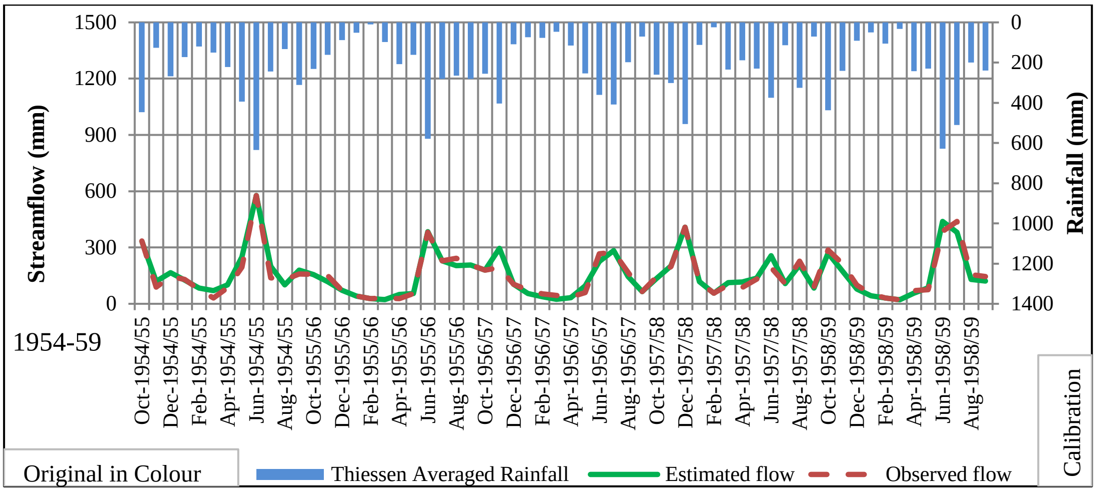


Figure 5-22: Calculated & Observed Monthly Flow hydrograph of Mahaweli Ganga

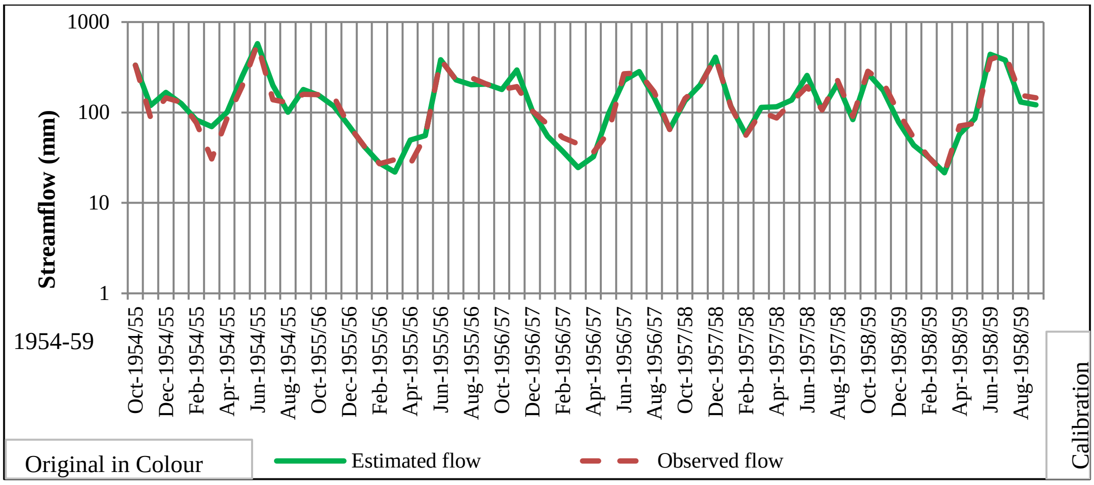


Figure 5-23: Logarithmic scale of Monthly Flow hydrograph of Mahaweli Gana

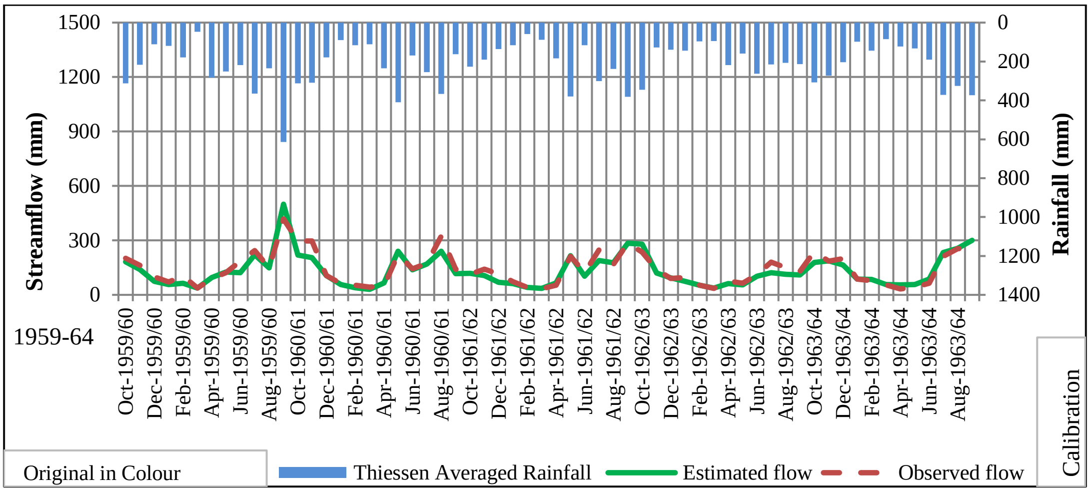


Figure 5-24: Calculated &Observed Monthly Flow hydrograph of Mahaweli Ganga

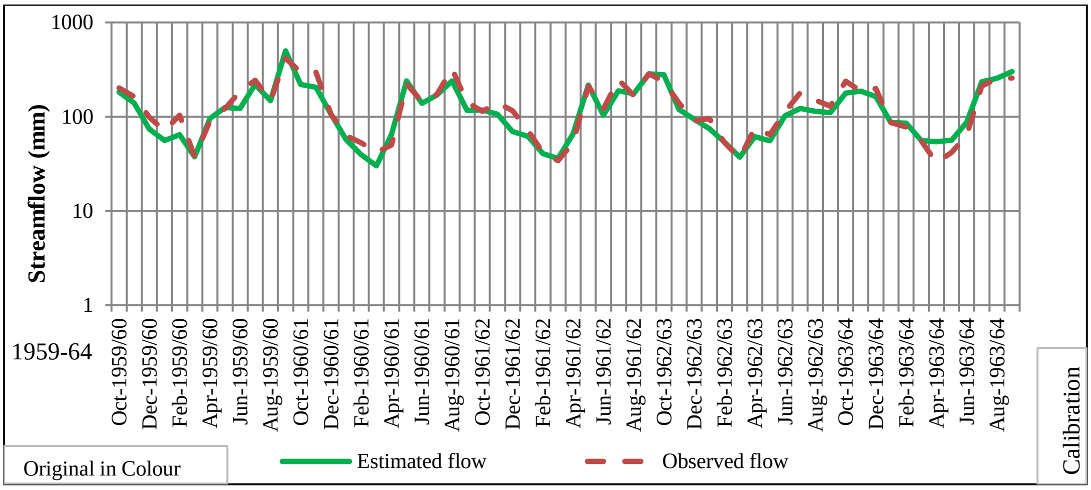


Figure 5-25: Logarithmic scale of Monthly Flow hydrograph of Mahaweli Ganga

Table 5-8: Water Balance Estimation for Calibration Period of Mahaweli Ganga

Water Years	Rainfall (mm)	Estimated flow (mm)	Observed flow (mm)	Water Balance Estimated flow (mm)	Water Balance Observed flow (mm)
1949/50	2544.4	1672.7	1699.5	871.8	844.9
1950/51	2923.5	2067.1	2069.4	856.3	854.1
1951/52	3209.8	2260.0	2239.5	949.8	970.3
1952/53	2254.3	1425.8	1461.8	828.5	792.5
1953/54	2779.5	1823.4	1638.7	956.1	1140.8
1954/55	3222.2	2305.8	2089.7	916.5	1132.6
1955/56	2416.1	1562.9	1619.0	853.2	797.1
1956/57	2372.7	1544.7	1519.4	828.0	853.3
1957/58	2740.4	1942.3	1858.3	798.0	882.1
1958/59	3010.9	1836.0	1976.8	1174.9	1034.1
1959/60	2951.8	1766.9	1885.5	1185.0	1066.3
1960/61	2713.9	1628.1	1914.0	1085.9	799.9
1961/62	2417.8	1467.9	1605.9	949.9	811.9
1962/63	2223.1	1224.2	1362.3	998.8	860.8
1963/64	2628.5	1745.7	1705.3	882.8	923.2

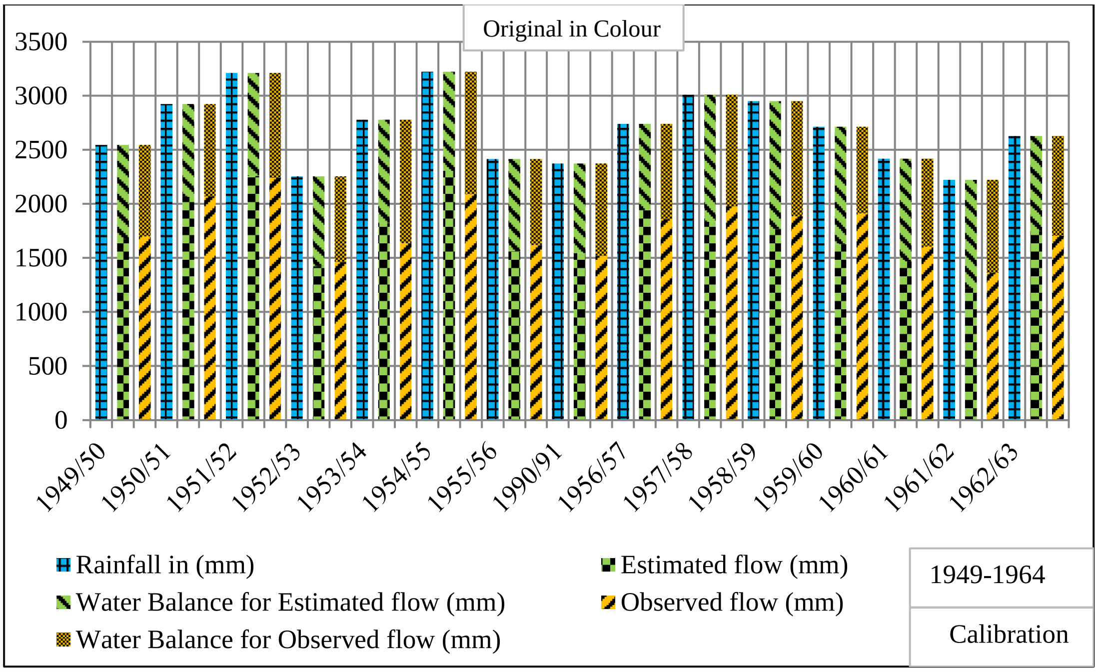


Figure 5-26: Water Balance for Calibration period of Mahaweli Ganga

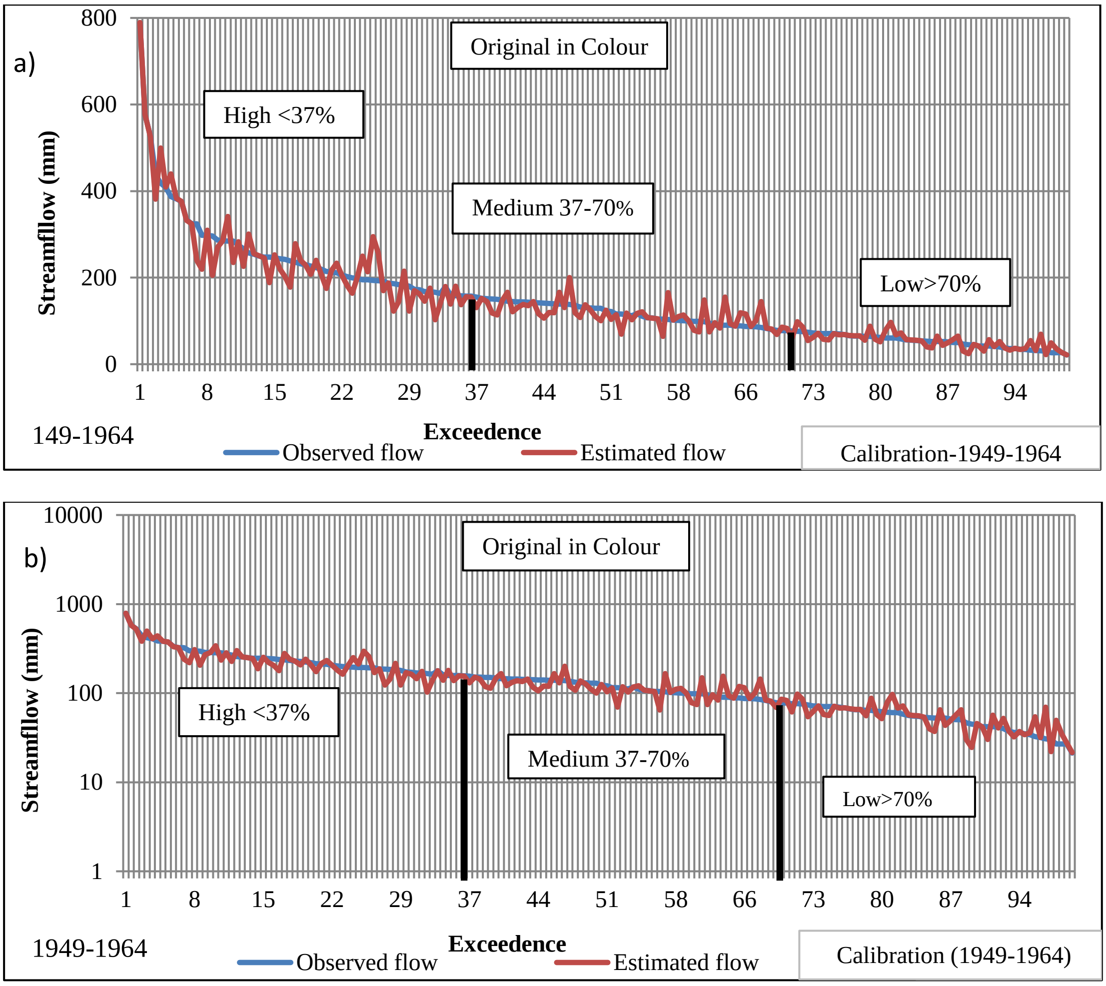


Figure 5-27: Normal and Log plot of Flow Duration curve of Mahaweli Ganga (a-b)

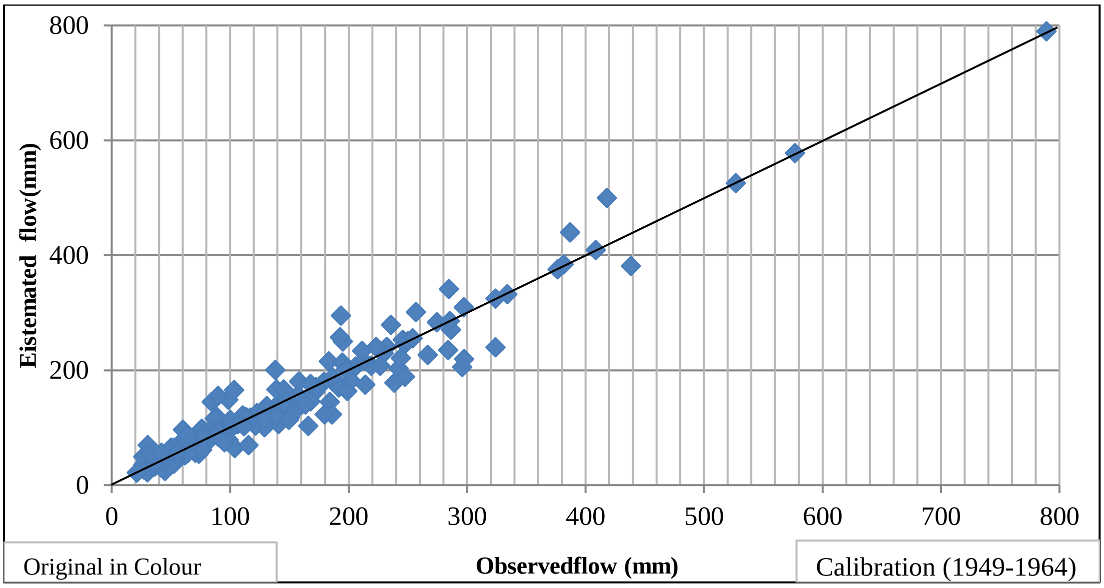


Figure 5-28: Monthly Comparison of Observed & Estimated flow of Mahaweli Ganga

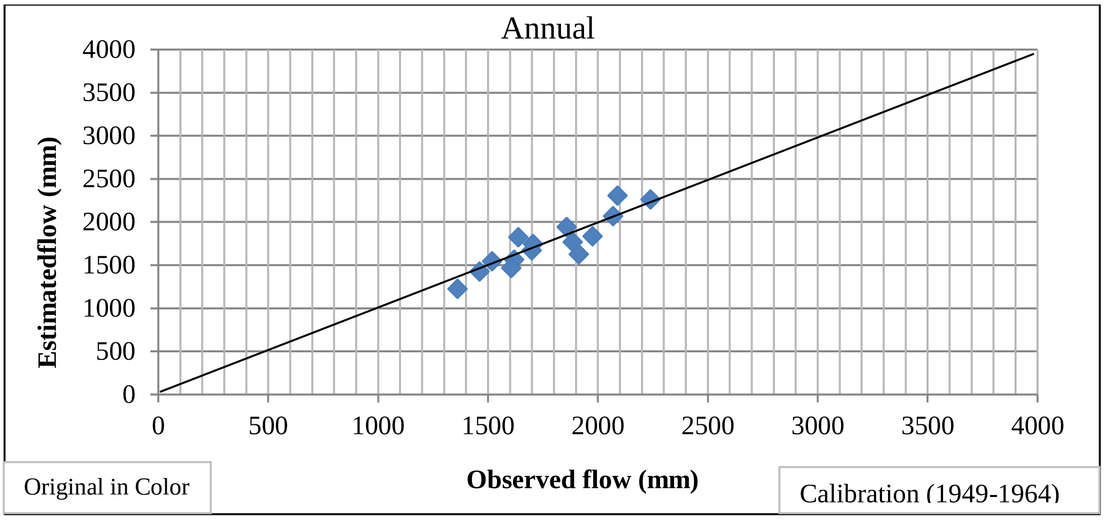


Figure 5-29: Annual Comparison of Observed & Estimated Flow of Mahaweli Ganga

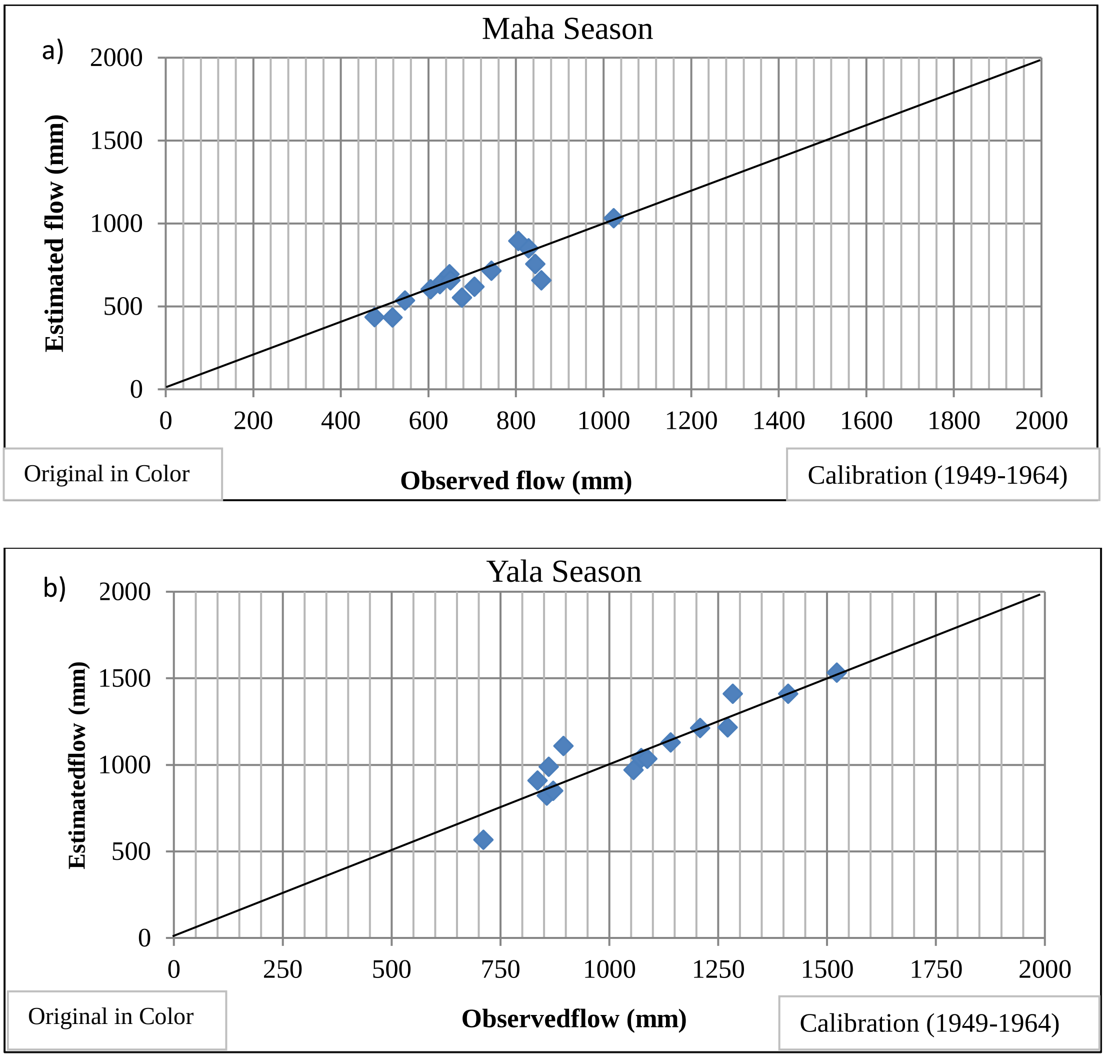


Figure 5-30: Seasonal Comparison of Observed & Estimated Flow of Mahaweli Ganga (a-b)

5.7 Evaluation of Verification results

5.7.1 Kalu Ganga at Ellagawa

During verification of Kalu Ganga at Ellagawa the MRAE for total flow was 0.153 while the model efficiency, which was determined by NASH-Sutcliffe, was 92.4%. The MRAE for high, medium and low flows for the verification period were 0.082, 0.124 and 0.234 respectively. The NASH-Sutcliffe values for high medium and low flows during verification were 87.4%, 60.0% and 64.8% respectively. The optimized parameters, MRAE and NASH-Sutcliffe values for verification period of Kalu Ganga at Ellagawa are in Table 5-9. Percentage error with respect to each month and each year for average and individual observations are shown in Figure 5-42. And Appendix-D, Figure D5.

Table 5-9: Estimated Parameters & Errors for Verification Period of Kalu Ganga

C	**Sc**	**MRAE**	**Total flow**	**High flow**	**Medium flow**	**Low flow**
1	800		0.153	0.082	0.124	0.234
		NASH-Sutcliffe	0.924	0.874	0.60	0.648

The monthly flow hydrographs of observed and calculated flows during the verification period are plotted and shown in normal and log scale Figure (5-31 to 5-36). The flow duration curve in normal and log scale to compare the matching of high, medium and low flow during verification are in Figure 5-38. The verification results of Kalu Ganga at Ellagawa showed that high flow peaks matched better than low flow and medium flow. The water balance estimations are in Table 5-10 and Figure 5-37. Figure 5-39, Figure 5-40 and Figure 5-41 show the comparison of monthly, annual and seasonal water balance of verification using a scatter plots respectively. Figure D2 and D7 in Appendix-D; indicate the simulated soil water content during the verification period.

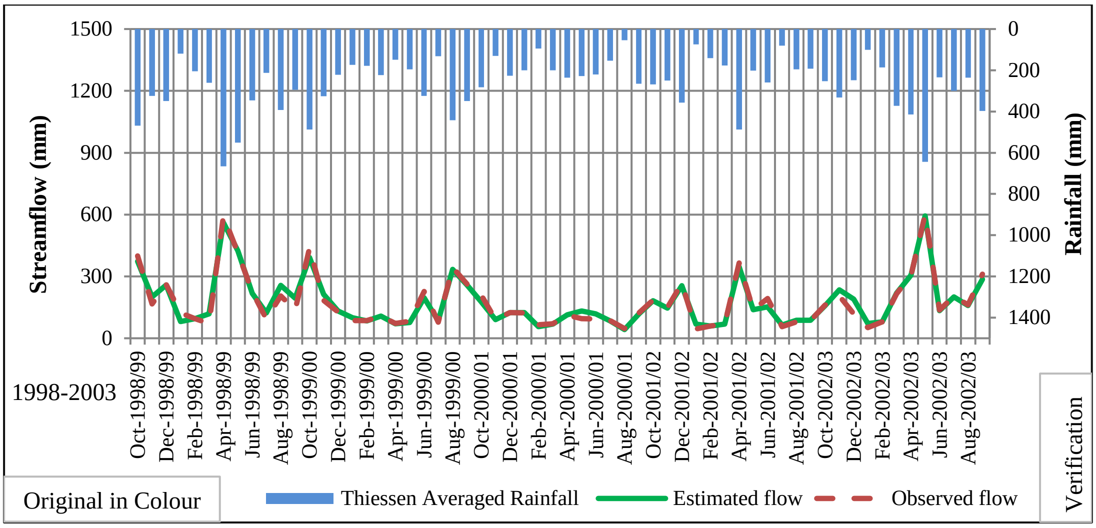


Figure 5-31: Calculated & Observed Monthly Flow hydrograph for Kalu Ganga

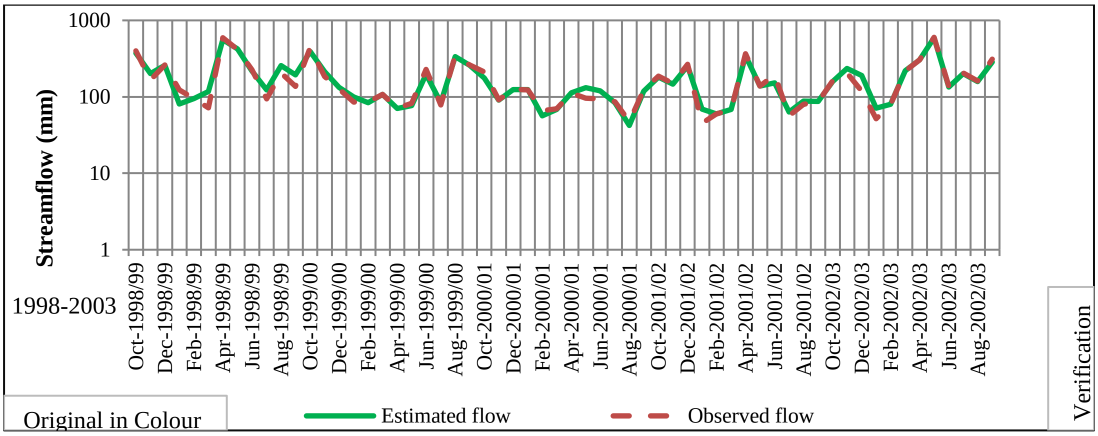


Figure 5-32: Logarithmic plot of Flow Monthly hydrograph for Kalu Ganga

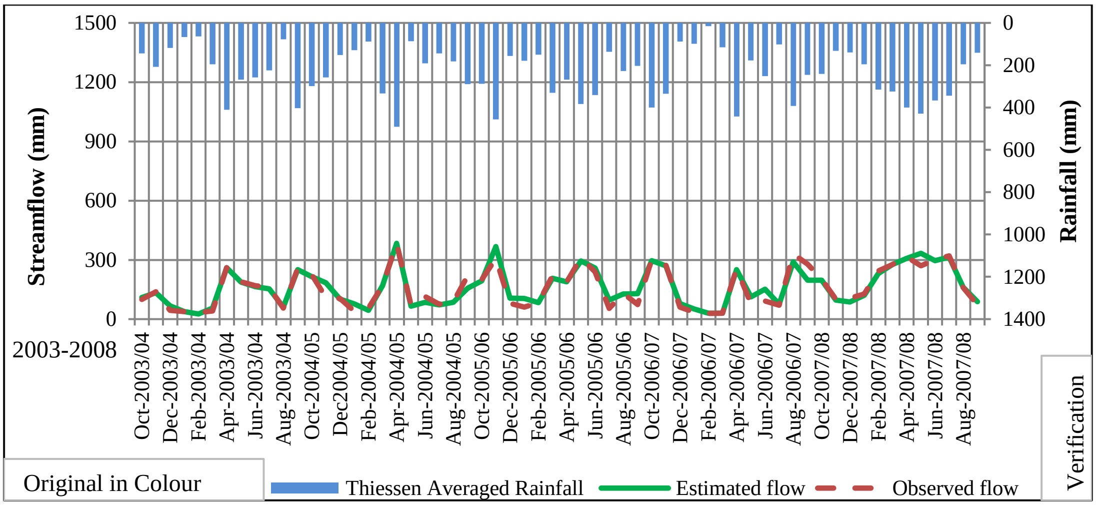


Figure 5-33: Calculated & Observed Monthly Flow hydrograph for Kalu Ganga

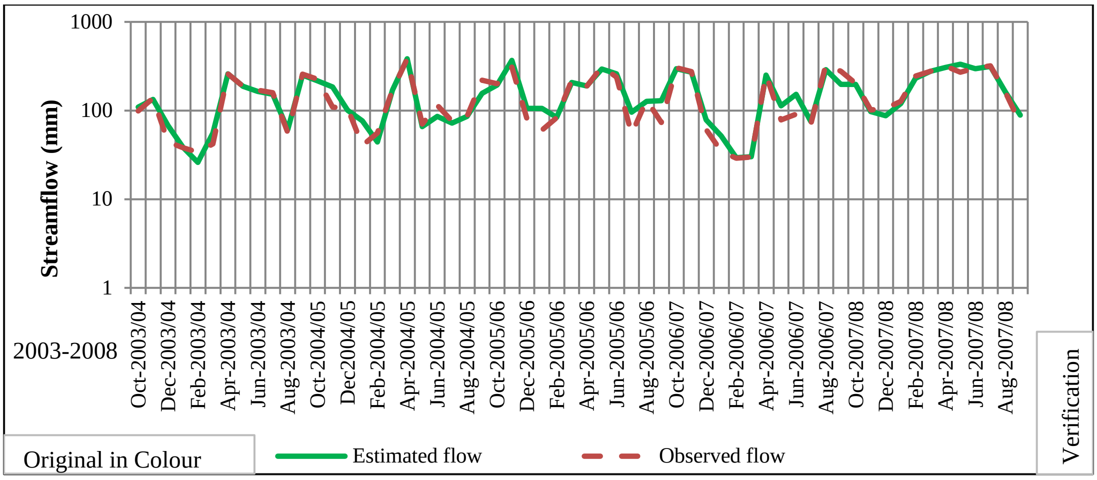


Figure 5-34: Logarithmic Plot of Monthly Flow Hydrograph for Kalu Ganga

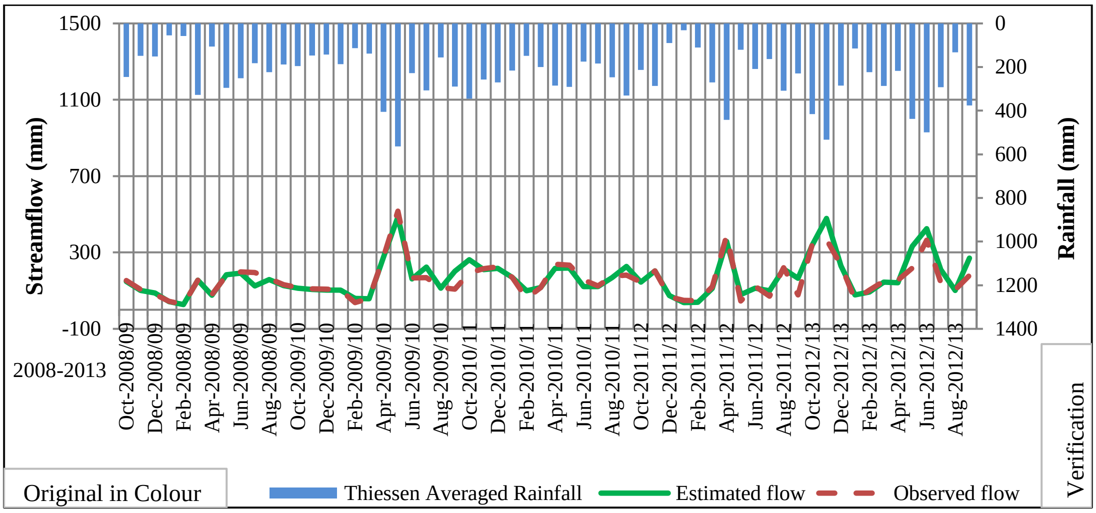


Figure 5-35: Calculated & Observed Monthly Flow hydrograph for Kalu Ganga

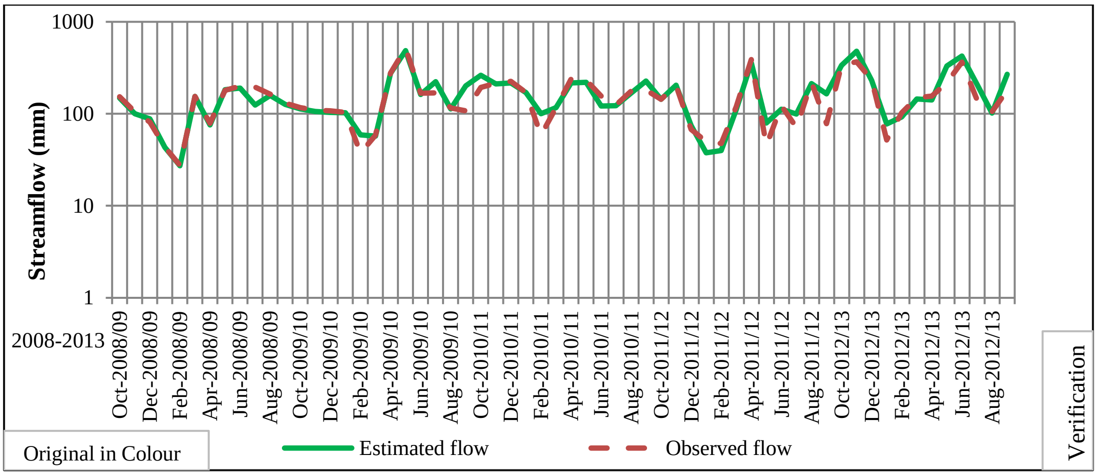


Figure 5-36: Logarithmic Plot of Monthly Flow hydrograph for Kalu Ganga

Table 5-10: Water Balance Estimations for Verification Period of Kalu Ganga

Water Year	Rainfall (mm)	Estimated flow (mm)	Observed flow (mm)	Water Balance Estimated flow (mm)	Water Balance Observed flow (mm)
1998/1999	4188.4	2902.2	2784.5	1286.3	1403.9
1999/2000	3201.5	2049.5	2094.5	1152.1	1107.0
2000/2001	2293.3	1249.4	1243.0	1043.9	1050.3
2001/2002	2682.7	1656.4	1694.9	1026.3	987.8
2002/2003	3718.4	2629.5	2550.9	1088.9	1167.5
2003/2004	2436.3	1506.3	1486.5	930.0	949.8
2004/2005	2642.5	1641.1	1655.5	1001.3	987.0
2005/2006	3115.7	2157.2	1949.2	958.5	1166.5
2006/2007	2664.8	1835.8	1836.0	828.9	828.7
2007/2008	3223.7	2510.2	2497.4	713.5	726.3
2008/2009	2235.2	1421.6	1511.9	813.7	723.3
2009/2010	2875.4	2001.8	1886.6	873.6	988.8
2010/2011	2947.8	2150.8	2089.2	796.9	858.6
2011/2012	2476.5	1639.7	1559.3	836.7	917.2
2012/2013	3812.7	2840.3	2413.7	972.4	1399.0

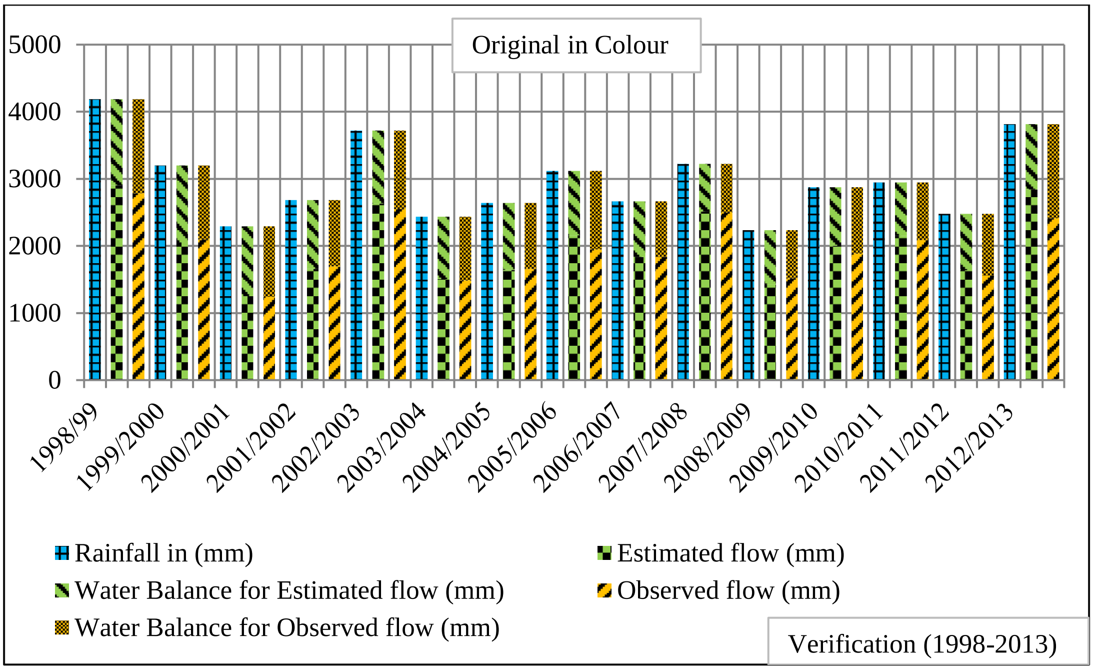


Figure 5-37: Water Balance Estimations for Verification Period of Kalu Ganga

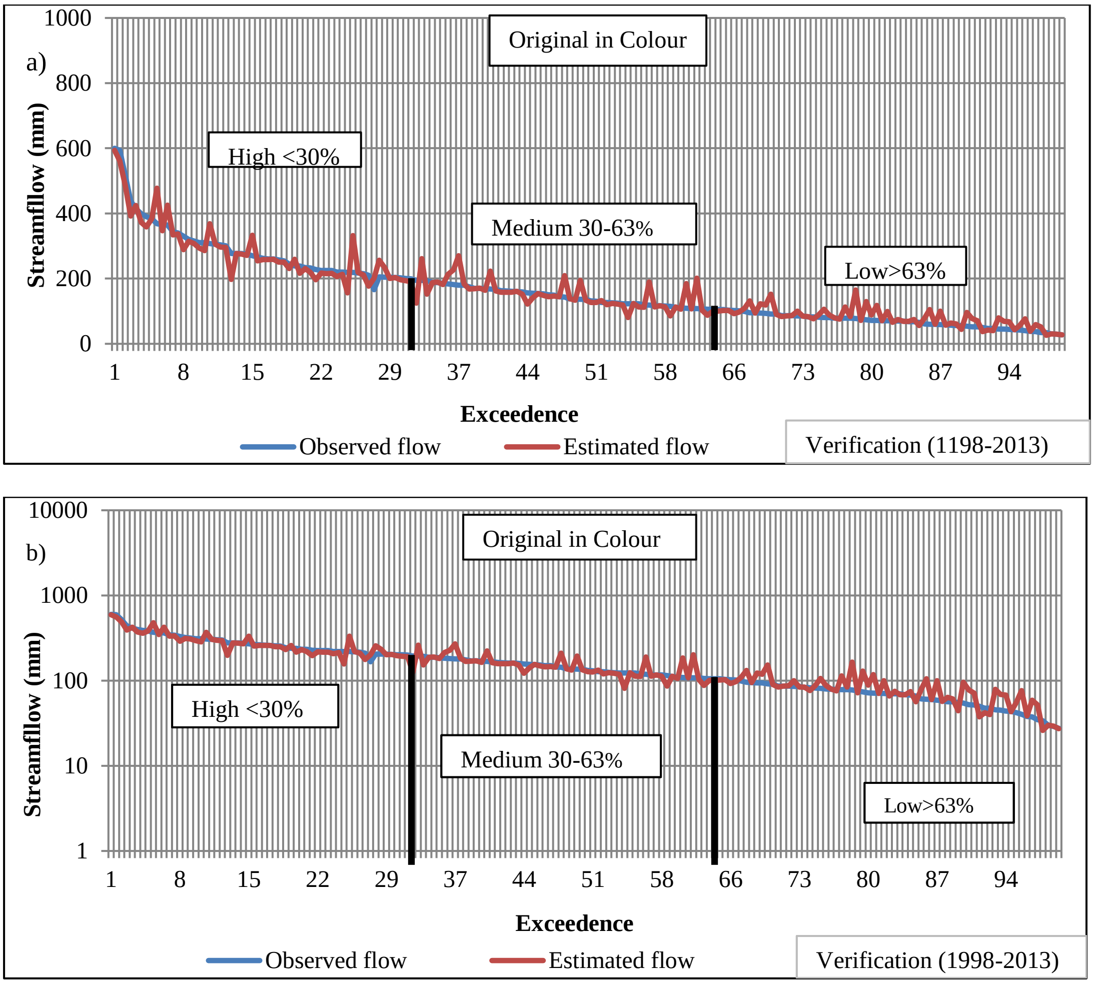


Figure 5-38: Flow Duration Curve of Discharges for Kalu Ganga (a-b)

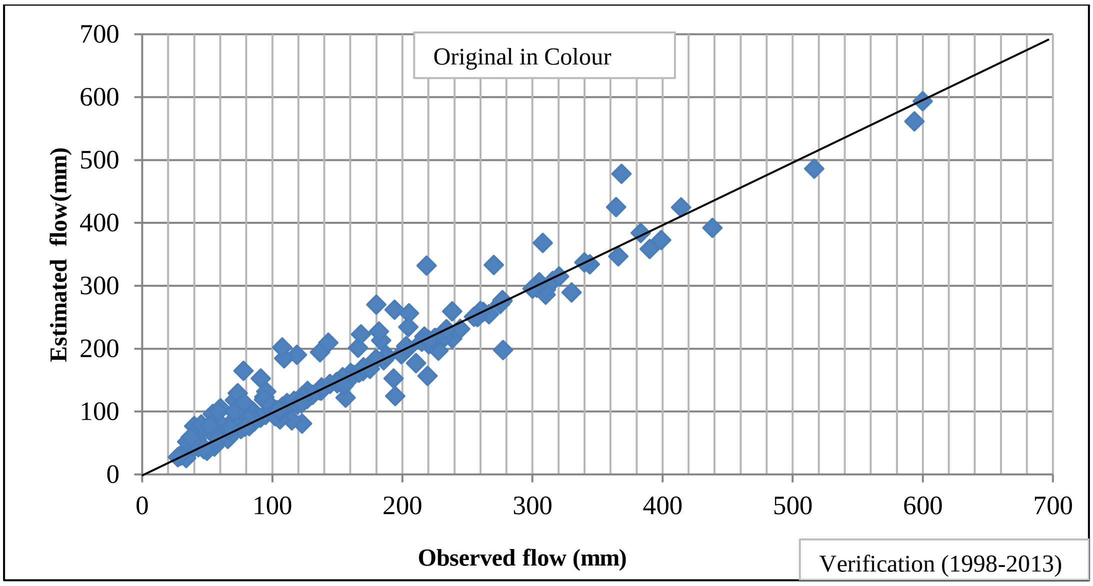


Figure 5-39: Monthly Comparison of Observed & Estimated flow for Kalu Ganga

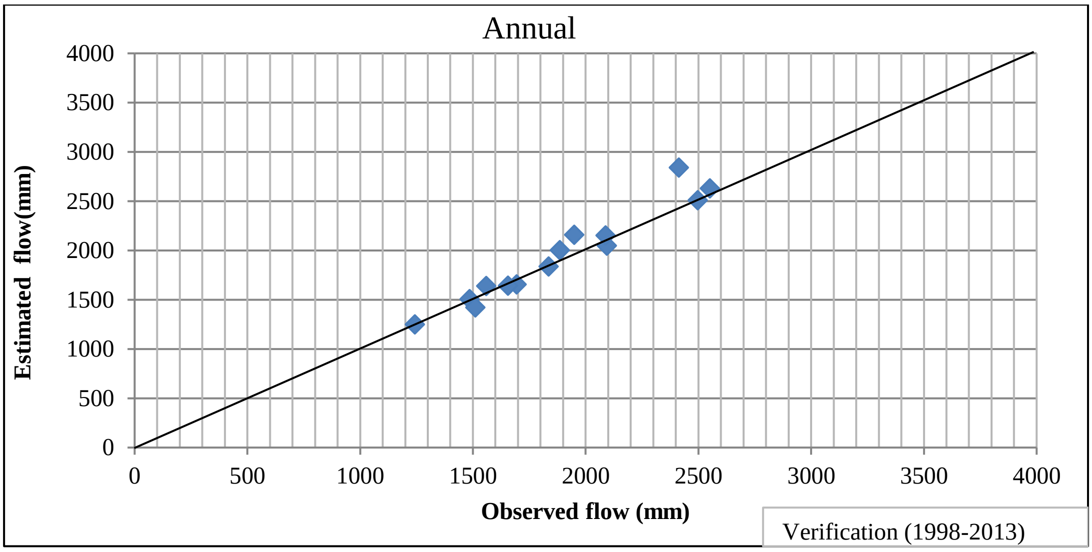
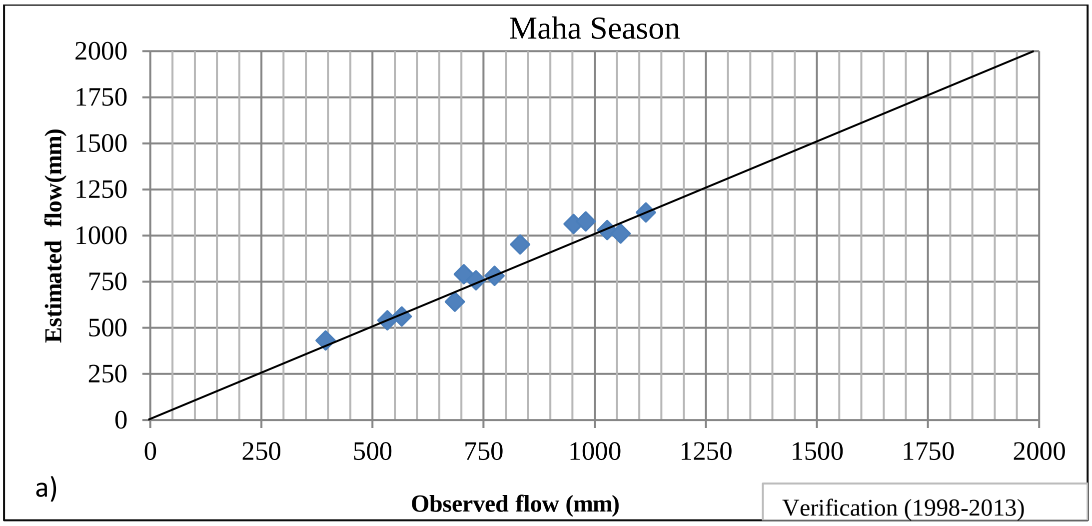


Figure 5-40: Annual Comparison of Observed & Estimated Flow of Kalu Ganga



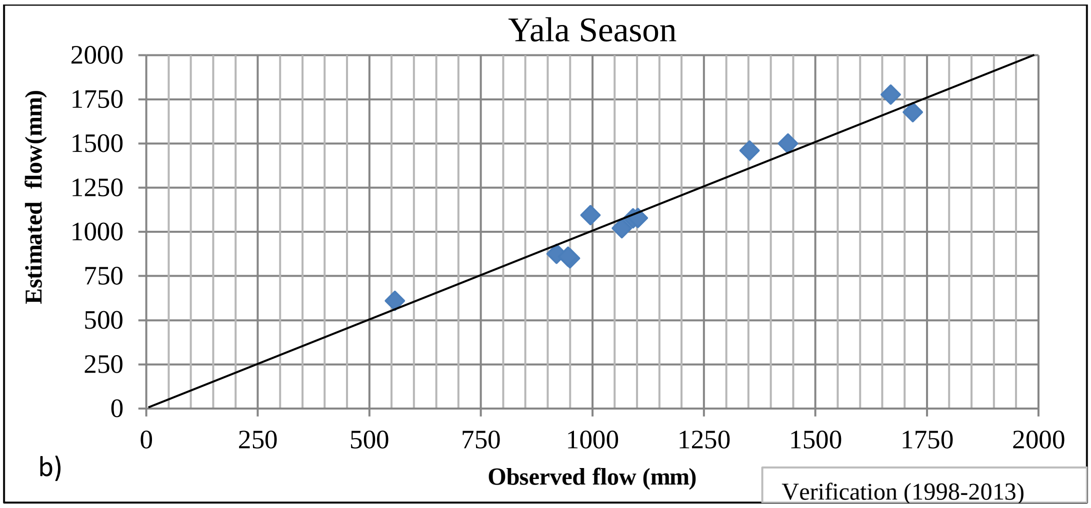


Figure 5-41: Seasonal Comparison of Observed & Estimated Flow of Kalu Ganga (a-b)

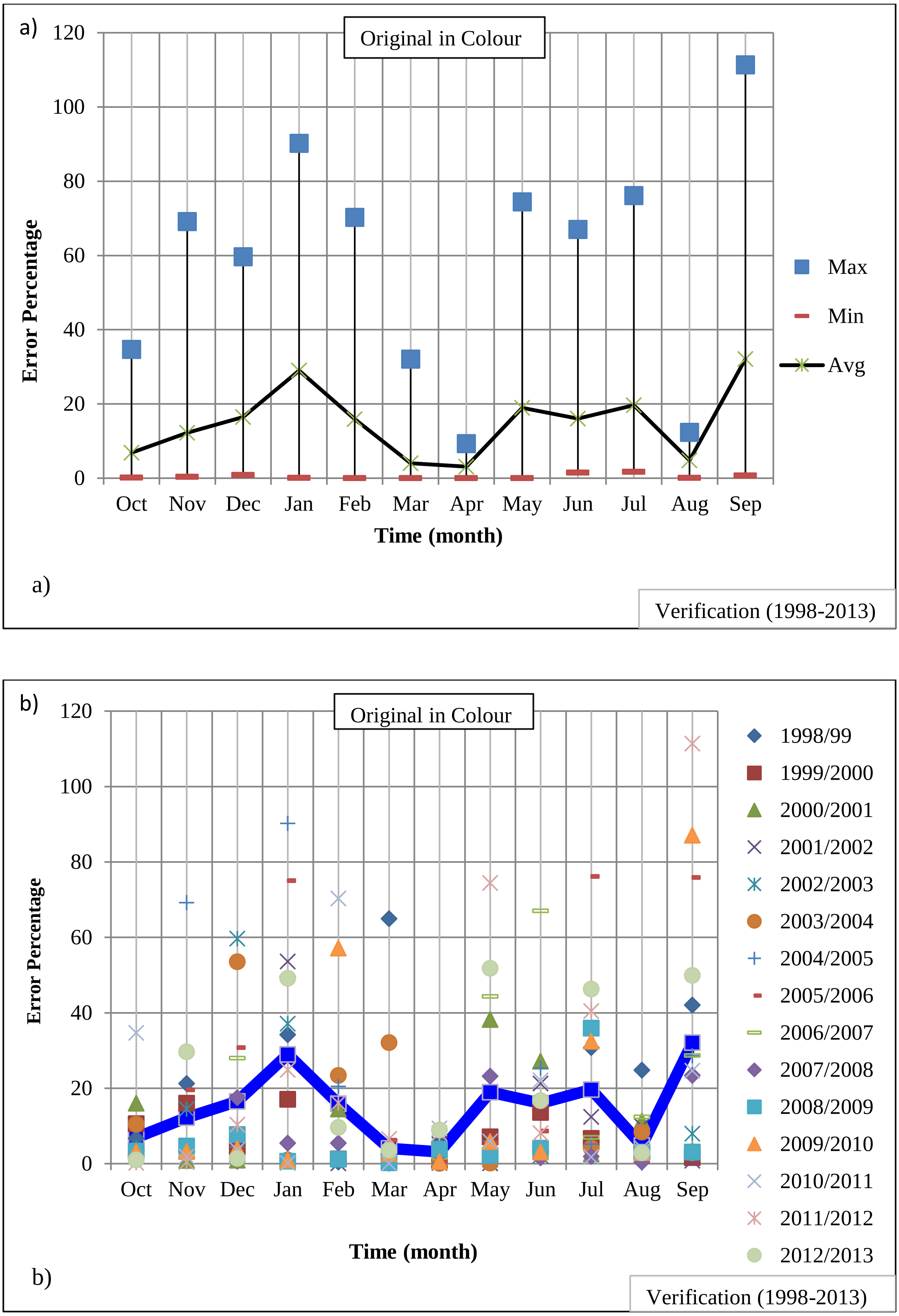


Figure 5-42: Estimated Error of Verification period for Kalu Ganga during each Month, each Year (a-b)

5.7.2 Evaluation of Verification results for Mahaweli at Morape

Data from 1964 to1979 were used for verification of Mahaweli Ganga watershed at Morape. In the verification period, the two parameter monthly water balance model produced a good matching of hydrographs. (Table 5-11). The MRAE value for total flow was found as 0.157 while high, medium and low flow MRAE values were 0.099, 0.195 and 0.184 respectively. The NASH-Sutcliffe efficiency for total flow was 94.1%; while the same for high, medium and low flows were 86.5%, 30.7% and 64.7% respectively.

Table 5-11: Estimated Parameters & Errors for Verification period of Mahaweli

C	**Sc**	**MRAE**	**Total flow**	**High flow**	**Medium flow**	**Low flow**
1.1	1200		0.157	0.099	0.195	0.184
		NASH-Sutcliffe	0.941	0.865	0.307	0.647

Monthly observed and calculated streamflow hydrographs plotted in normal and log scale (Figure 5-43 to 5-48) shows the very good matching of hydrographs in most of the years and in the case of a majority of monthly values. The matching of high, medium and low flows between observed flow and calculated flow is indicated in Figure 5-50. The results of verification showed that the high flows match better than the medium and low flows respectively. Water balance estimation for verification period demonstrated a very good match (Table 5-12 and Figure 5-49). Comparison of monthly, annual and seasonal water balance of verification using a scatter plots are shown from Figure 5-51 to Figure 5-53 and percentage error with respect to each month and each year for average and individual observations are shown in Figure 5-54 and Appendix-D (Figure D5). In the same Appendix, Figure D4 and Figure D9 indicate the simulated soil water content in verification period of Mahaweli Ganga at Morape.

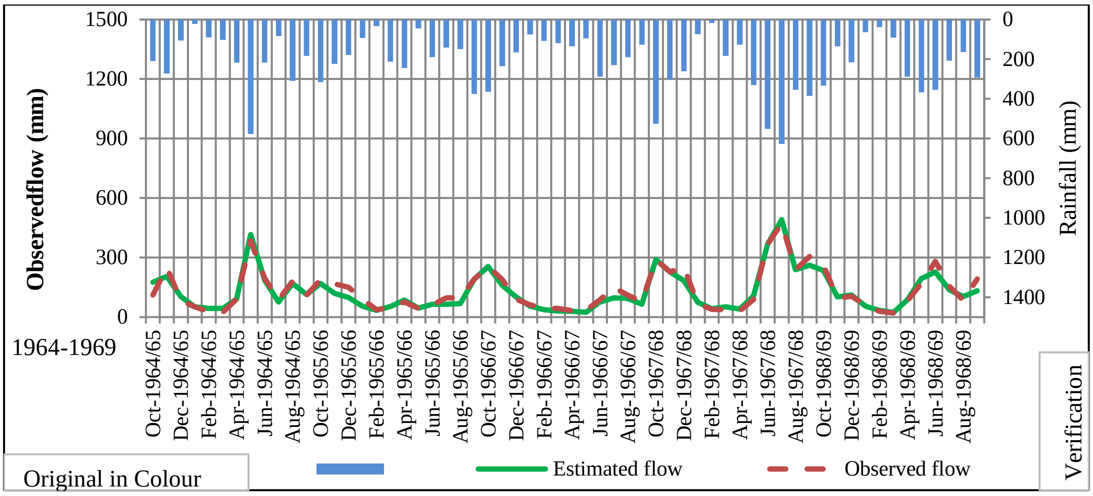


Figure 5-43: Calculated & Observed Monthly Flow hydrograph of Mahaweli Ganga

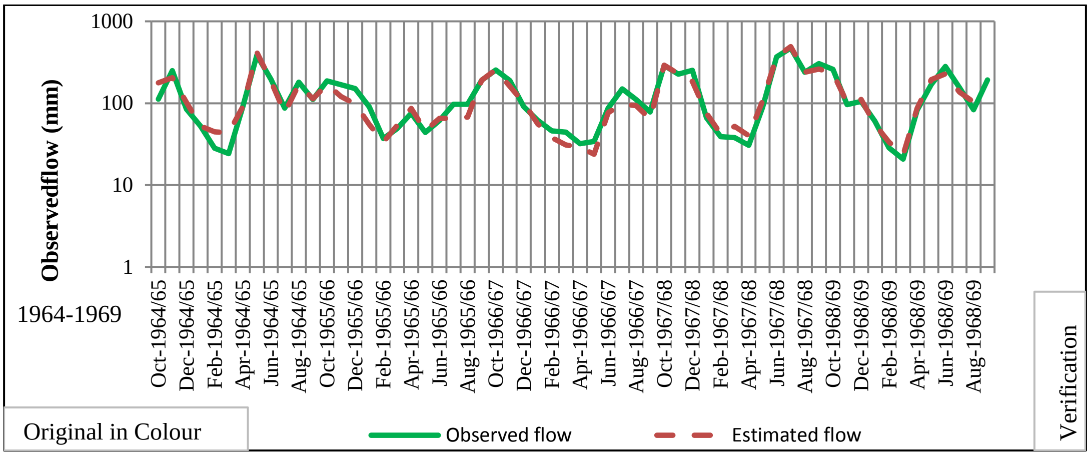


Figure 5-44: Logarithmic plot of Monthly Flow hydrograph of Mahaweli Ganga

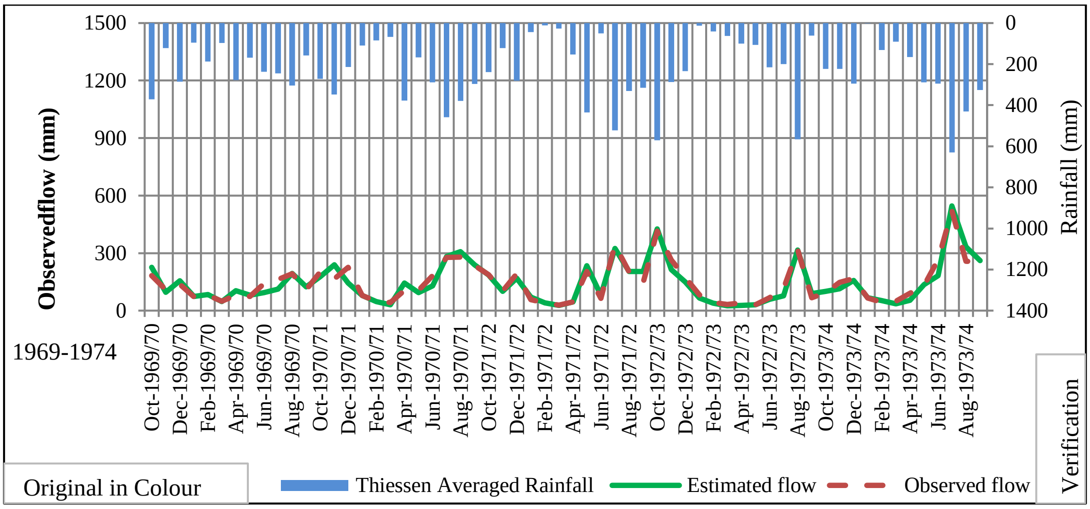


Figure 5-45: Calculated & Observed Monthly Flow hydrograph of Mahaweli Ganga

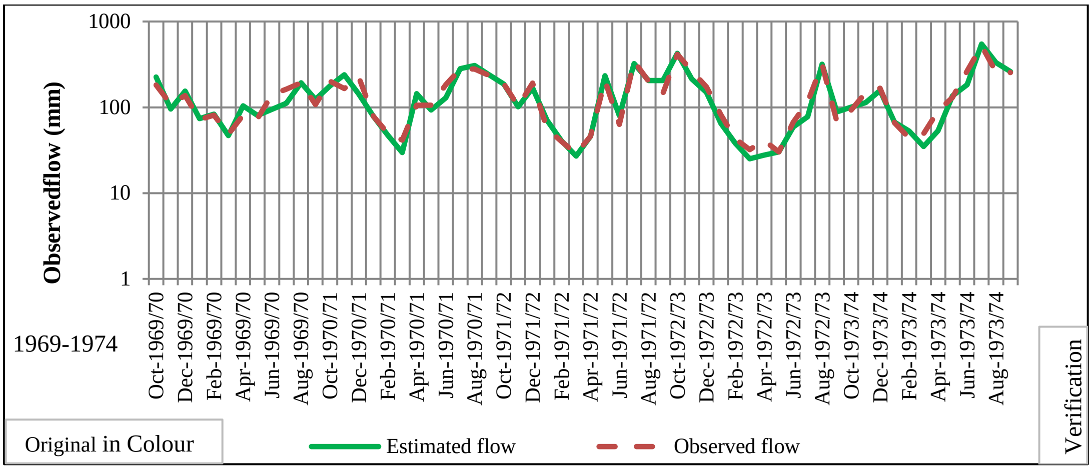


Figure 5-46: Logarithmic plot of Monthly Flow hydrograph in Mahaweli Ganga

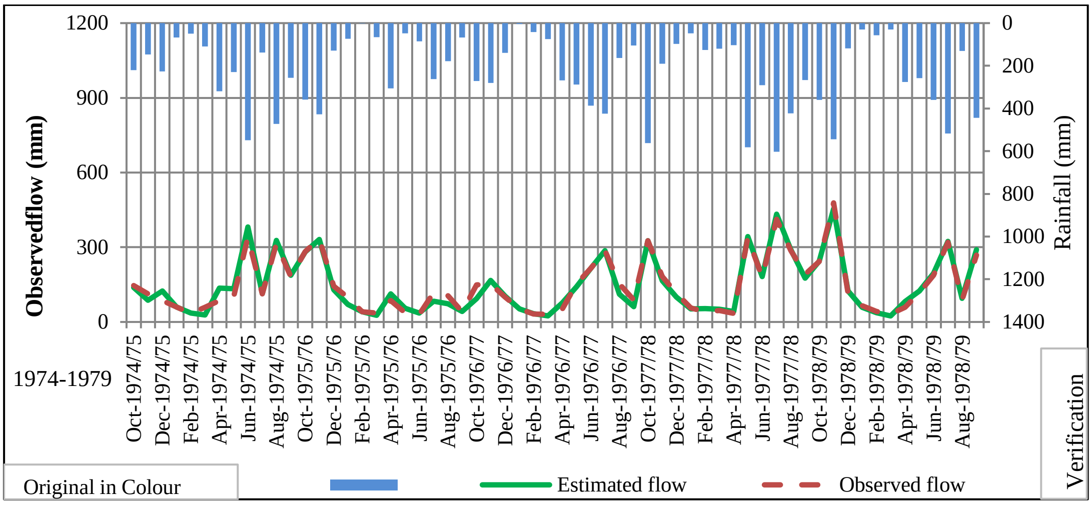


Figure 5-47: Calculated & Observed Monthly Flow hydrograph of Mahaweli Ganga

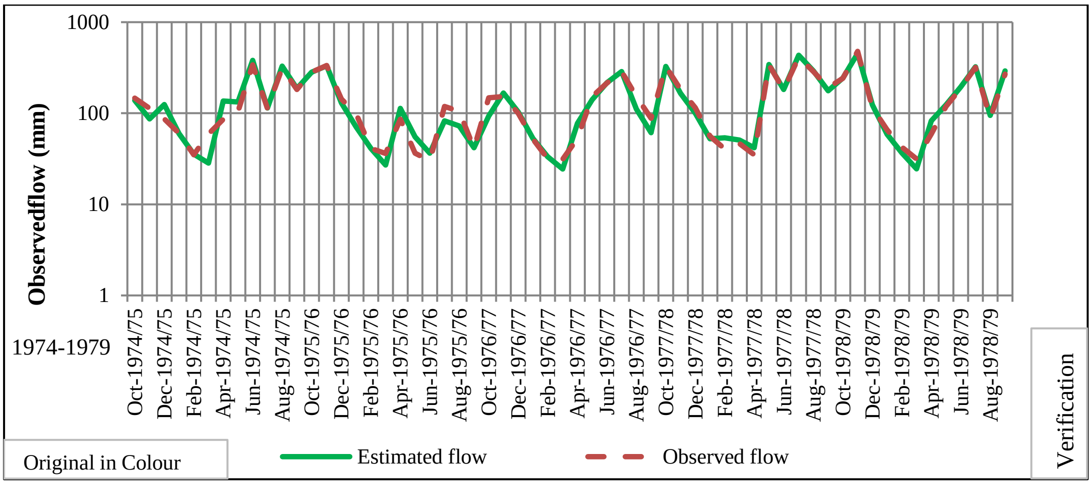


Figure 5-48: Logarithmic scale of Monthly Flow hydrograph of Mahaweli Ganga

Table 5-12: Water Balance Estimations for Verification Period of Mahaweli Ganga

Water Year	Rainfall (mm)	Estimated flow (mm)	Observed flow (mm)	Water Balance Estimated flow (mm)	Water Balance Observed flow (mm)
1964/65	2387.3	1676.5	1599.5	710.9	787.8
1965/66	2197.9	1050.9	1248.6	1147.0	949.3
1966/67	2131.2	1026.8	1177.7	1104.4	953.5
1967/68	3734.5	2378.7	2416.0	1355.8	1318.5
1968/69	2550.5	1440.0	1532.3	1110.5	1018.2
1969/70	2549.9	1386.8	1388.2	1163.1	1161.7
1970/71	3058.7	1910.9	1950.3	1147.8	1108.4
1971/72	2529.3	1687.6	1610.9	841.7	918.5
1972/73	2456.7	1516.8	1646.8	939.9	809.9
1973/74	3099.9	2037.4	2086.5	1062.5	1013.4
1974/75	2785.4	1753.7	1639.4	1031.7	1146.0
1975/76	2002.5	1283.0	1354.0	719.5	648.5
1976/77	2447.1	1367.6	1465.8	1079.4	981.3
1977/78	3412.3	2216.8	2211.5	1195.5	1200.8
1978/79	3123.4	2051.9	2017.1	1071.5	1106.3

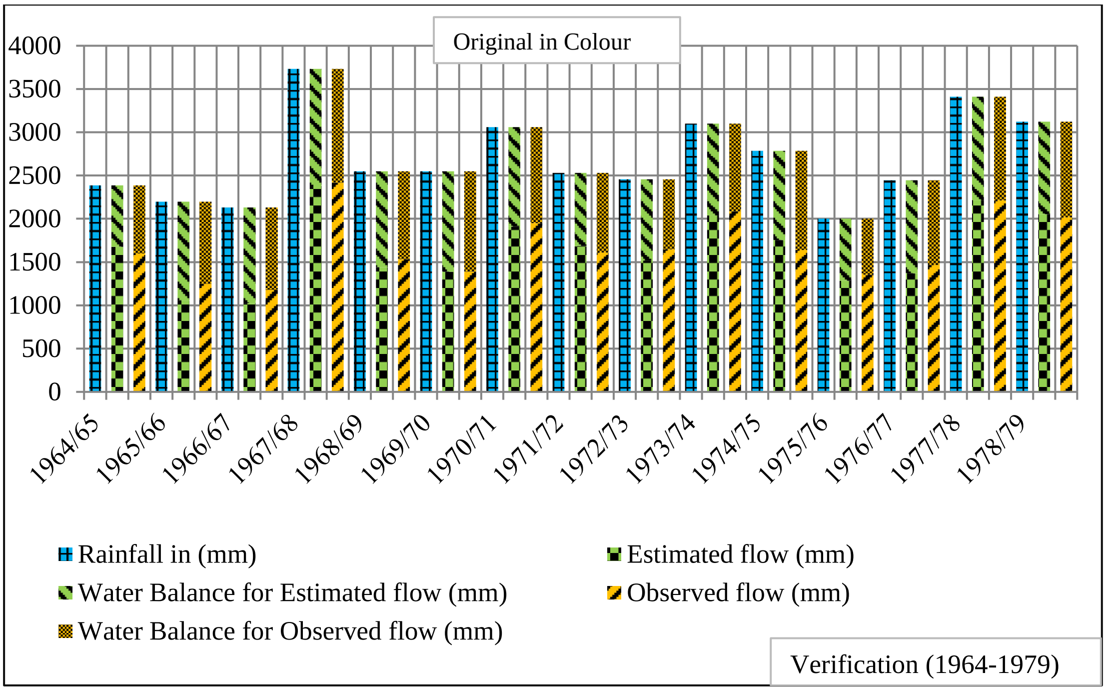

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Figure 5-49: Water Balance for Verification Period of Mahaweli Ganga

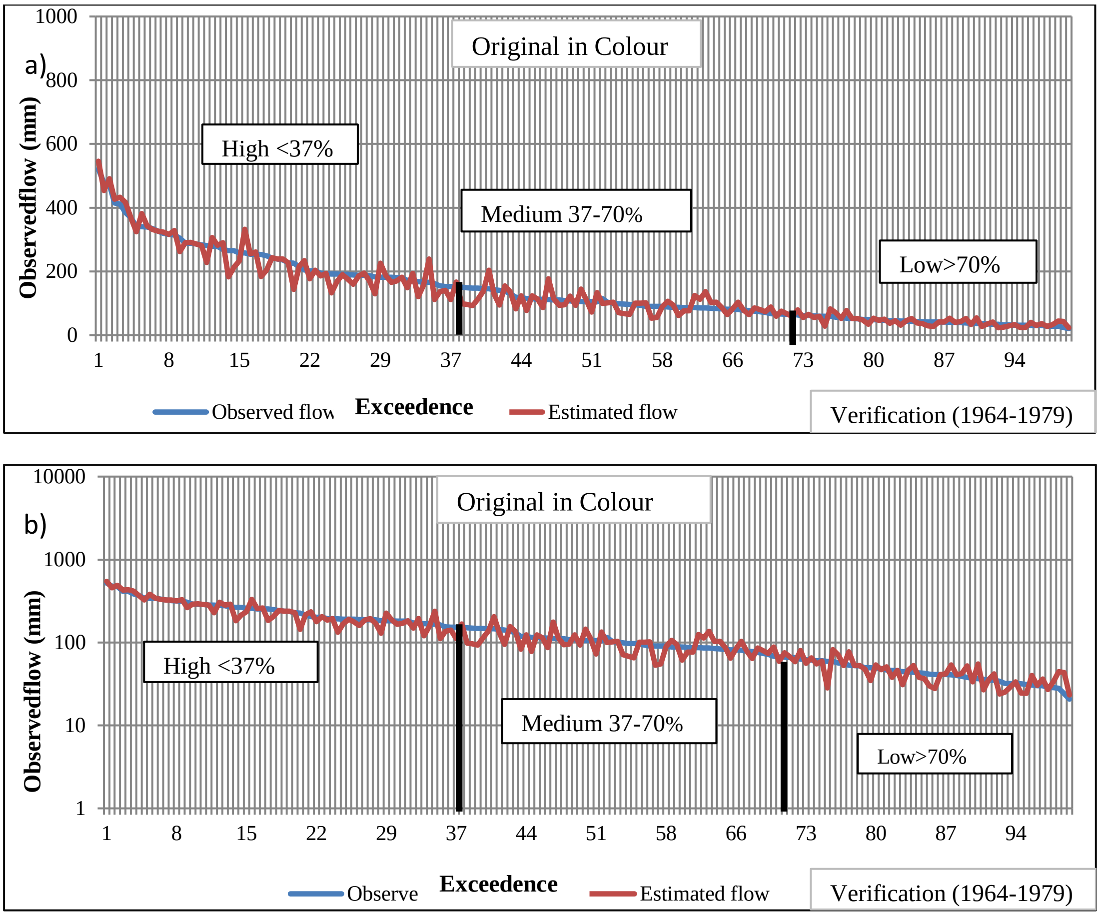


Figure 5-50: Normal and Log plot of Monthly Flow Duration curve in Mahaweli Ganga (a-b)

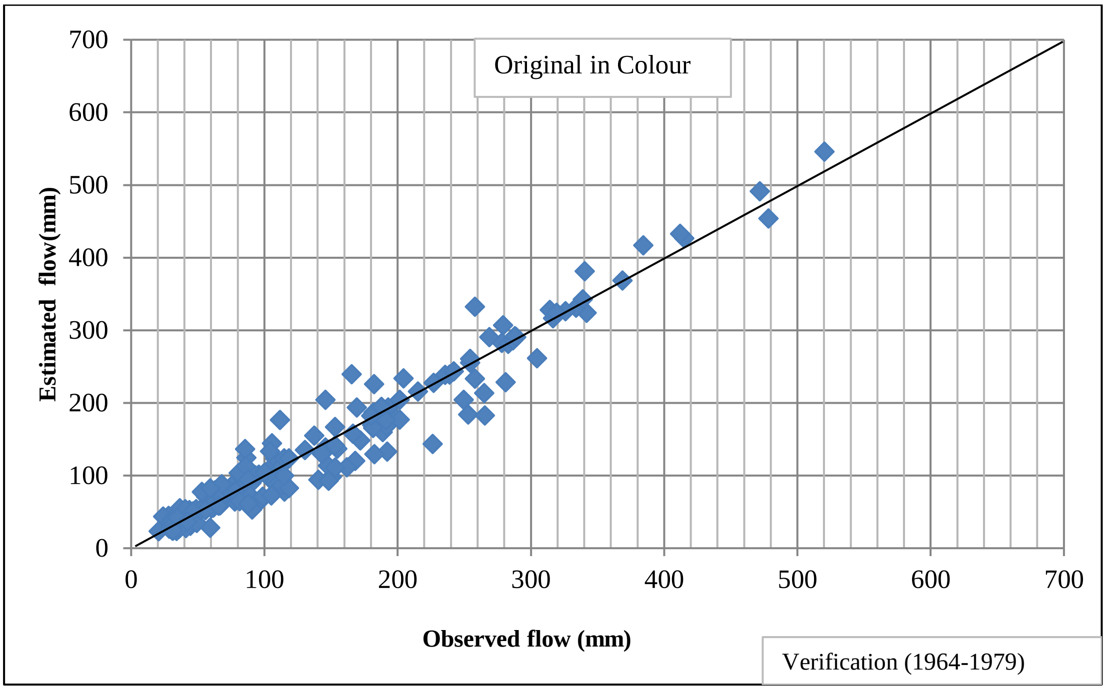


Figure 5-51: Monthly Comparison of Observed & Estimated flow for Mahaweli Ganga

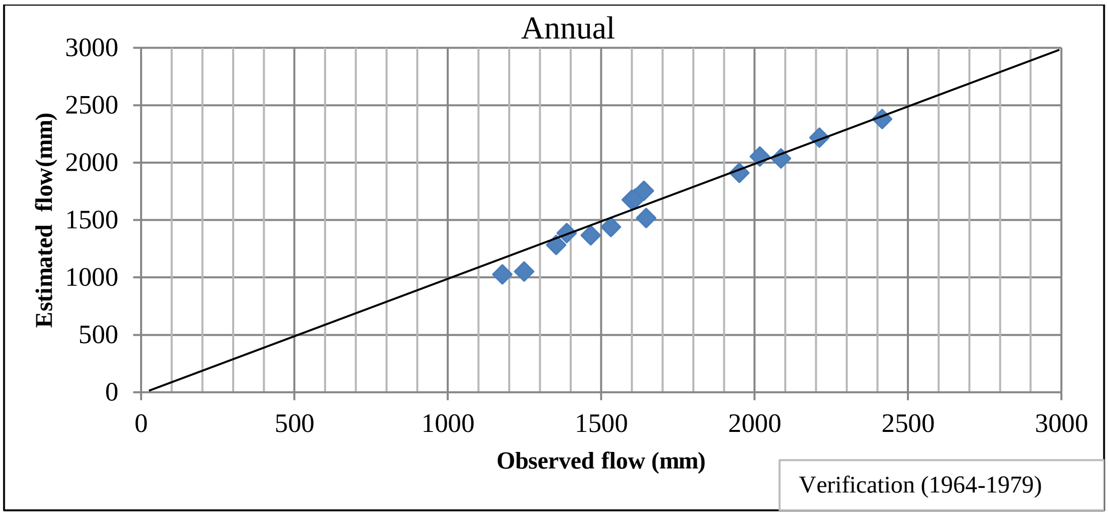
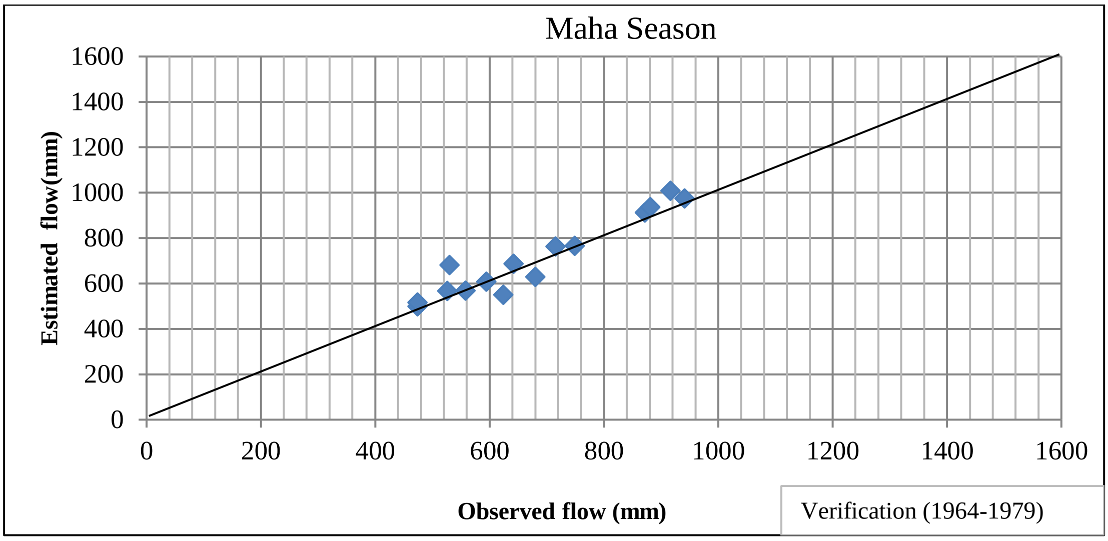


Figure 5-52: Annual Comparison of Observed & Estimated flow for Mahaweli Ganga



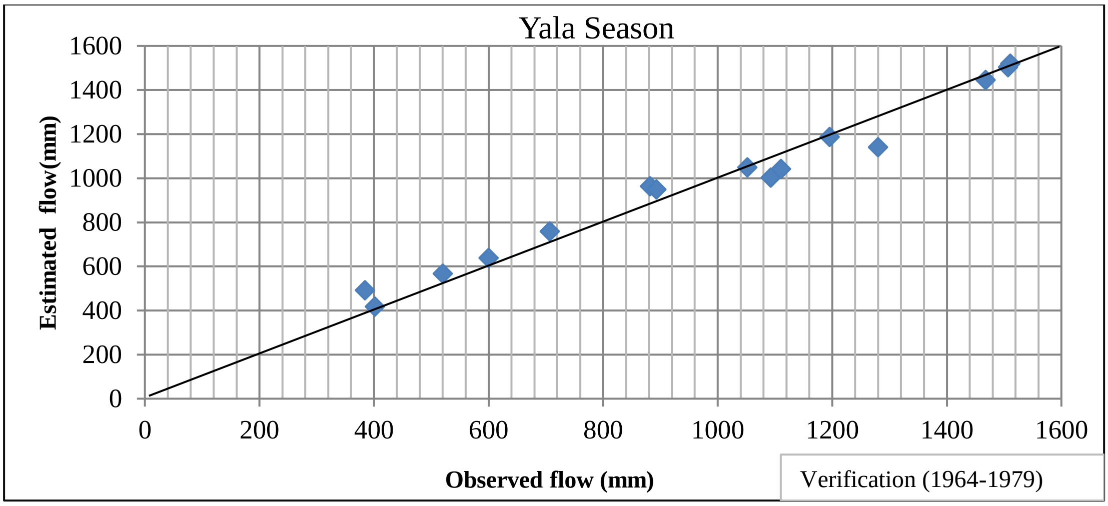


Figure 5-53: Seasonal Comparison of Observed & Estimated flow for Mahaweli Ganga

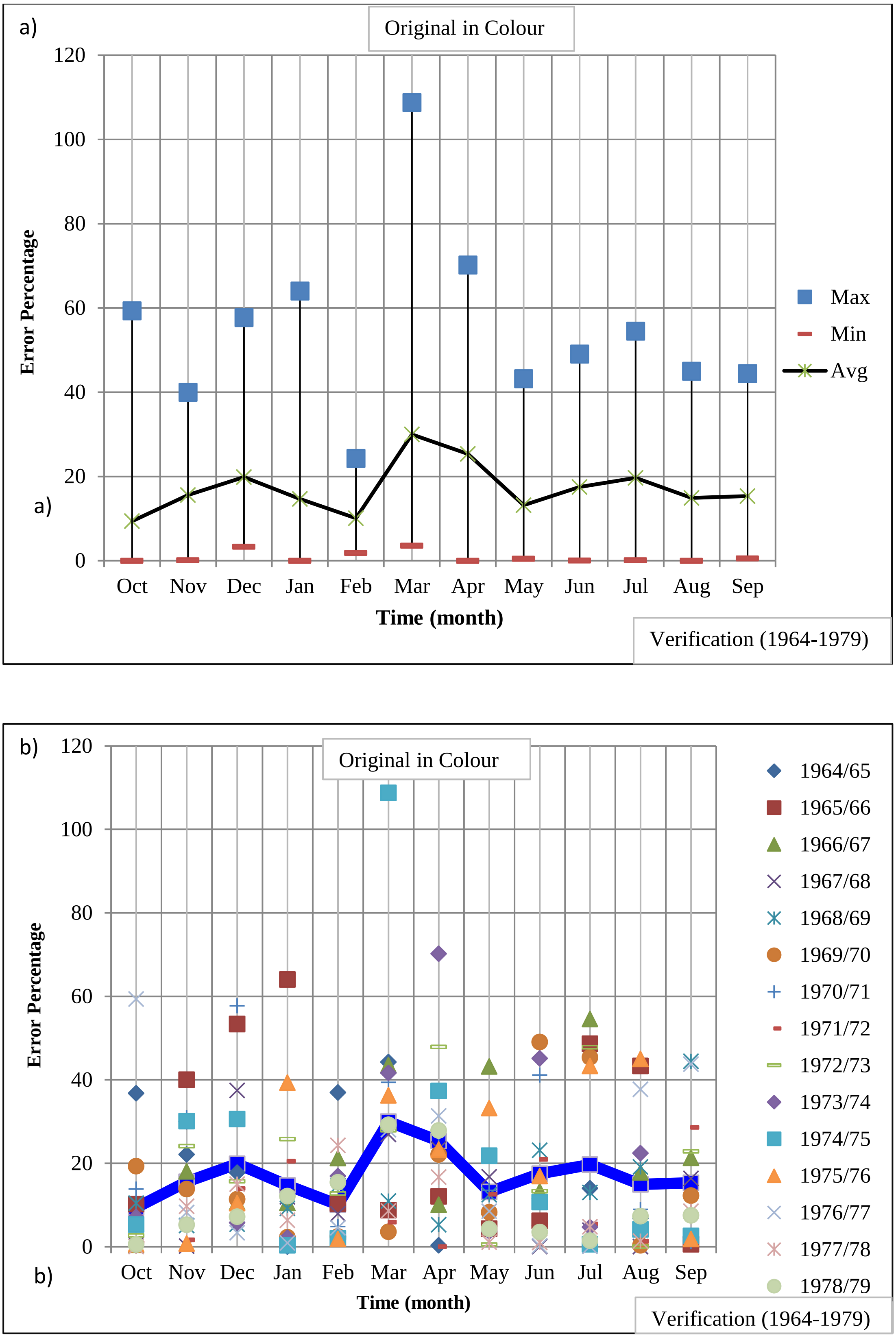


Figure 5-54: Estimated Error of Verification Period for Mahaweli Ganga during each Month, each Year (a-b)

6 MODEL DEVELOPMENT AND ITS APPLICATION POTENTIAL FOR EVALUATION OF WATER RESOURCES

In recent years, the increasing imbalance between water supply and water demands has given rise to a greater attention from both the relevant authorities and the general public on water resources planning programs, in which long-term forecasting of water cycle and its distribution is one of the important topics. For the evaluation of water resources under different conditions, monthly water balance models have been widely employed for the conversion of rainfall into runoff. Therefore, the two parameter monthly water balance model, using 75% probable rainfall and evaporation, was used for the evaluation of water resources in both catchments, namely Kalu Ganga at Ellagawa and Mahaweli Ganha at Morape.

During the parameter optimization, it was realized that the optimum value of the parameter SC is robust and rather insensitive to the initial values of parameters. The SC value also appeared to have an obvious distribution law with respect to location of catchment. The parameter C value did not indicate as sensitive as SC with respect to location of the catchment. During optimization, the SC parameter values of Kalu Ganga at Ellagawa for outputs in monthly, annual, and seasonal time scale were determined as 800 (monthly), 600 (Annual) and 600 (Maha),1000 (Yala). These values obtained for Mahaweli at Morape were 1200 (monthly), 1400 (Annual) and 1300 (Maha), 1600 (Yala). The optimum values of parameter C for Kalu Ganga at Ellagwa were found as 1 (monthly), 1 (Annual) and 0.9 (Maha), 1 (Yala) respectively, while; these value were obtained for Mahaweli at Morape as 1.1 (monthly), 1 (Annual) and 1.1 (Maha), 1 (Yala). These results hint that the SC parameter has a higher spatial variability when with the C parameter.

During the calibration and verification of the model for both catchments, Kalu Ganga at Ellagawa and Mahaweli at Morape, it was identified that the model has a very higher capability to assist in water resources management. However, the model performed better in annual and seasonal time scales when compared to monthly time scale. The MRAE value for Kalu Ganga at Ellagawa at monthly time scale was calculated as 0.145. In annual, Maha season, Yala season time scales the respective values were 0.042 and 0.069, 0.054. For Mahaweli at Morape, the MRAE values at monthly time scale was 0.152. In annual, Maha season, Yala season time scales value of MRAE was found as 0.056, 0.077 and 0.067 respectively.

Since the models for kalu Ganga and Mahaweli Ganga has been calibrated and verified, it is now possible to evaluate water resources with a suitable rainfall input. In this work it was considered whether the models could be used for water resources infrastructure planning. Therefore stream flow response with 75% probable rainfall was evaluated.

6.1 Model Development & Yield estimation for Kalu Ganga at Ellagwa

Kalu Ganga at Ellagwa is located in Agro-Ecological regions of WL2. The 75% probable rainfall and evaporation data were collected form WL2 region and from Colombo meteorology station respectively.

The successful calibrated and verified two parameter monthly water balance model was used, using 75% probable rainfall and evaporation data, with respect to the identified parameters, as input. The initial value of soil water content was found as 133.3 mm. The computed monthly stream flow values are in Table 6-1. Plotted curve is in Figure 6.1.

Table 6-1: Estimated Flow using 75% Rainfall for Kalu Ganga at Ellagawa

Time	75% Rainfall (mm)	Evaporation (mm)	Estimated flow (mm)	Estimated flow (m3/sec)
Oct	292.1	78.6	141.6	34.3
Nov	203.2	77.7	130.0	32.5
Dec	76.2	89.0	56.9	13.8
Jan	38.1	93.3	32.0	7.7
Feb	50.8	93.9	22.1	5.9
Mar	101.6	106.1	22.3	5.4
Apr	177.8	101.2	46.3	11.6
May	152.4	95.1	55.3	13.4
Jun	177.8	89.0	75.4	18.9
Jul	101.6	93.9	49.5	12.0
Aug	88.9	104.9	34.8	8.4
Sep	101.6	97.5	31.2	7.8

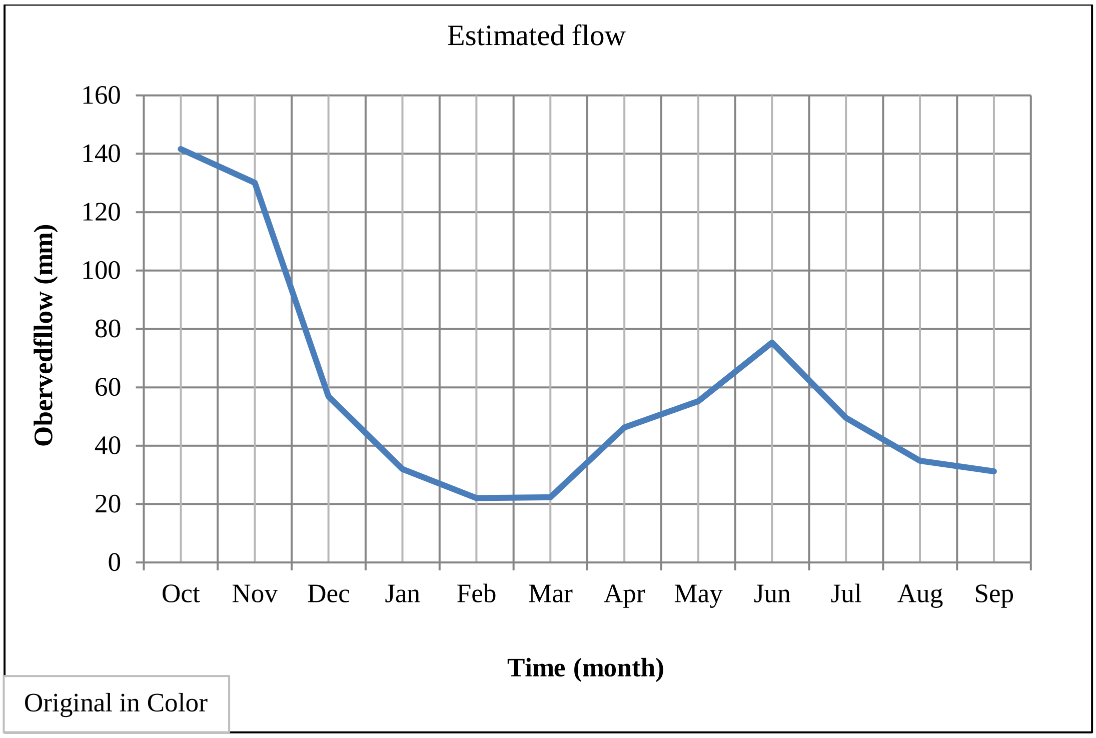


Figure 6-1: Estimated flow using 75% Rainfall for Kalu Ganga at Ellagawa

6.1.1 Yield Estimation

6.1.1.1 Yield Estimation for Maha

75% probable rainfall was used for yield estimation in Maha season for Kalu Ganga at Ellagwa which are in the Table 6-2 and plotted in Figure 6-2.

Table 6-2: Estimated Yield for Maha Season using 75% Rainfall for Kalu Ganga

Yield for Maha Season			
Month	Rainfall in inch	Yield in Ac.Ft	Yield in Ha.m
October	11.5	115198.7	14209.6
November	8	80138.2	9884.9
December	3	30051.8	3706.8
January	1.5	15025.9	1853.4
February	2	20034.6	2471.2
March	4	40069.1	4942.5
Total	30	300518.4	37068.4

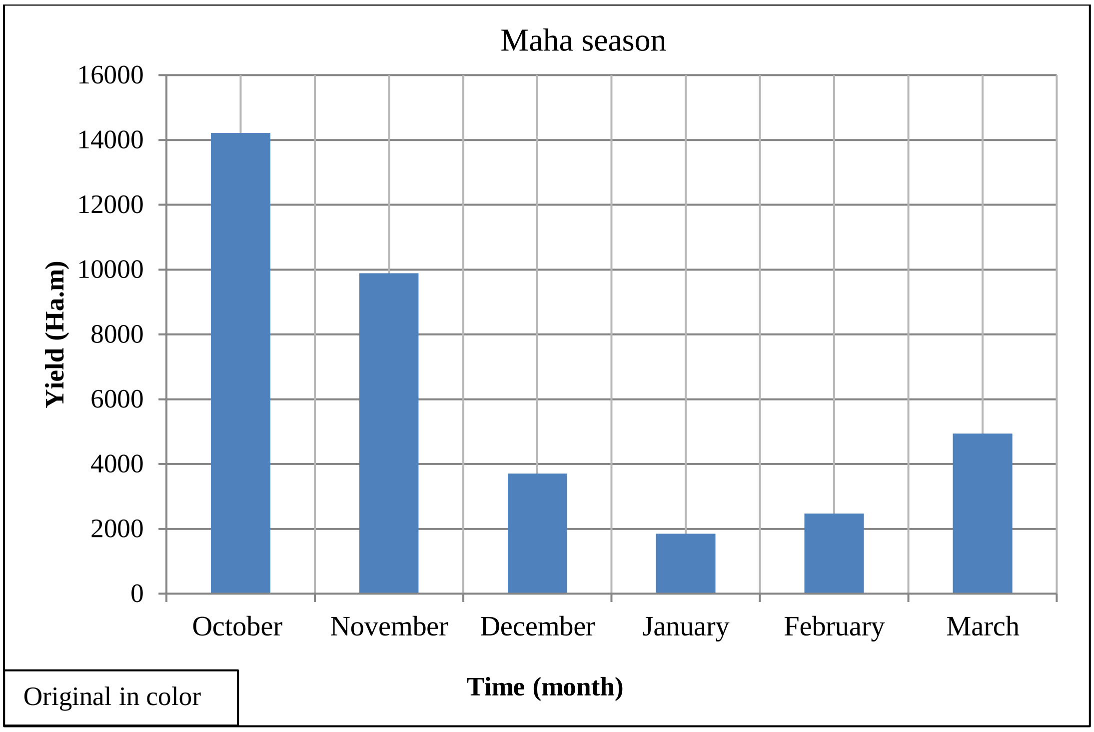


Figure 6-2: Estimated Yield in Maha Season for Kalu Ganga at Ellagawa

6.1.1.2 Yield Estimation for Yala Season

Yield for Yala season was calculated using 75% probable rainfall for Kalu Ganga at Ellagwa (Table 6-3 & Figure 6-3).

Table 6-3: Estimated Yield for Yala Season for Kalu Ganga at Ellagawa

Yield for Yala Season			
Month	Rainfall in inch	Yield in Ac.Ft	Yield in Ha.m
April	7	70121.0	8649.3
May	6	60103.7	7413.7
June	7	70121.0	8649.3
July	4	40069.1	4942.5
August	3.5	35060.5	4324.6
September	4	40069.1	4942.5
Total	31.5	315544.3	38921.8

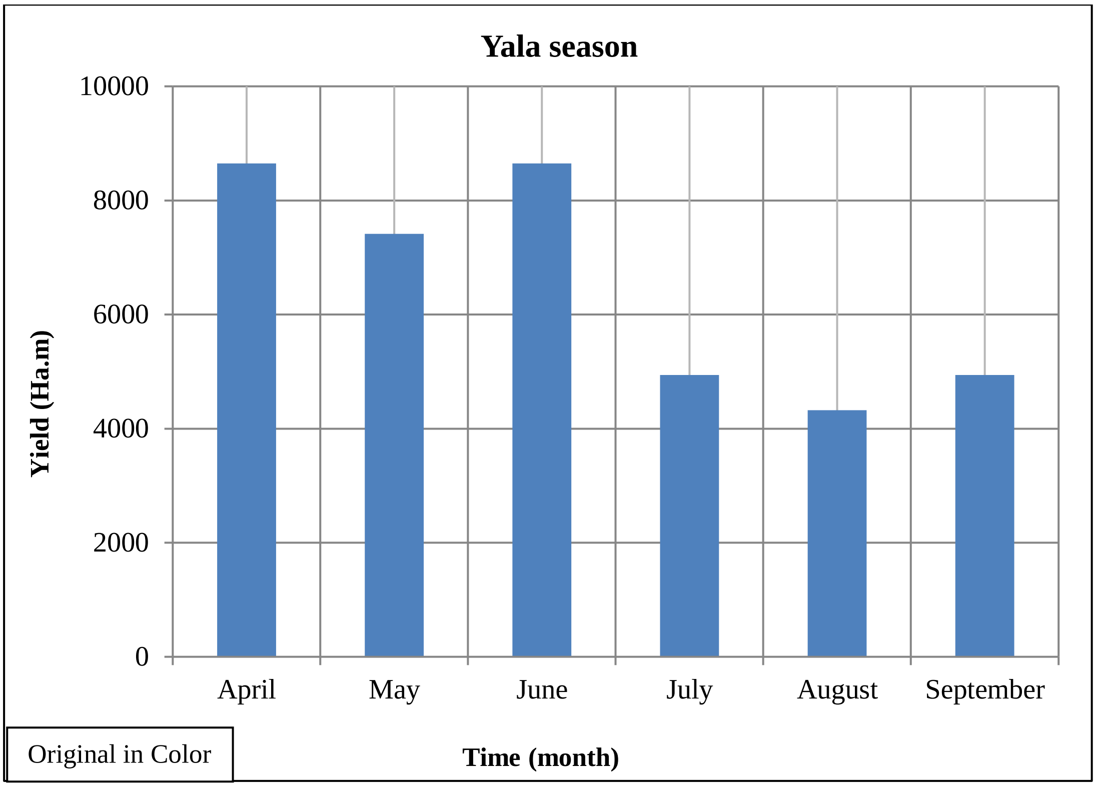


Figure 6-3: Estimated Yield for Yala Season for Kalu Ganga at Ellagawa

6.2 Model Development & Yield estimation for Mahaweli at Morape

Mahaweli Ganga at Morape is located in Agro-Ecological WU2. The 75% probable rainfall for Mahaweli at Morape was collected form d WU2 region while; the evaporation data was collected from Kanda-Ela station.

The two parameter monthly water balance model was used, using 75% probable rainfall and evaporation as input. The identified parameters each C and SC were applied in model to generate the stream flow. The initial value of soil water content was found as a 279.68 mm. Computed monthly stream flow values are in Table 6-4. Plotted curve is in Figure 6-4.

Table 6-4: Estimated Flow using 75% Rainfall for Mahaweli Ganga at Morape

Time	75% Rainfall (mm)	Evaporation (mm)	Estimated flow (mm)	Estimated flow (m3)
Oct	279.4	63.1	116.9	60.7
Nov	203.2	61.9	93.5	50.1
Dec	127.0	59.1	60.5	31.4
Jan	88.9	60.0	39.3	20.4
Feb	50.8	65.8	24.4	14.0
Mar	88.9	84.7	19.5	10.1
Apr	165.1	66.4	33.5	17.9
May	139.7	68.9	36.7	19.0
Jun	279.4	53.6	91.3	49.0
Jul	228.6	59.7	97.5	50.6
Aug	203.2	61.6	88.3	45.8
Sep	177.8	64.9	74.3	39.9

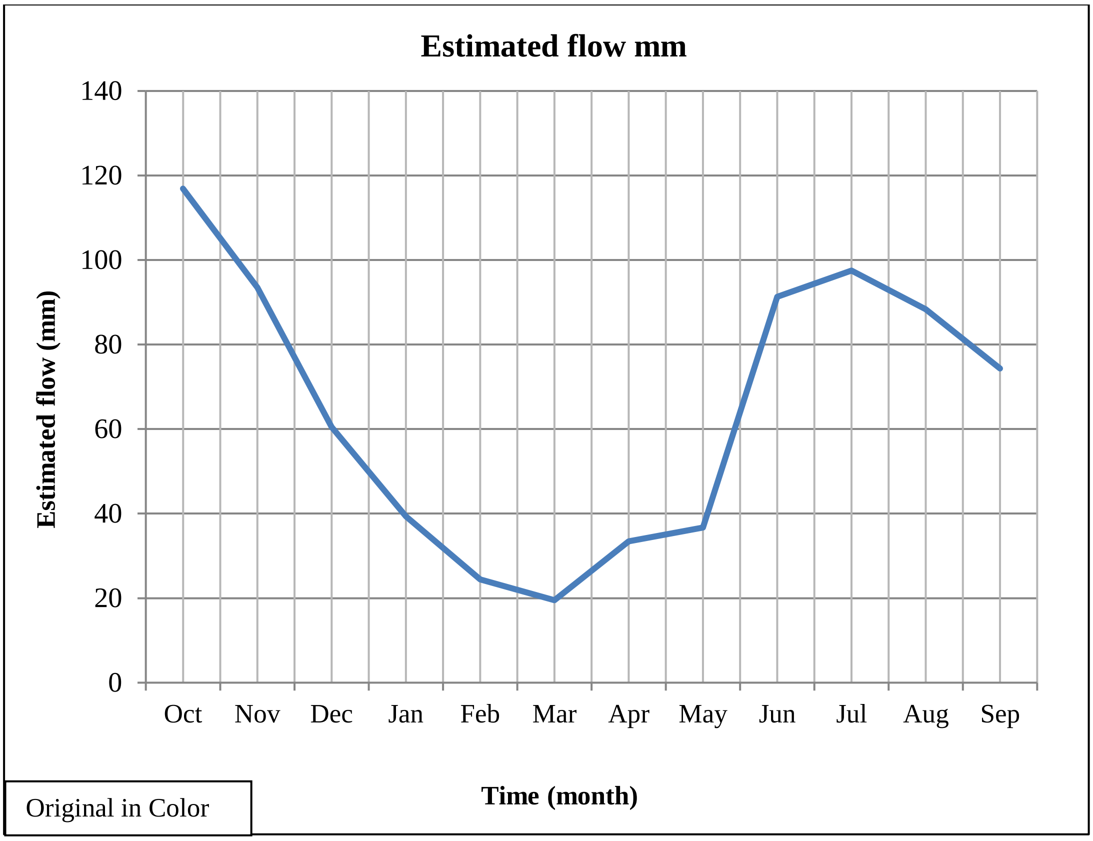


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Figure 6-4: Estimated flow using 75% Rainfall for Mahaweli Ganga at Morape

6.2.1.1 Yield Estimation for Maha

Yield for Maha season was calculated using 75% probable rainfall (Table 6-5, Figure 6-5). Yield for Yala season are in Table 6-6 and Figure 6-6.

Table 6-5: Estimated Yield for Maha Season for Mahaweli at Morape

Yield for Maha season			
Month	**Rainfall in inch**	**Yield in Ac.Ft**	**Yield in Ha.m**
October	11	42966.0	5299.8
November	8	31248.0	3854.4
December	5	19530.0	2409.0
January	3.5	13671.0	1686.3
February	2	7812.0	963.6
March	3.5	13671.0	1686.3
Total	33	128898.0	15899.3

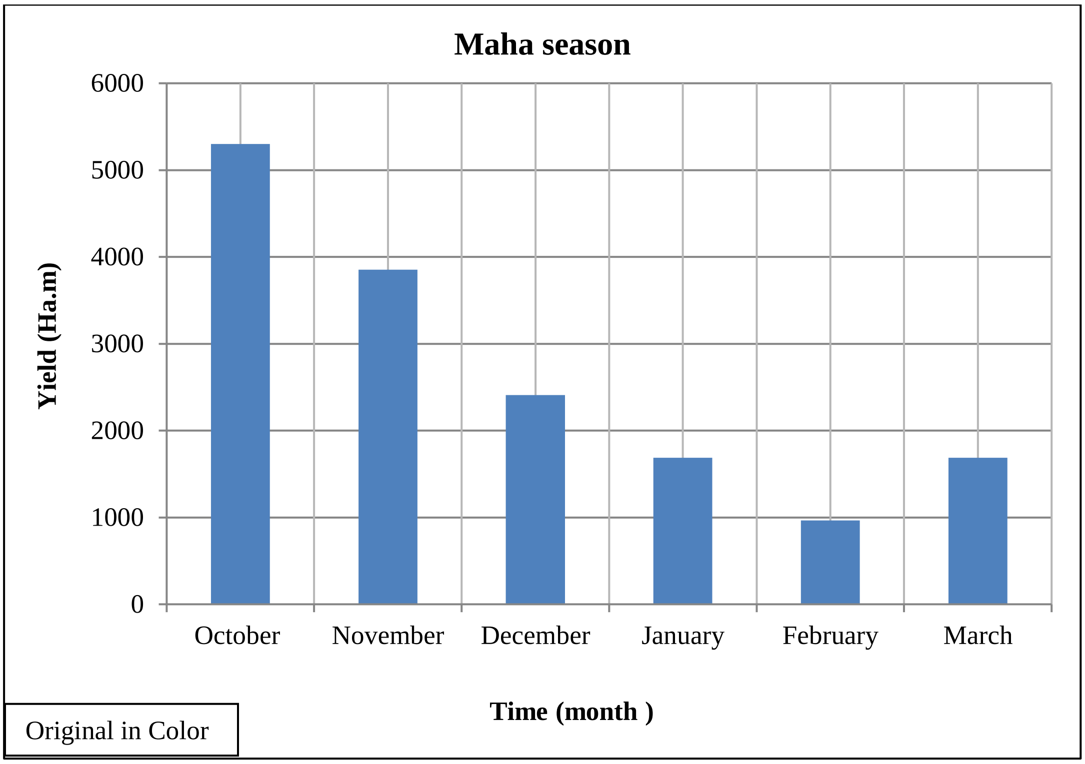
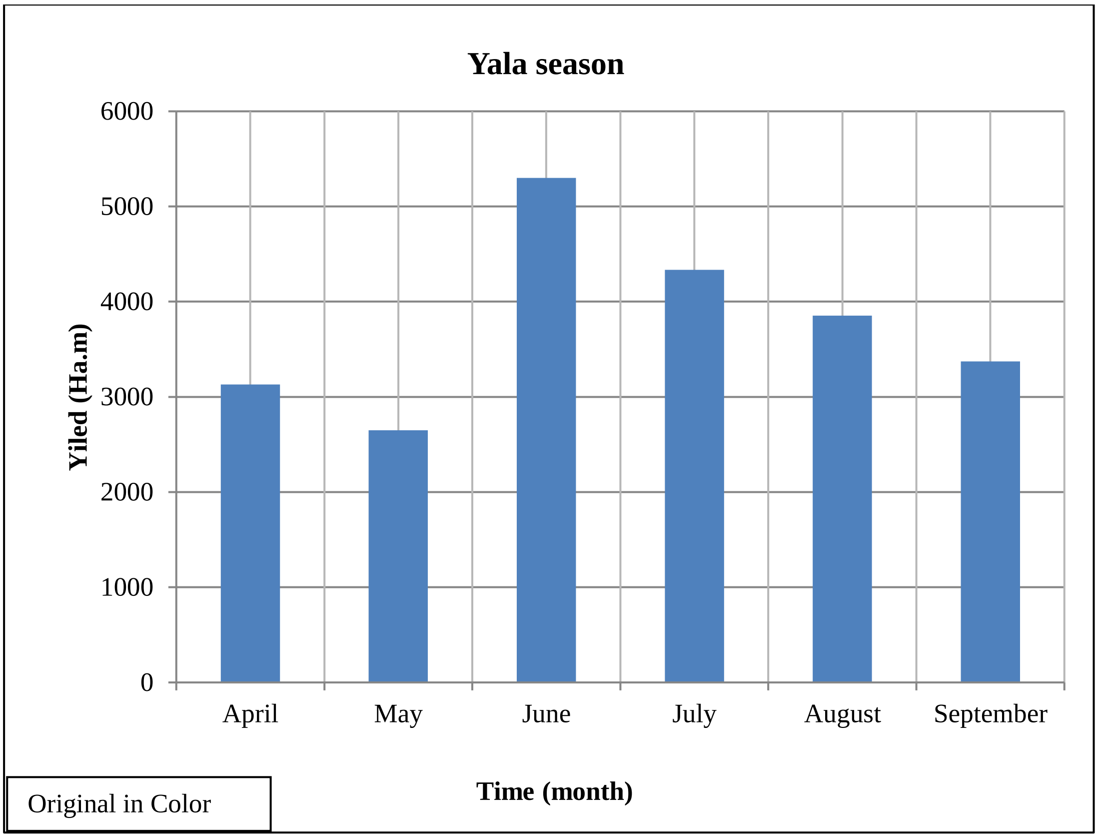


Figure 6-5: Estimated yield in Maha Season for Mahaweli at Morape

6.2.1.2 Yield Estimation for Yala

Table 6-6: Estimated yield in Yala Season for Mahaweli at Morape

Yield for Yala season			
Month	**Rainfall in inch**	**Yield in Ac.Ft**	**Yield in Ha.m**
April	6.5	25389.0	3131.7
May	5.5	21483.0	2649.9
June	11	42966.0	5299.8
July	9	35154.0	4336.2
August	8	31248.0	3854.4
September	7	27342.0	3372.6
Total	47	183582.0	22644.5



Original in Color

Figure 6-6: Estimated yield in Yala Season for Mahaweli Ganga at Morape

7 DISCUSSION

7.1 Model selection

The two parameter monthly water balance model was selected for evaluation of water resources estimation in both Kalu Ganga at Ellagawa and Mahaweli at Morape. A literature review was done for evaluation of different types of monthly water balance models to check their potential and weaknesses in calibration and verification of monthly inputs. Accordingly, different types of monthly water balance models were reviewed with different parameters, varied between 2 to 12 parameter, and different inputs. After an evaluation, the two parameter monthly water balance model was selected considering the following advantages and potential.

- Two parameter monthly water balance models are easy to handle
- Less parameters and good performance
- Taking less time to operation
- Data availability for selected catchments

7.2 Data collection and checking

Thirty years of monthly rainfall, stream flow and pan evaporation data were collected for both Kalu Ganga at Ellagwa and Mahaweli at Morape. Five rainfall stations were selected for Kalu Ganga at Ellagawa. They are Galatura estate, Balangoda Post office, Wellandura estate and Ratnapura. The stream flow and evaporation data for Kalu Ganga at Ellagwa were collected from Irrigation Department gauging station and Ratnapura evaporation station, respectively. Rainfall data for Mahaweli at Morape were collected from three stations. They are Sandringham, Nuwara Eliyamet Station and Oonagalla estate. Streamflow and pan evaporation data were collected from Morape gauging station and Kande Ela evaporation station.

Prior to using data in the model, data checking was done to check the quality of the data. The quality of the data was checked with many methods. These methods were single mass curve, filling the missing data, outlier testing, graphical checking, runoff coefficient checking and double mass curve analysis. Single mass curve analysis was done for both catchments to find out the correlation between the rainfall stations.

Missing data were filled after single mass curve analysis using regression method. Higher and lower outliers were tested to find out the unrealistic data. Thiessen polygon was developed using ArcGIS. Graphical checking was done by plotting monthly, annual and seasonal data to check and compare rainfall and stream flow patterns and then to observe the compatibility. Prior to using the rainfall records, all stations were checked to continuity and consistency through double mass curve analysis. Finally, after data checking and filling of the missing data, they were used for modelling. Monthly Maximum, minimum and averaged of stream flow and pan evaporation along with Thiessen averaged rainfall for both catchments Kalu Ganga at Ellagwa and Mahaweli at Morape are in Table7-1 and Table 7-2 respectively.

Table 7-1: Max, Mean & Min of Monthly Data of Kalu Ganga at Ellagawa

Water Months	Thiessen Rainfall (mm/month)			Observedflow (mm/month)			Pan evaporation (mm/month)		
	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max
Oct	143.5	371.3	650.2	99.0	276.4	565.0	44.8	93.3	137.8
Nov	130.1	334.2	566.8	90.9	242.4	531.2	43.5	93.7	140.1
Dec	40.3	206.2	538.8	44.1	137.8	350.4	41.7	86.6	118.3
Jan	20.3	137.3	412.4	34.7	85.8	280.6	52.3	97.2	136.1
Feb	10.0	130.4	315.0	25.0	70.0	244.6	61.0	118.5	171.5
Mar	34.3	225.5	399.1	20.8	106.0	277.0	44.4	122.0	186.5
Apr	105.5	339.9	665.5	62.8	213.9	593.7	45.4	104.4	151.1
May	40.3	387.2	644.7	45.4	270.6	600.0	71.3	104.0	136.7
Jun	160.2	351.3	771.2	91.3	252.3	716.0	59.8	95.1	136.5
Jul	17.4	263.9	609.6	51.0	181.5	493.0	29.3	91.0	143.0
Aug	46.9	249.1	567.4	43.1	179.6	443.8	46.9	90.7	131.8
Sep	107.8	321.1	616.8	41.0	215.3	513.8	53.0	97.3	138.6

Table 7-2: Max, Mean & Min Monthly Data of Mahaweli Ganga at Morape

Water Months	Thiessen Rainfall (mm/month)			Observedflow (mm/month)			Pan evaporation (mm/month)		
	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max
Oct	193.7	330.8	570.9	93.4	215.8	415.1	48.5	85.7	118.6
Nov	121.7	241.6	544.8	88.5	194.3	478.3	52.1	78.5	124.2
Dec	57.7	178.7	505.7	68.7	144.6	408.7	34.1	73.7	125.5
Jan	12.0	88.9	235.3	42.0	72.2	117.0	50.0	85.0	139.4
Feb	9.8	83.4	187.8	26.8	47.7	104.0	49.0	92.1	148.1
Mar	26.7	105.6	235.1	20.8	41.0	100.3	59.0	115.3	165.9
Apr	99.4	218.2	377.9	26.8	63.2	105.7	58.2	87.6	127.0
May	29.3	266.2	709.1	30.1	125.1	384.5	63.0	91.6	136.9
Jun	50.8	330.9	931.5	30.1	188.4	386.9	42.2	86.4	132.0
Jul	83.9	329.7	629.8	87.0	238.9	520.4	45.2	87.7	151.9
Aug	111.9	273.8	565.9	83.5	197.7	324.2	46.7	88.6	155.0
Sep	61.3	254.3	613.8	41.0	174.9	418.0	57.9	88.0	129.3

Comparison of averaged Thiessen and Arithmetic Mean rainfall data in annual and seasonal time scales for both catchments Kalu Ganga at Ellagwa and Mahaweli at Morape are in Table No.5-3 to 5-6. In the Kande Ela evaporation station, located in Mahaweli at Morape, there were missing data (1976-1979) which was filled with data from station nearest station at Bandarawela.

During model development several higher and unrealistic runoff coefficients were found. Some months were having high observedflow, while the rainfall was very less. In some occasions the abnormal values were due to the mismatch of rainfall and streamflow occurrence with each calendar month. Such values were kept for computations. After an evaluation, the unrealistic runoff coefficients amounting to 6% in Kalu Ganga and 5% in Mahaweli Ganga were avoided in computations. Runoff coefficient analysis details are indicated in Appendix-A (Figure A14-A21).

7.3 Model Development

7.3.1 High Medium and Low flows

The flow duration curve for the entire dataset was plotted to determine the high, medium and low flows. Each year flow duration curves do not clearly classifying the flow stages, due to the wide variation. Nevertheless, normal and semi log flow duration curves were plotted for annual average data to easily indentify the flow stages. Comparing and rationalizing the flow types in Kalu Ganga at Ellagwa was found as high (<30 %), medium between (30-63%) and low >63%. In Mahaweli at Morape the flow stages were high (<37%), medium between (37-70%) and low >70%. The flow duration curves are in Figures 5-1 to 5-7.

7.3.2 Initial soil water content

Initial soil water content value, S(0) affects the monthly runoff in the early months. In this study for both catchments Kalu Ganga at Ellagawa and Mahaweli at Morape, the initial value of soil water content was determined after five complete model runs over the calibration data as the warm-up period. During the warm-up period, it was identified that the model reacts are significantly influenced by initial soil water content. The initial soil water content estimated for Kalu Ganga at Ellagwa and Mahaweli at Morape were 220.97 mm and 326.30 mm respectively. The warm-up period values for both catchments at varying time scales are indicated in Figure 5-8. Calculated monthly soil moisture contents during calibration and verification of both catchments are indicated in Appendix-D.

7.3.3 Objective functions and behaviour

Many objective functions used in literature were reviewed. Different types such as the following were recognized. AE, RMSE, RMS. SSR, SMS, SAR, WRMS, RE, REm, CRM, EF, MRAE, RAEM, MAER, and Nash-Sutcliffe. The mean ratio of absolute error (MRAE) suggested by World Meteorological Organization (WMO, 1975), which match each and every point of the two hydrographs relative to the observed value at that particular time point corresponding to the computation step was used as the primary objective function. In this study, Nash-Sutcliffe which has been used in many literatures to match the peaks was used as the secondary objective function.

MRAE error criterion was used to optimise parameters by evaluating the observed and simulated runoffs. The efficiency criterion, Nash-Sutcliffe coefficient Efficiency was used for the observation of model efficiency.

7.3.4 Evaluation of parameter optimization

Parameter optimization which was done with the calibration enabled the finding of C and SC. Firstly, the parameter optimization was done at a coarser resolution to find out the optimum values of C and SC. After approximate identification of the coarser minimum, the finer resolution search enabled the identification of the C and SC values with respect to the minimum MRAE value. The optimum value of C and SC obtained for both catchments Kalu Ganga at Ellagawa and Mahaweli at Morape were as 1, 800 and 1.1, 1200 respectively. During the optimization procedure, it was revealed that the optimum value of SC is very robust and insensitive to the initial values. The SC value appears to have distribution law with respect to locations of the catchments while, the C value varies with respect to the location of catchments. It was noted that, the model performance is more sensitive to parameter SC when compared to C.

7.3.5 Calibration and verification

The model with respect to monthly flow showed a good performance for both catchments Kalu Ganga at Ellagawa and Mahaweli at Morape. During the calibration period, the minimum MRAE value was obtained as 0.145 for Kalu Ganga at Ellagawa and 0.152 for Mahaweli at Morape. In the verification period, the minimum value of MRAE estimated for Kalu Ganga at Ellagawa and Mahaweli at Morape were 0.153 and 0.157 respectively. During the calibration, the Nash-Sutcliffe produced respectively results as 93.55% and 93.59% for both catchments Kalu Ganga at Ellagawa and Mahaweli at Morape while; these respective values during the verification period were 92.4% and 94.1% respectively. During the Calibration period, the average values of MRAE and Nash-Sutcliffe for Kalu Ganga at Ellagawa and Mahaweli at Morape were found as 0.148 and 93.6% respectively while; these respective values during verification period were 0.155 and 93.25% respectively. The two parameter monthly water balance model produced excellent results of MRAE when optimized for annual and seasonal water balance when compared with monthly. The minimum MRAE values for Kalu Ganga at Ellagawa found in annual and seasonal time scale were 0.042, 0.069 (Maha) and 0.054 (Yala) while; the same was 0.145 in monthly time scale. For Mahaweli at Morape, the minimum value of MRAE for annual and seasonal time scales were 0.056, 0.077 (Yala) and 0.067 (Maha) while; the same was 0.152 in monthly time scale.

7.3.6 Monthly water balance model for water resources

For evaluation of water resources, the two parameter monthly water balance model was developed using 75% probable rainfall and evaporation data for 12 months time period. In this study, accordingly, yield was estimated for both catchments Kalu Ganga at Ellagawa and Mahaweli at Morape as 37069 Ha.m and 15900 Ha.m for Maha season respectively. In Yala season yield was estimated as 38922 Ha.m for Kalu Ganga at Ellagawa and 22644 Ha.m for Mahaweli at Morape. It was realized that yield in Yala season of both catchments is more than the yield in Maha season and this is only because the rainfall in Yala season is more than rainfall in Maha season in both catchments Kalu Ganga at Ellagawa and Mahaweli at Morape.

The two-parameter monthly water balance model demonstrated the capability in simulating the monthly runoff with a simple structure and just two parameters. Hence, this two-parameter monthly water balance model can be easily and effectively incorporated in water resource planning programs, for these two basins and similar watersheds.

8 CONCLUSIONS

1. The two-parameter monthly water balance model proved to as an efficient model when simulating the monthly runoff with a simple structure and only two parameters.

2. The C value appears to have a good correlation with respect to the location of catchments while the SC value has not shown a large variation. The C value for Kalu Ganga at Ellagawa and Mahaweli at Morape was obtained as 1 and 1.1 while the SC was obtained as 800 and 1200, respectively.

3. During the optimization procedure, it was identified that the optimum value of SC is very robust and insensitive to initial values.

4. The two parameter monthly water balance model showed a higher sensitivity to C when compared with SC.

5. Two parameter monthly water balances showed excellent performance while using MRAE as the objective functions.

6. MRAE value for calibration period for Kalu Ganga at Ellagawa and Mahaweli at Morape were found as 0.145 and 0.152 while; for verification period the respective MRAE values were 0.153 and 0.157.

7. During the calibration and verification periods the respective model efficiency values for Kalu Ganga at Ellagawa found using Nash–Sutcliffe coefficient were 93.6% and 92.4% respectively. For Mahaweli at Morape, 93.6% and 94.1% were the respective efficiency values.

8. The average values of MRAE and Nash–Sutcliffe for both catchments Kalu Ganga at Ellagawa and Mahaweli Ganga at Morape in calibration period were found as 0.148 & 93.6% respectively while; for verification the respective values were 0.155 and 93.25%.

9. The two-parameter monthly water balance model produced less error of MRAE in annual and seasonal time scale when compared with monthly.

9 RECOMMENDATIONS

1. It is recommended to perform the application of this model in several other watersheds to study and confirm the behavior of C and SC.
2. It is recommended to commence investigating the best objective function for optimizing the 2- parameter water balance models.
3. It is recommended to investigate modeling of watersheds with 2-parameter water balance model using daily values as inputs and then aggregating same for monthly outputs.

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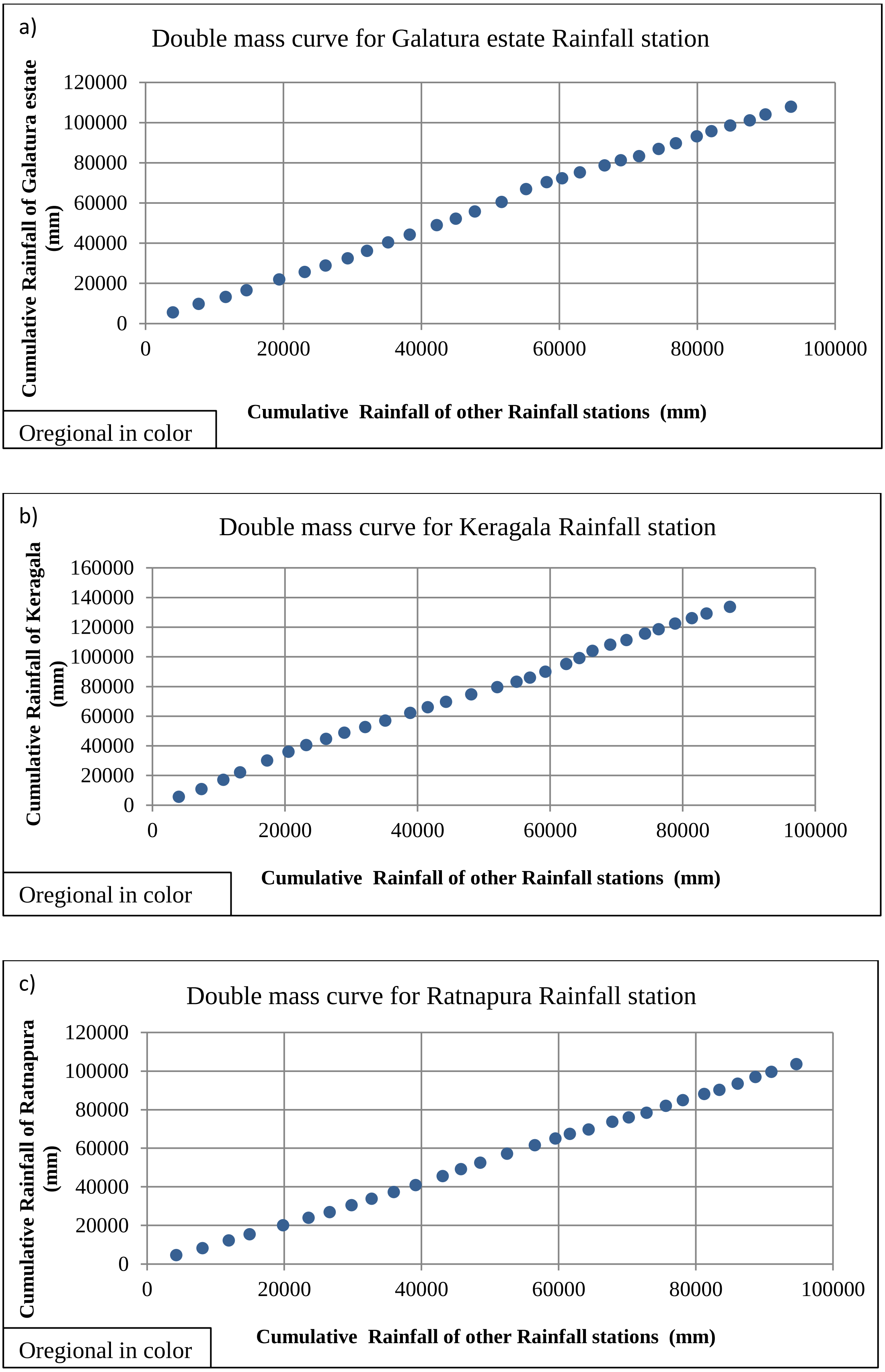
Appendix-A

Data checking



a) Double mass curve for Galatura estate Rainfall station

Oregional in color

b) Double mass curve for Keragala Rainfall station

Oregional in color

c) Double mass curve for Ratnapura Rainfall station

Oregional in color

Figure A 1: Double mass curve Analysis for Rainfall Stations in Kalu Ganga (a-c)

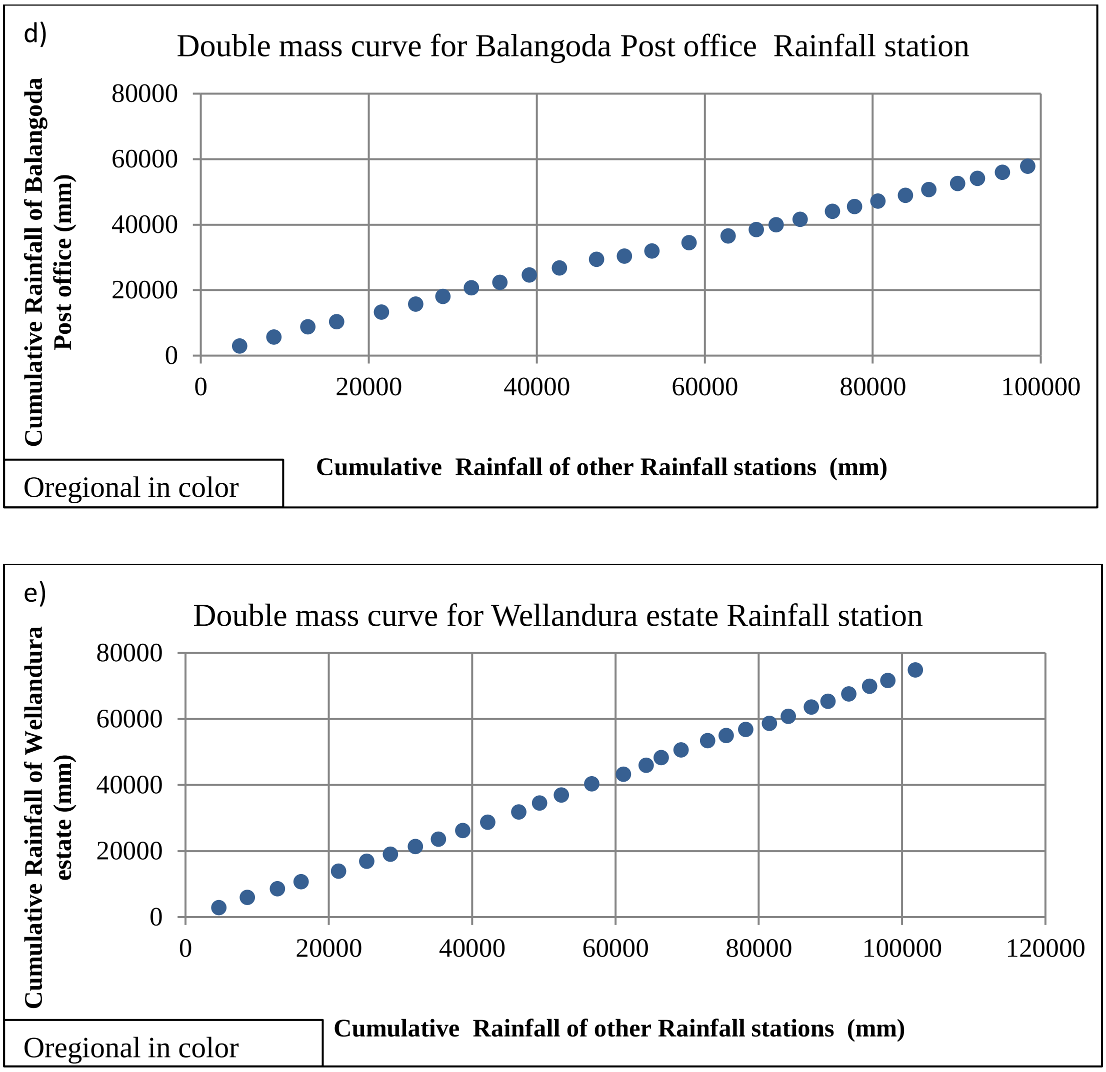


Figure A 2: Double mass curve Analysis for Rainfall Stations in Kalu Ganga (d-e)

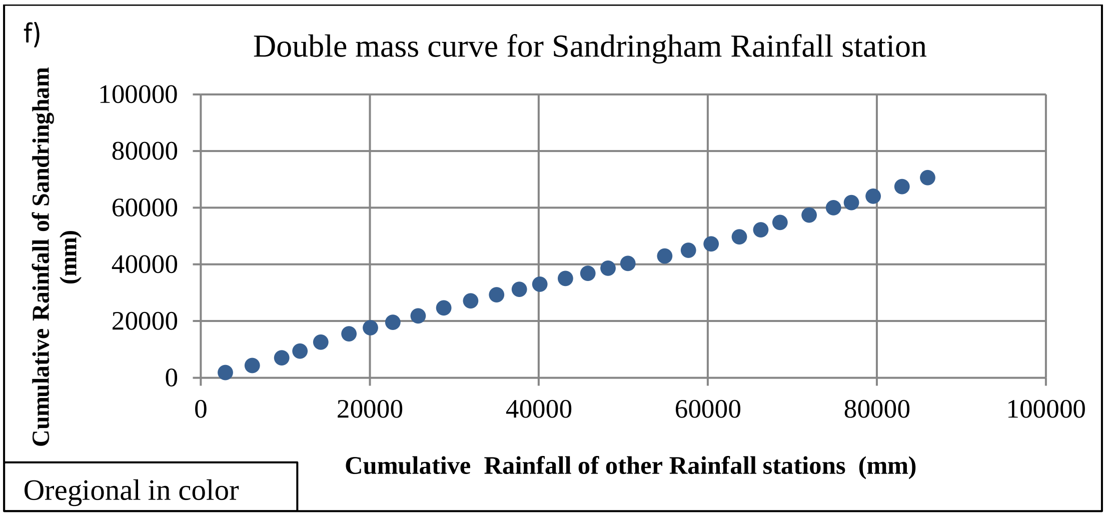


Figure A 3: Double mass curve Analysis for Rainfall stations in Mahaweli Ganga (f)

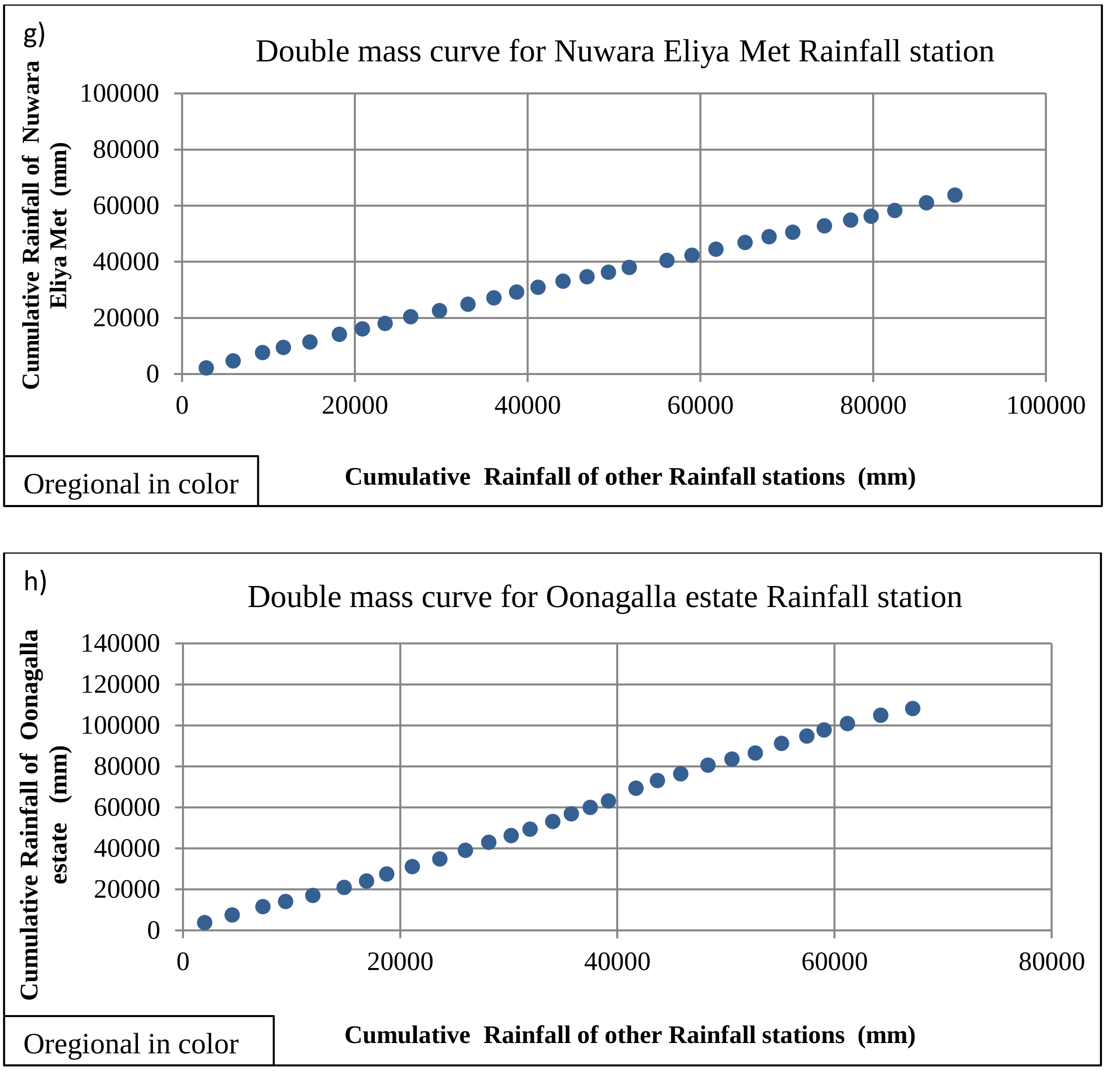


Figure A 4: Double mass curve Analysis for Rainfall stations in Mahaweli Ganga (g-h)

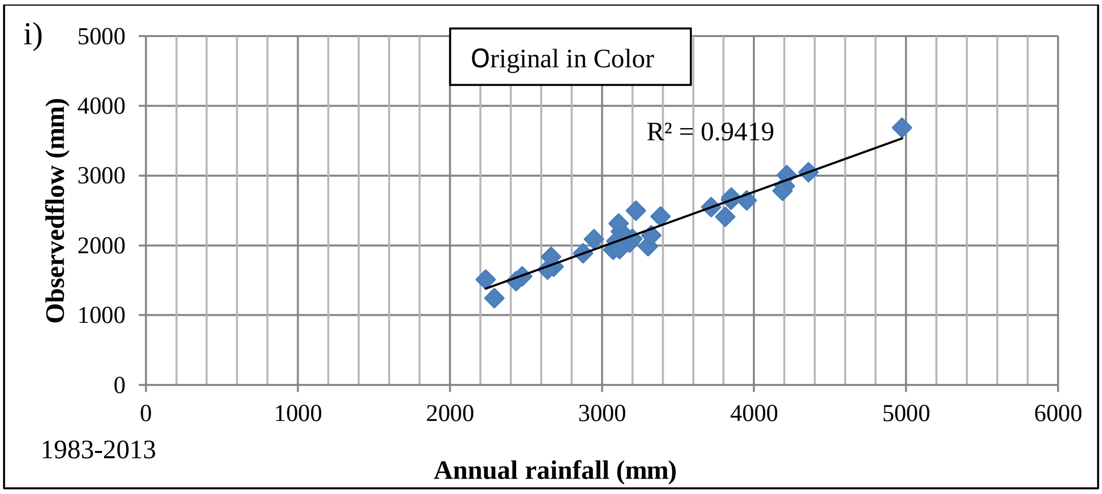


Figure A5: Annual Variation of Observedflow and Thiessen Rainfall in Kalu Ganga (i)

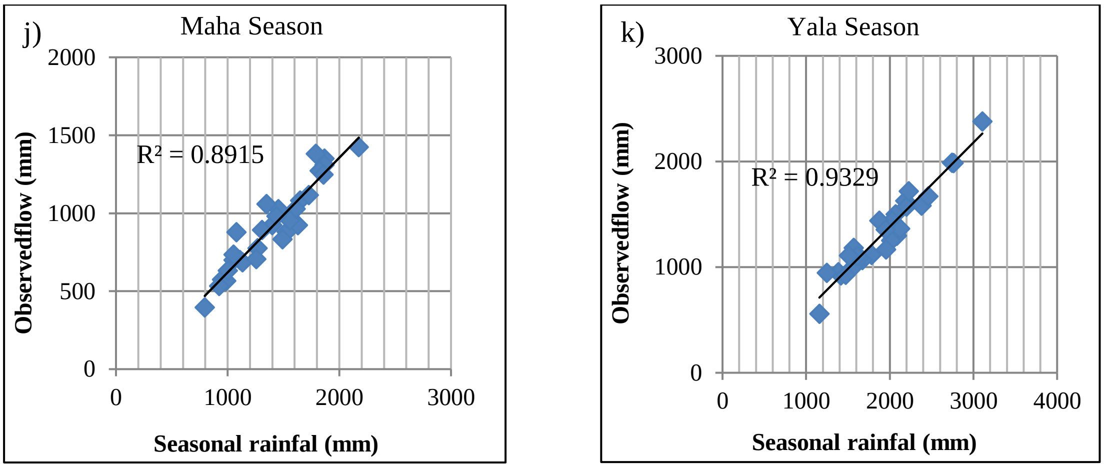


Figure A6: Seasonal Variation of Observedflow and Thiessen Rainfall–Kalu Ganga (j-k)

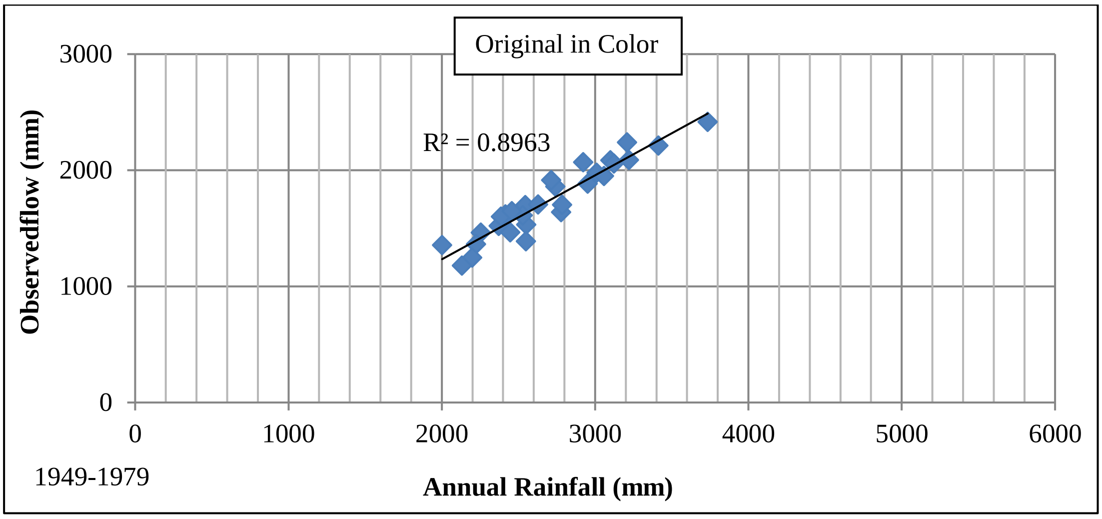


Figure A7: Annual Variation of Observedflow and Thiessen Rainfall in Mahaweli Ganga

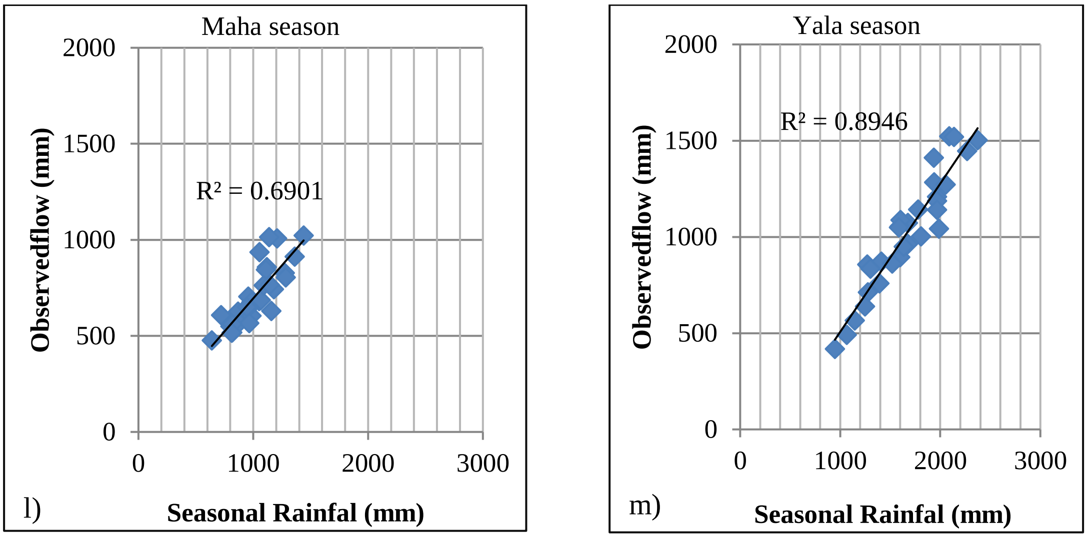


Figure A8: Seasonal Variation of Observedflow &Thiessen Rainfall –Mahaweli Ganga (l-m)

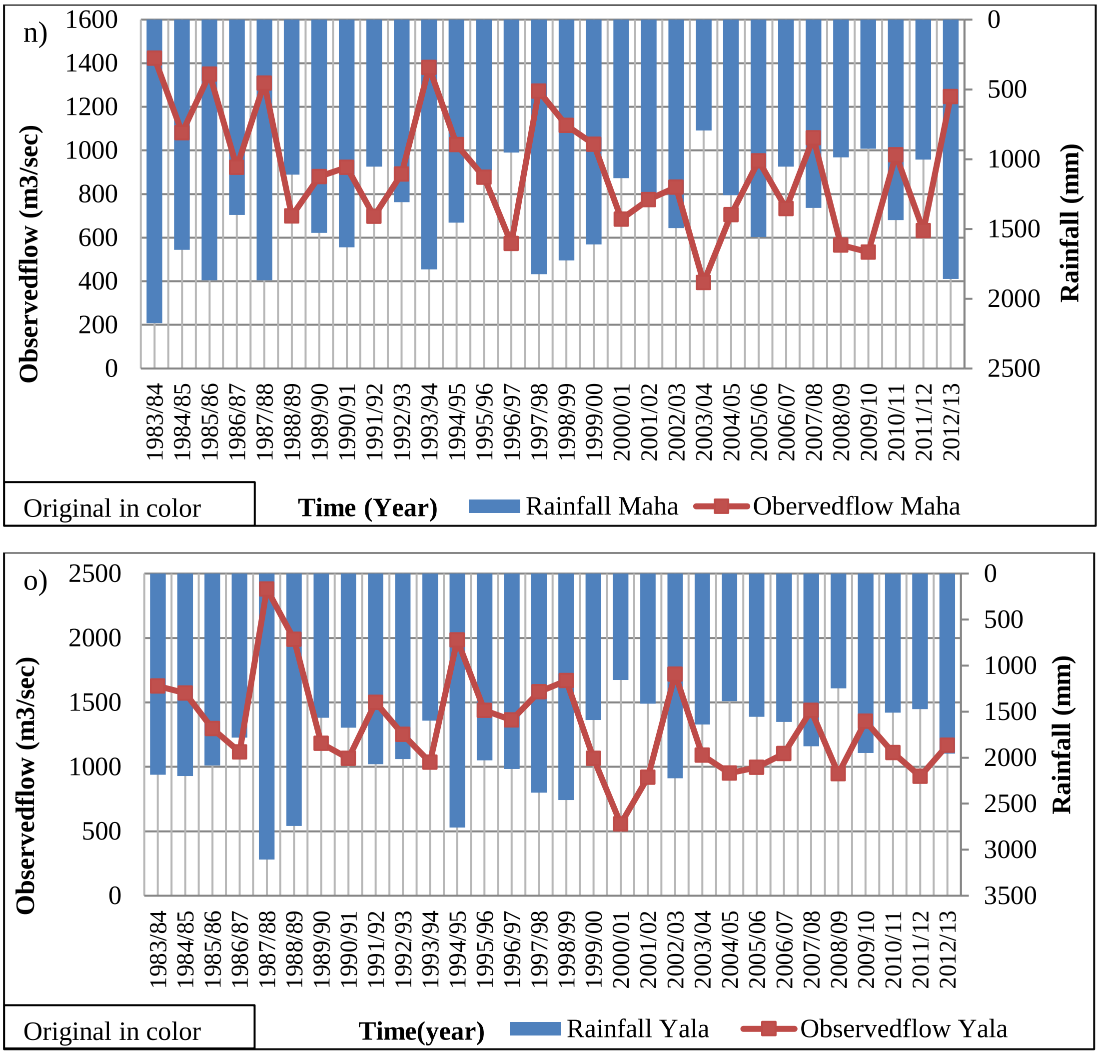


Figure A9: Variation of Seasonal Thiessen Rainfall and Observedflow in Kalu Ganga (n-o)

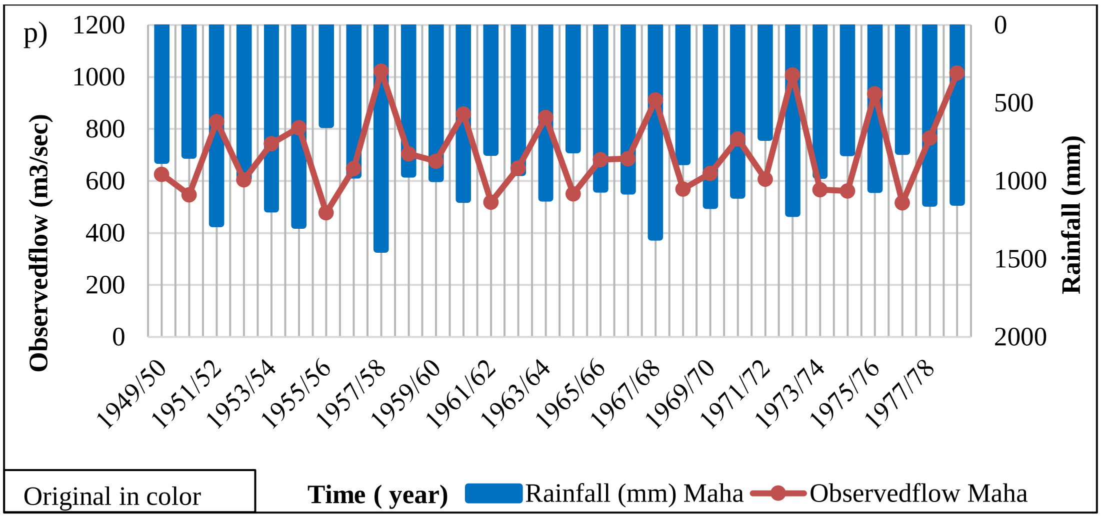


Figure A10: Variation of Seasonal Thiessen Rainfall and Observedflow in Mahaweli Ganga

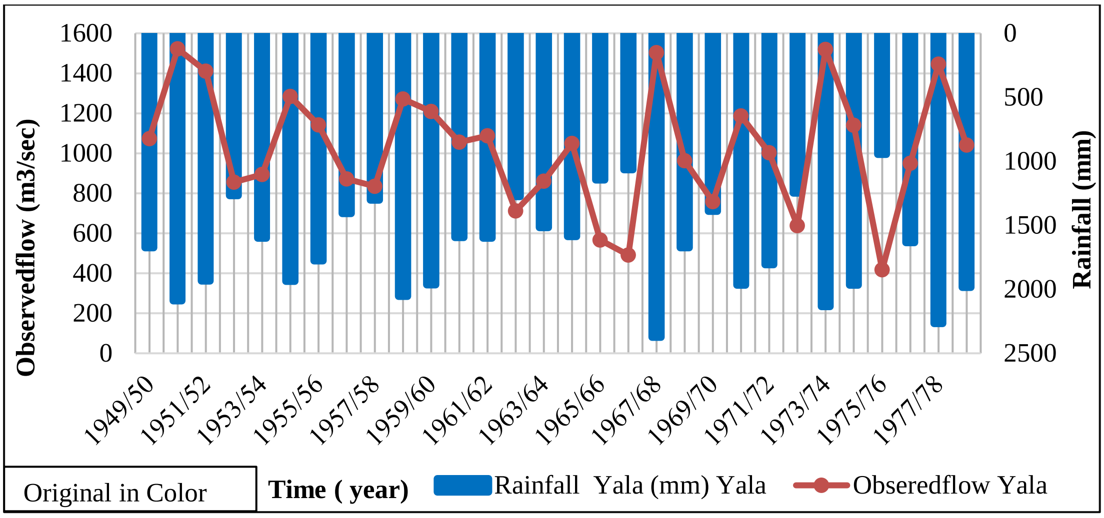


Figure A 11: Variation of Seasonal Thiessen Rainfall & Observedflow in Mahaweli Ganga

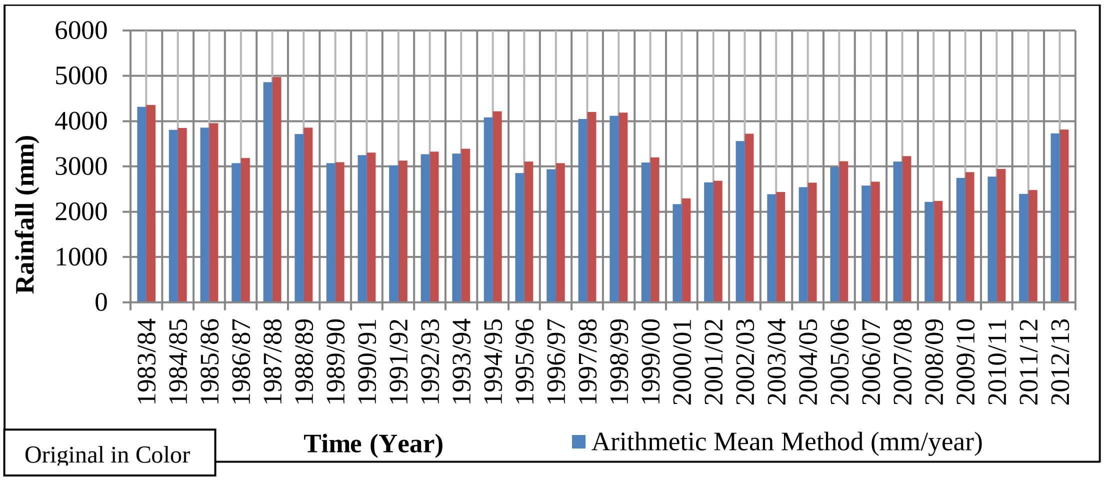


Figure A12: Comparison of Thiessen and Arithmetic Mean Rainfall in Kalu Ganga

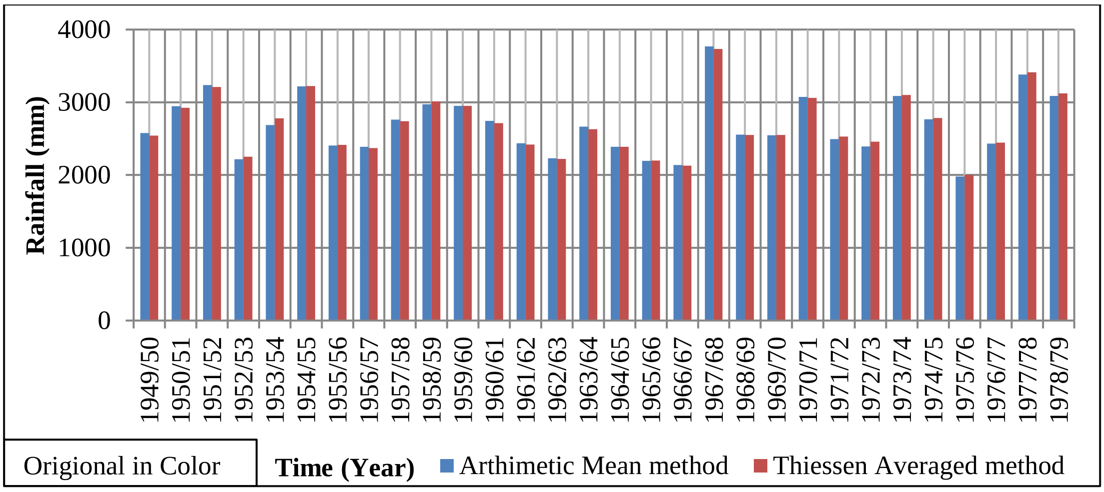


Figure A13: Comparison of Thiessen and Arithmetic Mean Rainfall in Mahaweli Ganga

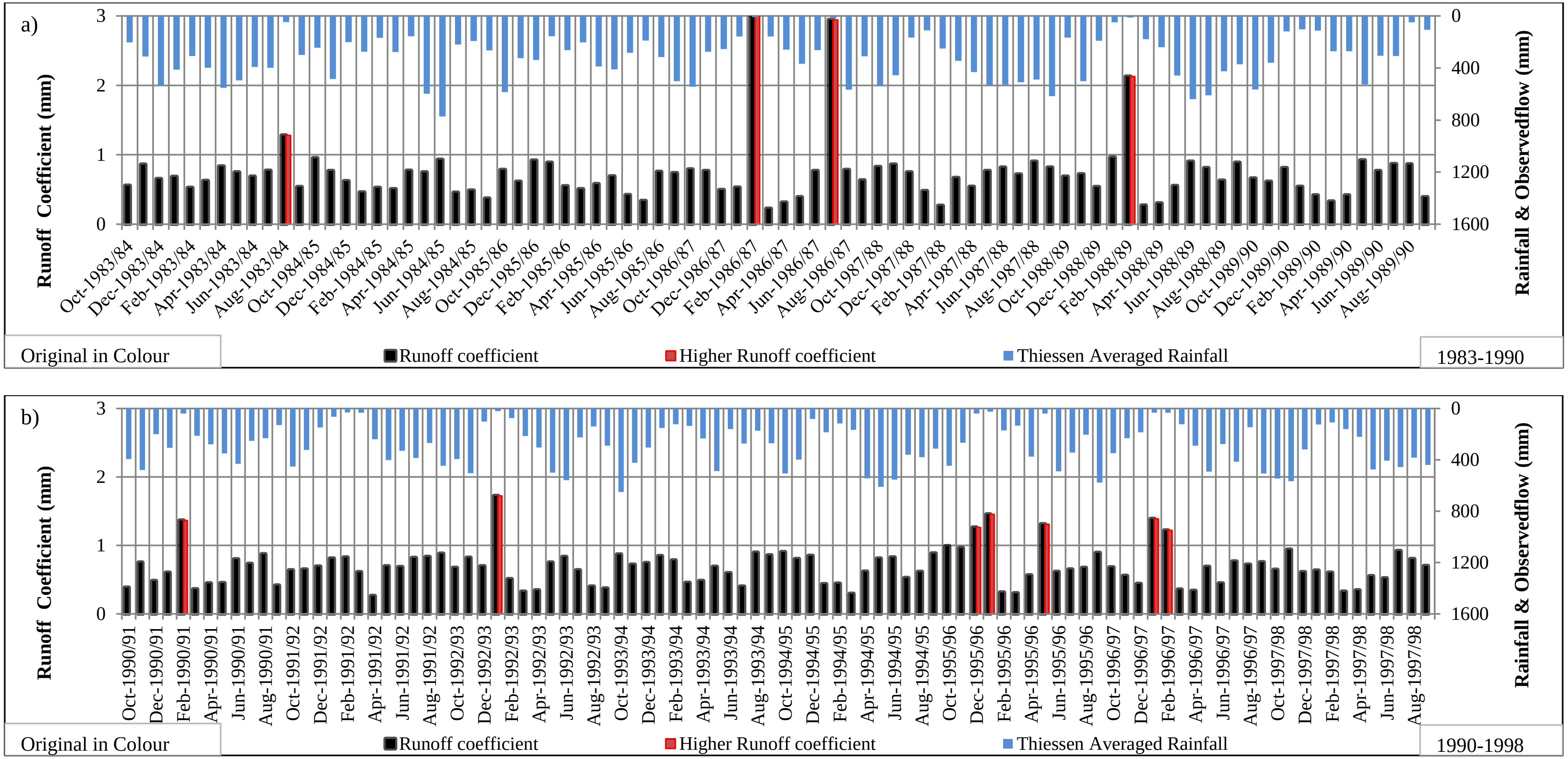


Figure A 14: Higher Runoff coefficients during the Calibration period of Kalu Ganga (a-b)

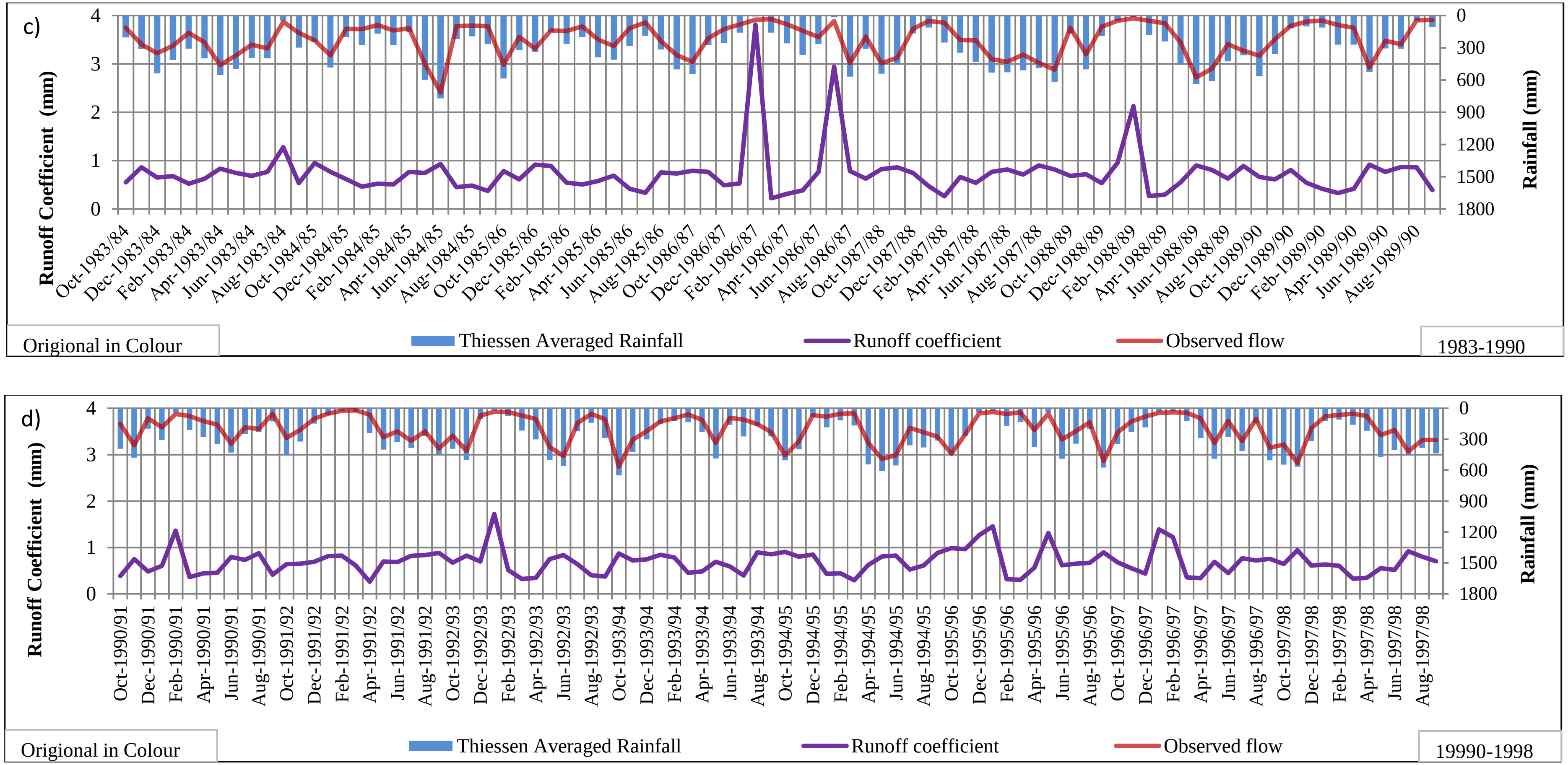


Figure A 15: Higher Runoff coefficients during the Calibration period of Kalu Ganga at Ellagawa (c-d)

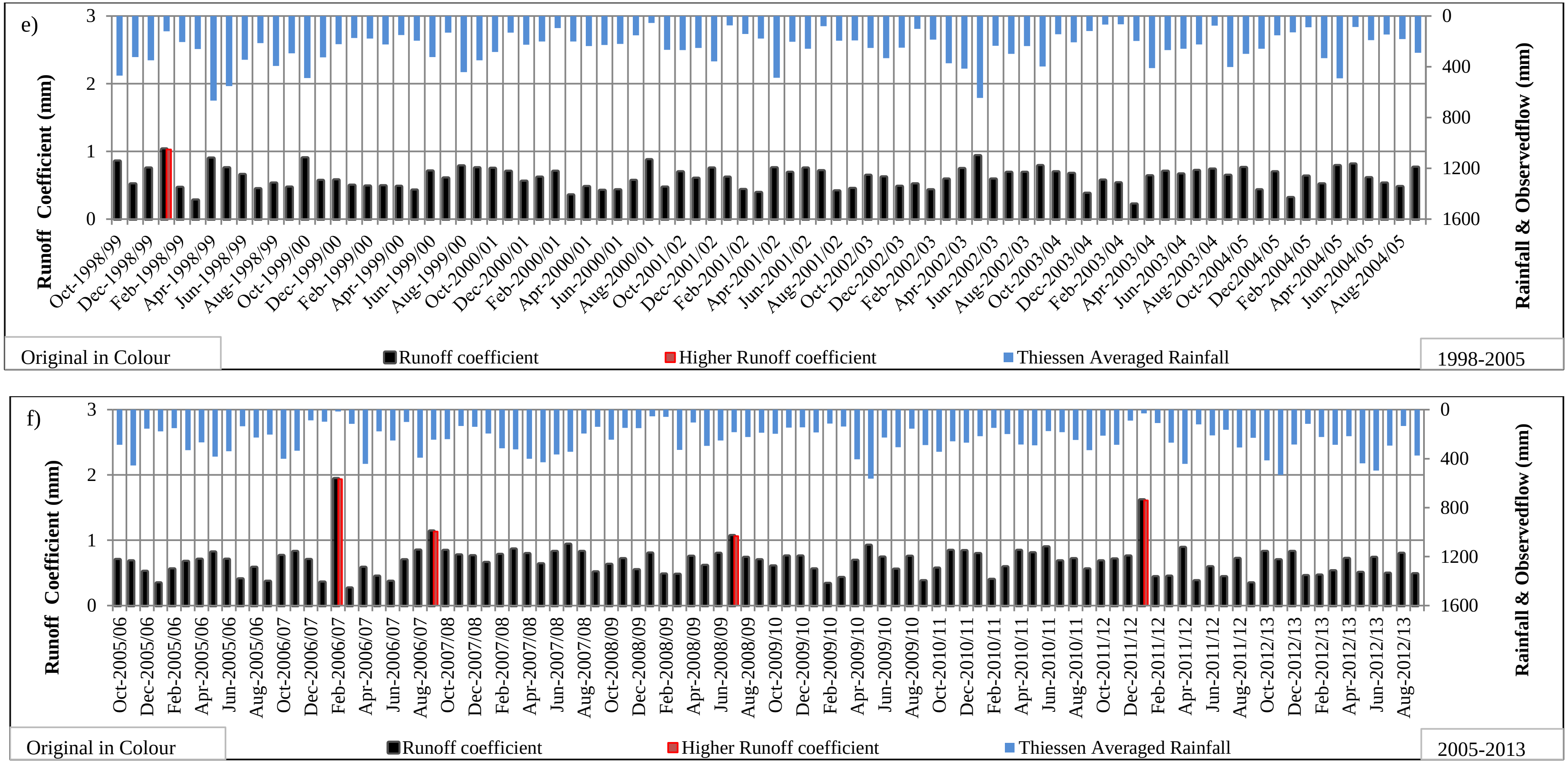


Figure A 16: Higher Runoff coefficients during Verification period of Kalu Ganga at Ellagawa (e-f)

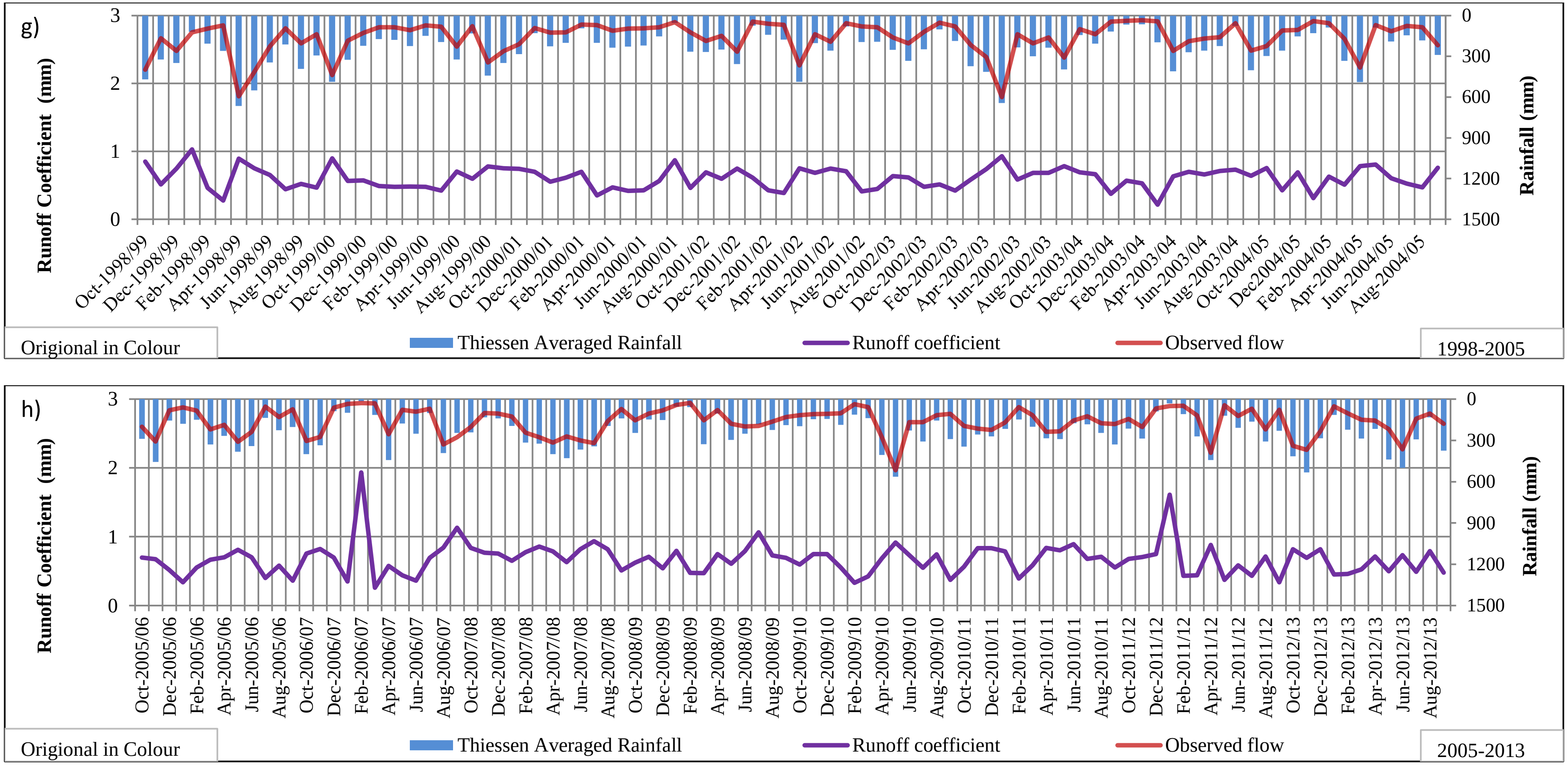


Figure A 17: Higher Runoff coefficients during Verification period of Kalu Ganga at Ellagawa (g-h)

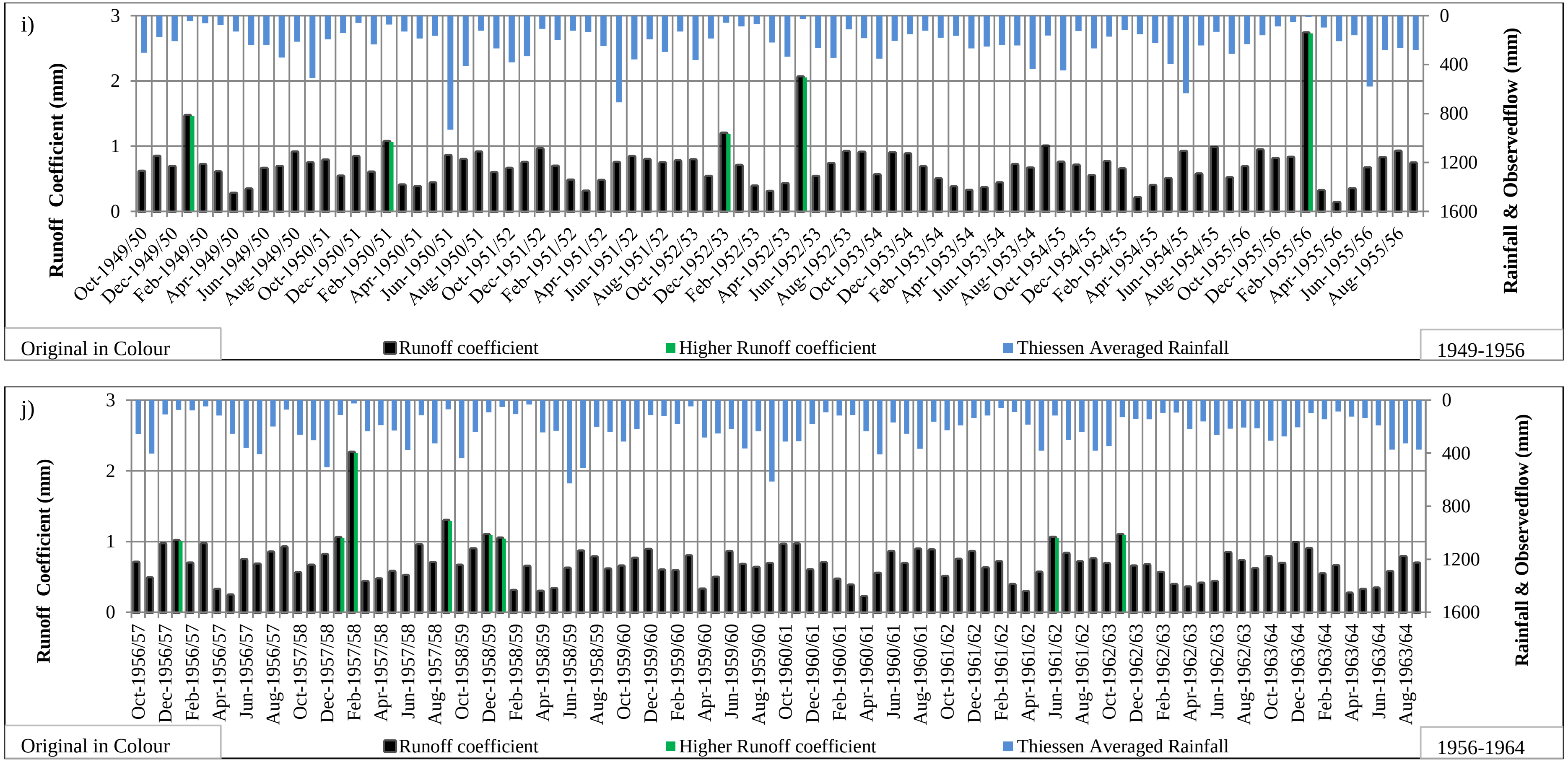


Figure A 18: Higher Runoff coefficients during Calibration period of Mahaweli Ganga at Morape (i-j)

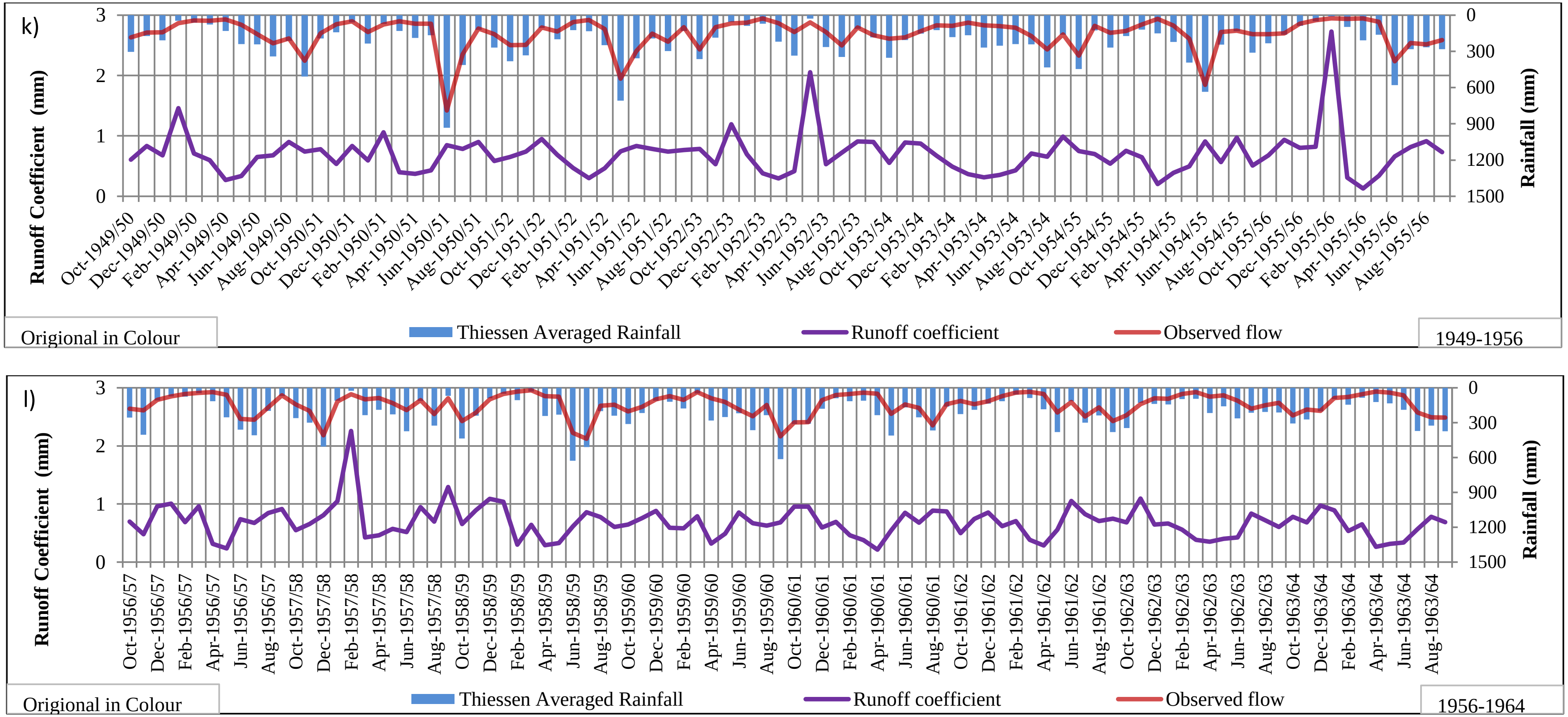


Figure A 19: Higher Runoff coefficients during Calibration period of Mahaweli Ganga at Morape (k-l)

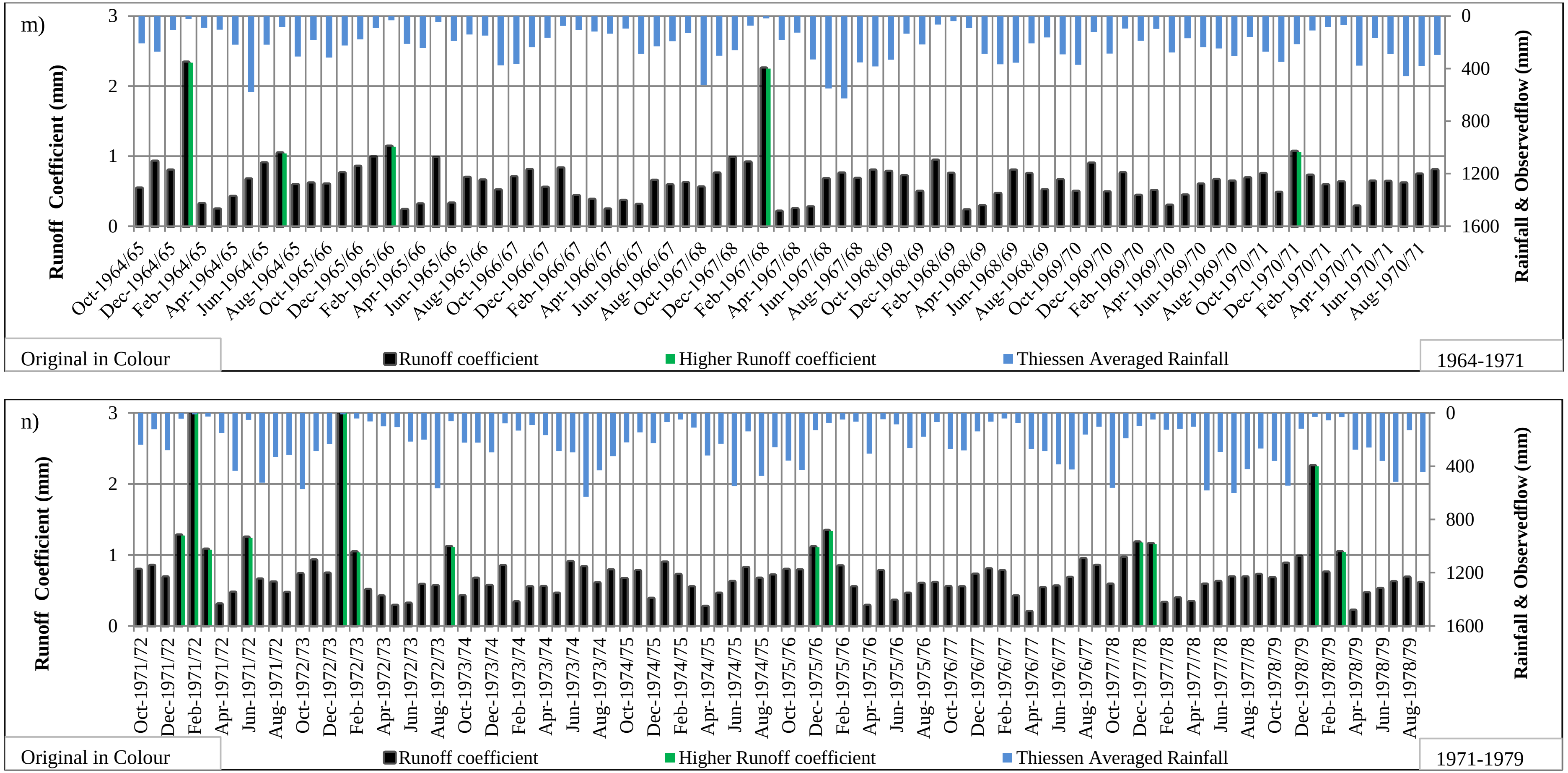


Figure A20: Higher Runoff coefficients during the Verification period of Mahaweli Ganga at Morape (m-n)

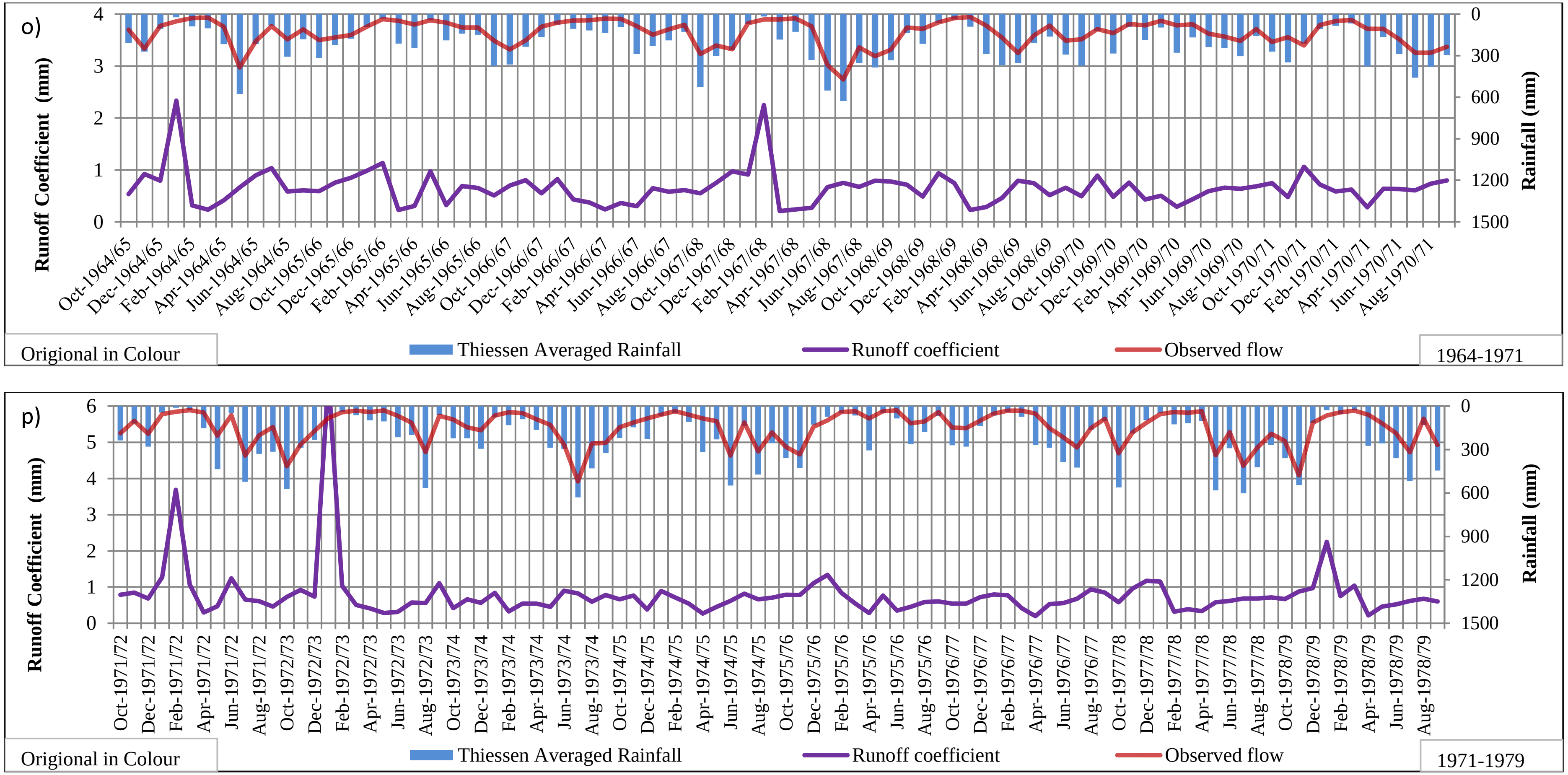


Figure A21: Higher Runoff coefficients during the Verification period of Mahaweli Ganga at Morape (o-p)

Appendix-B

Summary of Annual, Seasonal and Monthly data

1) Watershed: Kalu Ganga at Ellagawa

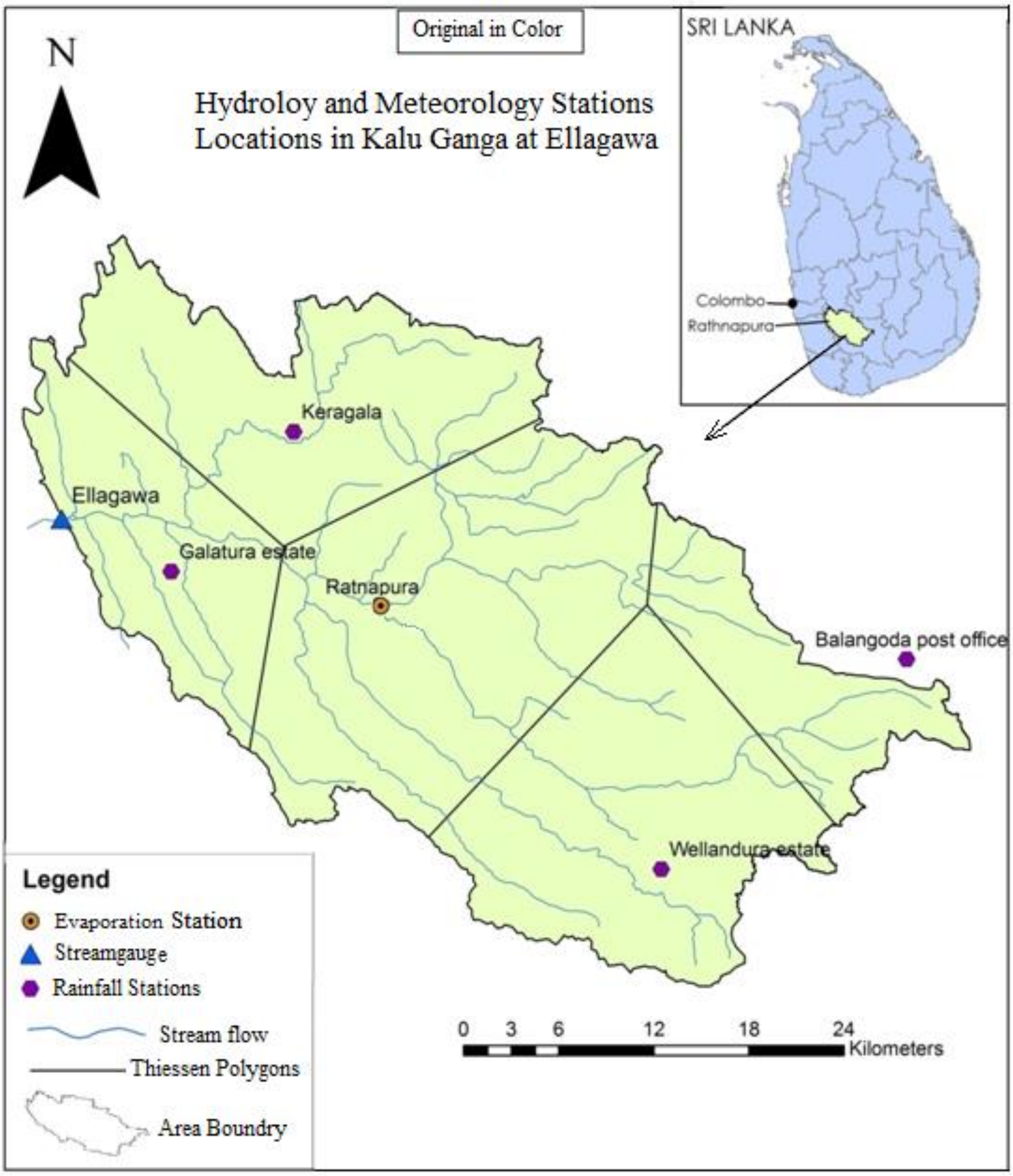


Figure B 1: Location of Used Stations in Kalu Ganga at Ellagawa

Table B 1: Galatura Estate Summary Monthly & Annual Rainfall Data in Kalu Ganga

Water Year	Galatura estate			
	Minimum (mm/month)	Mean (mm/month)	Maximum (mm/month)	Annual Total (mm/year)
1983/1984	56.00	466.35	1093.40	5596.25
1984/1985	106.40	352.10	851.00	4225.26
1985/1986	134.50	290.17	588.30	3482.06
1986/1987	15.01	278.38	711.00	3340.51
1987/1988	140.90	445.13	748.50	5341.60
1988/1989	5.50	304.30	793.90	3651.60
1989/1990	60.80	274.56	744.00	3294.70
1990/1991	30.23	290.78	507.90	3489.38
1991/1992	1.50	317.68	608.00	3812.20
1992/1993	20.90	346.94	705.20	4163.30
1993/1994	102.70	317.78	595.60	3813.30
1994/1995	89.90	394.18	782.40	4730.10
1995/1996	21.30	269.60	705.50	3235.18
1996/1997	35.20	297.89	627.80	3574.68
1997/1998	16.20	396.30	652.70	4755.60
1998/1999	173.40	535.60	1572.80	6427.20
1999/2000	123.00	289.23	750.00	3470.70
2000/2001	26.00	162.98	302.00	1955.80
2001/2002	36.40	244.18	649.50	2930.10
2002/2003	60.00	281.68	572.30	3380.10
2003/2004	3.00	215.23	702.00	2582.80
2004/2005	75.00	173.03	330.90	2076.40
2005/2006	137.50	294.37	541.00	3532.40
2006/2007	2.00	238.06	463.00	2856.67
2007/2008	114.0	290.71	796.00	3488.50
2008/2009	40.70	212.48	334.00	2549.80
2009/2010	62.00	234.71	439.00	2816.50
2010/2011	42.00	213.21	434.00	2558.50
2011/2012	43.00	241.25	462.00	2895.00
2012/2013	69.70	321.88	534.50	3862.60

Table B 2: Keragala Summary Monthly & Annual Rainfall Data in Kalu Ganga

Water Year	Keragala			
	Minimum (mm/month)	Mean (mm/month)	Maximum (mm/month)	Annual Total (mm/year)
1983/1984	53.20	466.81	897.50	5601.76
1984/1985	71.00	443.37	1009.70	5320.41
1985/1986	143.00	509.60	761.00	6115.16
1986/1987	6.20	432.07	1247.00	5184.83
1987/1988	32.30	664.56	1077.30	7974.70
1988/1989	15.30	481.31	1043.20	5775.77
1989/1990	50.30	376.41	955.30	4516.87
1990/1991	50.23	356.81	639.60	4281.68
1991/1992	25.00	347.28	715.06	4167.41
1992/1993	32.90	312.48	714.60	3749.73
1993/1994	135.40	360.01	750.40	4320.10
1994/1995	80.50	439.38	846.80	5272.55
1995/1996	11.23	310.99	689.40	3731.93
1996/1997	42.20	304.22	695.50	3650.68
1997/1998	136.70	417.60	724.40	5011.20
1998/1999	139.30	404.38	708.60	4852.58
1999/2000	132.40	311.90	582.80	3742.80
2000/2001	14.60	232.40	419.50	2788.82
2001/2002	85.00	328.42	716.00	3941.00
2002/2003	84.00	434.42	895.00	5213.00
2003/2004	28.00	333.17	811.00	3998.00
2004/2005	159.25	399.39	1081.00	4792.71
2005/2006	120.10	352.22	601.50	4226.68
2006/2007	0.00	254.88	580.90	3058.60
2007/2008	67.00	360.33	730.22	4323.92
2008/2009	70.00	246.59	470.90	2959.13
2009/2010	110.50	318.23	997.70	3818.75
2010/2011	77.10	307.11	538.20	3685.31
2011/2012	21.10	263.32	800.00	3159.80
2012/2013	85.00	375.07	611.70	4500.80

Table B 3: Ratnapura Summary Monthly & Annual Rainfall Data in Kalu Ganga

Water Year	Ratnapura			
	Minimum (mm/month)	Mean (mm/month)	Maximum (mm/month)	Annual Total (mm/year)
1983/1984	48.88	382.67	564.00	4591.98
198419/85	133.20	299.61	746.20	3595.30
1985/1986	121.30	338.89	700.20	4066.63
1986/1987	11.20	256.85	660.40	3082.16
1987/1988	72.60	395.50	694.30	4746.05
1988/1989	7.80	316.95	632.20	3803.42
1989/1990	51.22	251.24	500.40	3014.90
1990/1991	50.66	294.27	511.40	3531.26
1991/1992	40.50	275.58	489.00	3307.00
1992/1993	13.40	291.23	701.50	3494.70
1993/1994	132.60	304.17	795.00	3650.00
1994/1995	54.80	384.15	665.50	4609.80
1995/1996	33.40	301.63	721.30	3619.55
1996/1997	20.20	283.73	588.90	3404.70
1997/1998	119.90	381.62	589.00	4579.40
1998/1999	118.10	369.73	708.60	4436.70
1999/2000	145.00	285.95	564.50	3431.40
2000/2001	58.00	198.38	363.10	2380.50
2001/2002	70.20	194.57	351.00	2334.80
2002/2003	71.70	329.15	718.30	3949.80
2003/2004	61.00	193.27	443.90	2319.20
2004/2005	52.20	200.49	325.00	2405.90
2005/2006	186.00	300.57	503.30	3606.80
2006/2007	9.00	244.42	460.00	2933.00
2007/2008	51.40	265.70	503.00	3188.40
2008/2009	22.20	177.63	290.10	2131.60
2009/2010	111.90	263.87	658.50	3166.50
2010/2011	174.30	287.23	436.60	3446.80
2011/2012	36.60	225.82	432.20	2709.80
2012/2013	96.30	336.61	542.80	4039.30

Table B 4: Balangoda Summary Monthly & Annual Rainfall Data in Kalu Ganga

Balangoda Post office				
Water Year	Minimum (mm/month)	Mean (mm/month)	Maximum (mm/month)	Annual Total (mm/year)
1983/1984	43.00	247.74	701.50	2972.90
198419/85	21.40	228.12	516.00	2737.40
1985/1986	55.00	252.67	662.80	3032.00
1986/1987	5.20	136.63	312.80	1639.60
1987/1988	66.50	245.03	458.50	2940.40
1988/1989	18.23	196.98	430.36	2363.75
1989/1990	19.50	201.07	396.40	2412.85
1990/1991	10.50	218.45	433.30	2621.40
1991/1992	8.50	134.57	360.90	1614.88
1992/1993	9.90	186.74	404.40	2240.83
1993/1994	13.50	180.94	436.30	2171.30
1994/1995	37.30	223.55	733.20	2682.56
1995/1996	6.33	80.67	178.60	968.08
1996/1997	21.80	131.76	483.70	1581.17
1997/1998	63.50	210.94	616.30	2531.30
1998/1999	17.40	164.99	355.00	1979.90
1999/2000	34.30	167.33	365.40	2007.90
2000/2001	31.60	118.22	236.30	1418.60
2001/2002	21.50	145.73	536.30	1748.80
2002/2003	8.50	198.68	451.50	2384.20
2003/2004	29.60	123.78	458.60	1485.40
2004/2005	15.60	134.05	447.10	1608.60
2005/2006	44.70	146.99	345.30	1763.90
2006/2007	11.00	151.93	500.30	1823.20
2007/2008	9.40	149.25	384.50	1791.00
2008/2009	26.90	136.78	331.30	1641.40
2009/2010	61.50	149.61	413.00	1795.30
2010/2011	26.50	154.52	299.50	1854.30
2011/2012	18.58	122.02	347.40	1464.28
2012/2013	57.70	252.68	591.30	3032.20

Table B 5: Wellandura estate Summary Monthly & Annual Rainfall Data in Kalu Ganga

Water Year	Wellandura estate			
	Minimum (mm/month)	Mean (mm/month)	Maximum (mm/month)	Annual Total (mm/year)
1983/1984	35.00	234.69	453.20	2816.26
198419/85	107.30	261.73	654.50	3140.70
1985/1986	63.30	213.75	412.90	2565.05
1986/1987	8.90	175.58	403.90	2107.00
1987/1988	120.50	273.33	402.40	3279.90
1988/1989	17.00	247.50	544.50	2970.04
1989/1990	26.30	177.10	390.50	2125.23
1990/1991	36.30	193.37	472.80	2320.40
1991/1992	20.01	183.28	326.00	2199.31
1992/1993	3.27	224.08	529.00	2688.97
1993/1994	46.72	206.42	591.90	2477.02
1994/1995	73.90	258.71	632.40	3104.50
1995/1996	17.26	226.05	492.90	2712.63
1996/1997	5.30	204.98	339.40	2459.78
1997/1998	49.80	280.73	702.60	3368.80
1998/1999	58.90	240.26	375.80	2883.10
1999/2000	66.80	230.27	338.80	2763.20
2000/2001	111.70	192.26	330.70	2307.10
2001/2002	56.63	190.17	470.00	2282.08
2002/2003	75.00	238.19	534.40	2858.27
2003/2004	15.30	127.66	250.00	1531.90
2004/2005	23.40	152.77	413.80	1833.28
2005/2006	36.10	151.05	298.50	1812.64
2006/2007	35.56	183.65	433.60	2203.83
2007/2008	54.00	228.94	567.00	2747.29
2008/2009	34.00	149.99	249.00	1799.93
2009/2010	94.80	179.11	310.50	2149.38
2010/2011	54.11	194.00	319.00	2328.03
2011/2012	24.50	145.47	284.96	1745.68
2012/2013	83.00	267.23	593.00	3206.75

Table B 6: Ellagawa Summary Observedflow Data in Kalu Ganga

Water Year	Ellagawa			
	Minimum (mm/month)	Mean (mm/month)	Maximum (mm/month)	Annual Total (mm/year)
1983/1984	60.00	254.13	460.00	3049.57
198419/85	88.50	221.14	716.00	2653.74
1985/1986	63.31	220.51	458.00	2646.08
1986/1987	35.00	169.86	443.77	2038.29
1987/1988	52.50	307.42	504.00	3688.99
1988/1989	26.00	223.98	576.00	2687.80
1989/1990	41.00	171.74	482.76	2060.91
1990/1991	53.46	165.72	360.00	1988.60
1991/1992	20.83	183.23	391.58	2198.73
1992/1993	35.00	178.71	465.00	2144.57
1993/1994	61.28	201.46	565.00	2417.52
1994/1995	49.00	250.81	493.00	3009.73
1995/1996	37.25	192.98	513.79	2315.78
1996/1997	39.47	161.36	382.00	1936.27
1997/1998	52.28	237.84	531.19	2854.06
1998/1999	71.44	232.04	593.73	2784.49
1999/2000	71.19	174.54	438.43	2094.51
2000/2001	47.58	103.58	210.50	1242.99
2001/2002	45.01	141.24	366.00	1694.86
2002/2003	51.87	212.58	600.00	2550.90
2003/2004	33.97	123.87	260.00	1486.48
2004/2005	40.20	137.96	383.23	1655.49
2005/2006	54.45	162.43	310.58	1949.18
2006/2007	29.00	153.00	330.12	1836.04
2007/2008	71.69	208.11	320.63	2497.37
2008/2009	27.57	125.99	199.18	1511.92
2009/2010	37.43	157.21	516.63	1886.55
2010/2011	58.75	174.10	238.45	2089.20
2011/2012	45.40	129.94	390.23	1559.28
2012/2013	52.02	201.14	368.63	2413.68

Table B 7: Ratnnapoura Summary Pan Evaporation Data in Kalu Ganga

Water Years	Ratnuapora			
	Minimum (mm/month)	Mean (mm/month)	Maximum (mm/month)	Annual Total (mm/year)
1983/1984	81.31	109.77	134.66	1317.23
198419/85	92.55	112.58	138.84	1350.95
1985/1986	91.30	115.28	142.06	1383.37
1986/1987	93.93	130.80	172.22	1569.56
1987/1988	86.46	114.46	137.61	1373.49
1988/1989	88.13	125.19	178.27	1502.26
1989/1990	88.86	118.55	150.33	1422.62
1990/1991	83.73	116.34	141.47	1396.10
1991/1992	95.70	122.67	186.45	1472.04
1992/1993	85.43	110.40	144.82	1324.79
1993/1994	81.45	103.58	124.46	1242.99
1994/1995	82.43	105.64	145.92	1267.71
1995/1996	87.79	104.54	153.16	1254.44
1996/1997	85.32	110.22	144.40	1322.64
1997/1998	83.60	105.82	146.72	1269.88
1998/1999	85.10	110.59	137.52	1327.13
1999/2000	65.82	100.57	124.48	1206.88
2000/2001	74.47	99.08	134.09	1188.98
2001/2002	69.96	92.83	114.97	1114.00
2002/2003	64.12	89.74	111.18	1076.83
2003/2004	64.59	89.71	107.29	1076.56
2004/2005	70.46	92.55	111.12	1110.66
2005/2006	73.08	81.93	87.62	983.22
2006/2007	52.98	79.04	105.78	948.51
2007/2008	29.30	63.20	96.36	758.45
2008/2009	55.70	76.90	120.25	922.78
2009/2010	41.74	74.49	106.18	893.89
2010/2011	45.43	66.67	94.72	800.06
2011/2012	57.50	79.07	106.13	948.82
2012/2013	43.31	82.73	128.85	992.78

Table B 8: Monthly & Annual Summary of Rainfall, Observedflow and Pan Evaporation Data in Kalu Ganga

Water Months	Thiessen Rainfall (mm/month)			Annual Total (mm/year)	Observedflow (mm/month)			Annual Total (mm/year)	Pan evaporation (mm/month)			Annual Total (mm/year)
	Min	Mean	Max		Min	Mean	Max		Min	Mean	Max	
Oct	143.5	371.3	650.2	11139.4	99.0	276.4	565.0	8291.4	44.8	93.3	137.8	2799.8
Nov	130.1	334.2	566.8	10026.0	90.9	242.4	531.2	7272.1	43.5	93.7	140.1	2811.0
Dec	40.3	206.2	538.8	6187.3	44.1	137.8	350.4	4133.2	41.7	86.6	118.3	2599.3
Jan	20.3	137.3	412.4	4118.6	34.7	85.8	280.6	2574.1	52.3	97.2	136.1	2915.5
Feb	10.0	130.4	315.0	3913.0	25.0	70.0	244.6	2100.6	61.0	118.5	171.5	3556.3
Mar	34.3	225.5	399.1	6763.8	20.8	106.0	277.0	3179.1	44.4	122.0	186.5	3659.5
Apr	105.5	339.9	665.5	10197.4	62.8	213.9	593.7	6415.8	45.4	104.4	151.1	3130.8
May	40.3	387.2	644.7	11615.0	45.4	270.6	600.0	8117.7	71.3	104.0	136.7	3121.5
Jun	160.2	351.3	771.2	10539.9	91.3	252.3	716.0	7570.1	59.8	95.1	136.5	2853.3
Jul	17.4	263.9	609.6	7915.8	51.0	181.5	493.0	5443.8	29.3	91.0	143.0	2730.9
Aug	46.9	249.1	567.4	7474.4	43.1	179.6	443.8	5387.9	46.9	90.7	131.8	2721.6
Sep	107.8	321.1	616.8	9634.4	41.0	215.3	513.8	6457.7	53.0	97.3	138.6	2920.2

Table B 9: Seasonal Rainfall, Observedflow and Evaporation Data in Kalu Ganga

Maha Season				Yala Season		
Water Years	Thiessen Rainfall (mm)	Observed flow (mm)	Evaporation (mm)	Thiessen Rainfall (mm)	Observed flow (mm)	Evaporation (mm)
1983/1984	2174.4	1423.1	632.2	2185.5	1626.4	685.0
198419/85	1648.9	1081.4	703.6	2201.3	1572.4	647.3
1985/1986	1867.4	1349.6	692.5	2084.8	1296.5	690.8
1986/1987	1399.7	923.4	779.6	1782.2	1114.9	789.9
1987/1988	1868.6	1309.4	711.4	3106.4	2379.6	662.1
1988/1989	1110.1	699.2	830.1	2742.5	1988.6	672.2
1989/1990	1528.4	879.6	759.3	1567.5	1181.3	663.3
1990/1991	1630.3	922.6	722.2	1673.1	1066.0	673.9
1991/1992	1054.2	698.6	793.0	2071.4	1500.1	679.0
1992/1993	1308.8	892.6	705.5	2016.5	1252.0	619.3
1993/1994	1789.5	1380.8	600.3	1597.1	1036.7	642.7
1994/1995	1454.5	1026.5	651.6	2760.8	1983.3	616.1
1995/1996	1080.9	877.3	634.4	2029.2	1438.4	620.0
1996/1997	951.8	573.6	710.3	2122.0	1362.6	612.4
1997/1998	1823.8	1272.7	645.4	2378.9	1581.4	624.5
1998/1999	1726.5	1115.2	653.3	2461.9	1669.3	673.9
1999/2000	1611.3	1028.0	626.3	1590.2	1066.5	580.5
2000/2001	1135.7	685.7	611.0	1157.6	557.3	578.0
2001/2002	1267.7	774.9	557.2	1415.0	920.0	556.8
2002/2003	1493.1	832.6	530.1	2225.3	1718.3	546.8
2003/2004	795.2	395.1	547.9	1641.1	1091.4	528.7
2004/2005	1258.1	705.5	522.3	1384.4	950.0	588.3
2005/2006	1558.5	952.9	495.7	1557.1	996.3	487.5
2006/2007	1053.1	733.5	495.4	1611.7	1102.6	453.1
2007/2008	1348.2	1058.3	336.5	1875.5	1439.0	421.9
2008/2009	986.7	565.8	516.5	1248.5	946.1	406.3
2009/2010	925.5	533.7	461.5	1949.9	1352.9	432.4
2010/2011	1436.8	979.8	385.3	1511.0	1109.4	414.8
2011/2012	1002.4	632.0	498.6	1474.1	927.3	450.2
2012/2013	1858.1	1247.2	532.3	1954.6	1166.5	460.5

Table B 10: Rainfall Average by Thiessen and Arithmetic Mean Method in Kalu Ganga

Water year	Arithmetic Mean Method (mm/year)	Thiessen Average Method (mm/year)
1983/1984	4315.83	4359.85
198419/85	3803.81	3850.17
1985/1986	3852.18	3952.13
1986/1987	3070.82	3181.83
1987/1988	4856.53	4974.99
1988/1989	3712.92	3852.50
1989/1990	3072.91	3095.97
1990/1991	3248.82	3303.41
1991/1992	3020.16	3125.62
1992/1993	3267.51	3325.24
1993/1994	3286.34	3386.67
1994/1995	4079.90	4215.27
1995/1996	2853.47	3110.08
1996/1997	2934.20	3073.86
1997/1998	4049.26	4202.67
1998/1999	4115.90	4188.43
1999/2000	3083.20	3201.51
2000/2001	2170.16	2293.31
2001/2002	2647.36	2682.67
2002/2003	3557.07	3718.40
2003/2004	2383.46	2436.28
2004/2005	2543.38	2642.46
2005/2006	2988.48	3115.66
2006/2007	2575.06	2664.76
2007/2008	3107.82	3223.69
2008/2009	2216.37	2235.25
2009/2010	2749.29	2875.36
2010/2011	2774.59	2947.77
2011/2012	2394.91	2476.47
2012/2013	3728.33	3812.70

2) Watershed: Mahaweli at Morape

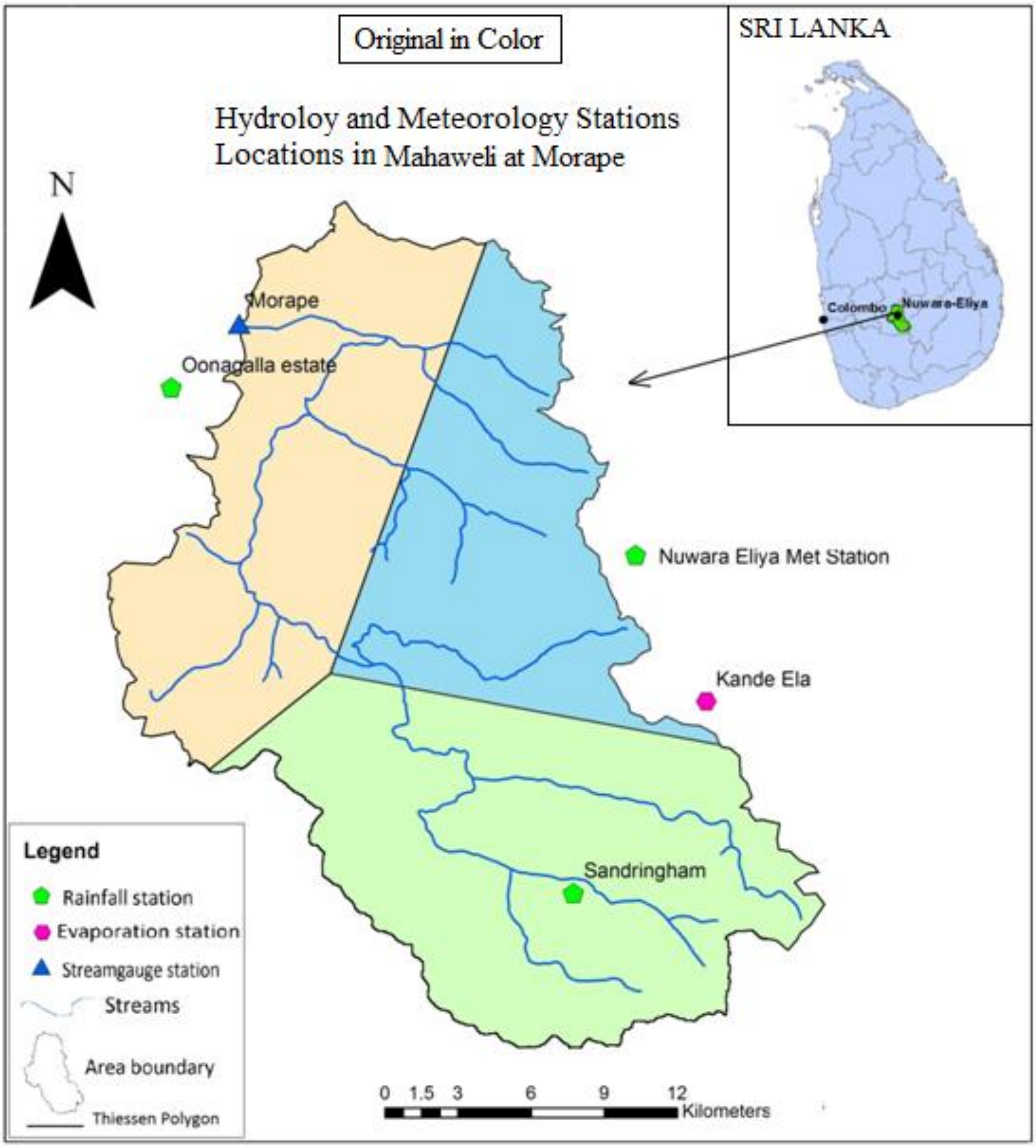


Figure B 2: Location of Stations in Mahaweli Ganga at Morape

Table B 11: Sandringham Summary Monthly & Annual Rainfall Data in Mahaweli Ganga

Water Years	Sandringham			
	Minimum (mm/month)	Mean (mm/month)	Maximum (mm/month)	Annual Total (mm/year)
1949/1950	37.00	158.19	450.00	1898.33
1950/1951	37.00	203.84	740.00	2446.12
1951/1952	77.00	229.22	620.49	2750.61
1952/1953	53.00	194.77	479.00	2337.26
1953/1954	151.00	261.01	431.00	3132.12
1954/1955	107.00	246.83	471.00	2962.00
1955/1956	2.00	181.37	515.20	2176.44
1956/1957	31.00	155.00	414.00	1860.00
1957/1958	22.00	191.83	420.12	2301.97
1958/1959	51.00	238.17	614.00	2858.00
1959/1960	48.00	207.25	399.00	2487.00
1960/1961	79.00	172.19	280.00	2066.30
1961/1962	81.00	165.03	315.00	1980.30
1962/1963	49.00	150.83	276.00	1810.00
1963/1964	45.00	163.67	285.00	1964.00
1964/1965	9.00	152.50	423.00	1830.00
1965/1966	47.00	151.67	278.00	1820.00
1966/1967	67.00	143.42	374.00	1721.00
1967/1968	10.00	213.33	469.00	2560.00
1968/1969	30.00	171.67	321.00	2060.00
1969/1970	81.00	188.58	414.00	2263.00
1970/1971	72.00	209.83	410.00	2518.00
1971/1972	11.00	206.33	510.00	2476.00
1972/1973	5.00	215.75	900.00	2589.00
1973/1974	55.00	218.83	522.00	2626.00
1974/1975	42.00	211.77	441.00	2541.25
1975/1976	24.00	150.50	399.00	1806.00
1976/1977	44.00	192.75	520.00	2313.00
1977/1978	47.00	276.17	610.00	3314.00
1978/1979	15.80	266.00	542.00	3192.00

Table B 12: NuwaraEliya Summary Monthly & Annual Rainfall Data in Mahaweli Ganga

Water Years	Nuwara Eliya Met Station			
	Minimum (mm/month)	Mean (mm/month)	Maximum (mm/month)	Annual Total (mm/year)
1949/1950	63.00	177.38	440.00	2128.50
1950/1951	67.10	217.03	830.00	2604.40
1951/1952	106.40	243.16	750.54	2917.96
1952/1953	0.30	153.46	333.80	1841.50
1953/1954	69.60	157.62	354.80	1891.42
1954/1955	93.50	234.01	475.70	2808.10
1955/1956	11.90	160.68	520.47	1928.17
1956/1957	43.40	154.38	316.70	1852.60
1957/1958	39.40	201.22	601.25	2414.61
1958/1959	12.20	184.13	464.30	2209.50
1959/1960	17.00	188.09	323.90	2257.10
1960/1961	87.90	187.16	298.40	2245.88
1961/1962	50.50	174.21	298.40	2090.50
1962/1963	82.80	143.43	236.70	1721.10
1963/1964	50.80	182.18	273.00	2186.10
1964/1965	34.50	133.99	370.60	1607.90
1965/1966	20.60	135.30	237.70	1623.60
1966/1967	81.50	136.58	280.00	1638.90
1967/1968	3.60	209.83	430.80	2518.00
1968/1969	38.90	157.38	299.70	1888.50
1969/1970	86.90	172.80	364.50	2073.60
1970/1971	19.10	207.18	370.00	2486.20
1971/1972	1.50	162.73	410.00	1952.70
1972/1973	3.80	139.17	366.00	1670.00
1973/1974	31.00	183.29	354.60	2199.50
1974/1975	49.30	179.80	403.90	2157.60
1975/1976	22.60	113.06	217.20	1356.70
1976/1977	49.90	166.64	350.00	1999.70
1977/1978	30.00	233.81	577.00	2805.70
1978/1979	16.90	224.92	558.30	2699.00

Table B 13: Oonagalla Estate Summary Monthly & Annual Rainfall Data in Mahaweli Ganga

Water Years	Oonagalla Estate			
	Minimum (mm/month)	Mean (mm/month)	Maximum (mm/month)	Annual Total (mm/year)
1949/1950	26.90	309.29	640.00	3711.52
1950/1951	56.90	316.27	1260.00	3795.20
1951/1952	99.60	336.37	790.45	4036.40
1952/1953	5.10	206.37	519.70	2476.45
1953/1954	72.10	252.68	540.00	3032.16
1954/1955	93.70	324.09	971.80	3889.10
1955/1956	18.50	259.60	710.25	3115.25
1956/1957	69.90	287.54	669.80	3450.50
1957/1958	16.80	297.26	572.50	3567.06
1958/1959	14.50	320.68	778.50	3848.10
1959/1960	71.10	342.26	522.50	4107.10
1960/1961	73.20	327.05	702.60	3924.60
1961/1962	36.80	270.39	531.10	3244.62
1962/1963	80.80	263.13	524.00	3157.60
1963/1964	76.20	320.05	647.70	3840.60
1964/1965	7.60	310.82	942.80	3729.80
1965/1966	12.20	262.06	425.20	3144.70
1966/1967	79.00	254.53	559.30	3054.30
1967/1968	37.80	518.63	1156.00	6223.60
1968/1969	42.20	309.40	676.70	3712.80
1969/1970	82.00	275.08	477.30	3300.90
1970/1971	80.80	351.21	596.10	4214.50
1971/1972	0.00	254.87	630.00	3058.40
1972/1973	27.70	242.78	720.12	2913.32
1973/1974	69.00	389.73	988.60	4171.6
1974/1975	29.20	300.15	882.10	3601.80
1975/1976	38.40	243.38	667.50	2920.50
1976/1977	36.10	263.73	570.00	3164.80
1977/1978	28.20	335.29	795.00	4023.50
1978/1979	17.30	281.11	604.80	3373.30

Table B 14: Morape Summary Monthly & Annual Observedflow Data in Mahaweli Ganga

Water Years	Morape			
	Minimum (mm/month)	Mean (mm/month)	Maximum (mm/month)	Annual Total (mm/year)
1949/1950	34.91	141.62	376.39	1699.50
1950/1951	50.41	172.45	789.13	2069.41
1951/1952	40.03	186.63	526.82	2239.55
1952/1953	26.78	121.81	284.17	1461.77
1953/1954	60.79	136.56	284.66	1638.67
1954/1955	30.64	174.14	577.00	2089.66
1955/1956	26.78	134.92	381.65	1619.01
1956/1957	36.35	126.62	274.78	1519.43
1957/1958	56.00	154.86	408.70	1858.32
1958/1959	21.25	164.74	438.36	1976.82
1959/1960	37.49	157.13	418.00	1885.53
1960/1961	42.01	159.50	324.20	1913.98
1961/1962	34.10	133.83	285.52	1605.90
1962/1963	36.08	113.52	235.73	1362.27
1963/1964	32.52	142.11	256.83	1705.28
1964/1965	24.22	133.30	384.49	1599.54
1965/1966	37.05	104.05	191.30	1248.59
1966/1967	32.04	98.14	254.51	1177.68
1967/1968	30.61	201.33	471.96	2416.01
1968/1969	20.76	127.69	281.22	1532.31
1969/1970	48.43	115.69	193.00	1388.24
1970/1971	41.51	162.52	279.22	1950.29
1971/1972	28.66	134.24	341.99	1610.89
1972/1973	30.15	137.23	415.13	1646.75
1973/1974	43.74	173.87	520.39	2086.47
1974/1975	56.24	141.79	340.52	1701.44
1975/1976	30.13	112.83	334.00	1353.96
1976/1977	31.13	122.15	286.64	1465.80
1977/1978	34.91	184.29	412.16	2211.54
1978/1979	31.63	171.44	478.26	2057.27

Table B 15: Kande Ela Summary Monthly & Annual Pan Evaporation Data in Mahaweli Ganga

Water Years	Kande Ela			
	Minimum (mm/month)	Mean (mm/month)	Maximum (mm/month)	Annual Total (mm/year)
1949/1950	49.00	73.01	124.50	876.10
1950/1951	49.00	73.01	124.50	876.10
1951/1952	47.00	78.74	120.90	944.90
1952/1953	59.20	74.91	115.30	898.90
1953/1954	56.40	71.66	91.70	859.90
1954/1955	42.20	69.86	93.70	838.30
1955/1956	57.40	79.25	122.90	951.00
1956/1957	62.00	88.78	144.80	1065.30
1957/1958	59.90	63.78	71.90	765.40
1958/1959	73.90	110.52	157.50	1326.20
1959/1960	88.10	96.37	142.20	1156.40
1960/1961	63.30	99.41	134.60	1192.90
1961/1962	59.90	71.41	106.40	856.90
1962/1963	59.90	86.90	114.80	1042.80
1963/1964	45.50	63.57	83.60	762.80
1964/1965	50.00	65.25	106.20	783.00
1965/1966	90.70	104.03	134.40	1248.30
1966/1967	82.60	106.01	133.60	1272.10
1967/1968	79.80	112.13	148.10	1345.50
1968/1969	88.90	109.95	165.90	1319.40
1969/1970	83.80	99.61	158.20	1195.30
1970/1971	60.20	96.26	158.20	1155.10
1971/1972	60.20	78.55	138.40	942.60
1972/1973	65.00	104.73	150.60	1256.70
1973/1974	71.90	92.15	139.40	1105.80
1974/1975	58.20	95.65	123.20	1147.80
1975/1976	48.50	97.83	145.50	1173.90
1976/1977	62.20	101.27	135.90	1215.20
1977/1978	34.10	89.02	132.00	1068.20
1978/1979	55.80	96.96	155.00	1163.50

Table B 16: Monthly & Annual Summary of Rainfall, Observedflow and Pan Evaporation Data in Mahaweli Ganga

Watere Months	Thiessen Rainfall (mm/month)			Annual Total (mm/year)	Observedflow (mm/month)			Annual Total (mm/year)	Pan evaporation (mm/month)			Annual Total (mm/year)
	Min	Mean	Max		Min	Mean	Max		Min	Mean	Max	
Oct	193.7	330.8	570.9	9922.8	93.4	215.8	415.1	5514.1	48.5	85.7	118.6	2570.0
Nov	121.7	241.6	544.8	7247.4	88.5	194.3	478.3	4752.2	52.1	78.5	124.2	2356.4
Dec	57.7	178.7	505.7	5361.8	68.7	144.6	408.7	3616.8	34.1	73.7	125.5	2210.4
Jan	12.0	88.9	235.3	2667.6	42.0	72.2	117.0	1861.6	50.0	85.0	139.4	2549.5
Feb	9.8	83.4	187.8	2502.7	26.8	47.7	104.0	1222.6	49.0	92.1	148.1	2762.7
Mar	26.7	105.6	235.1	3168.0	20.8	41.0	100.3	1013.5	59.0	115.3	165.9	3459.2
Apr	99.4	218.2	377.9	6547.5	26.8	63.2	105.7	1603.6	58.2	87.6	127.0	2626.9
May	29.3	266.2	709.1	7985.3	30.1	125.1	384.5	3198.5	63.0	91.6	136.9	2747.5
Jun	50.8	330.9	931.5	9927.5	30.1	188.4	386.9	5098.9	42.2	86.4	132.0	2593.4
Jul	83.9	329.7	629.8	9890.7	87.0	238.9	520.4	5871.2	45.2	87.7	151.9	2630.8
Aug	111.9	273.8	565.9	8213.2	83.5	197.7	324.2	4873.7	46.7	88.6	155.0	2659.1
Sep	61.3	254.3	613.8	7627.8	41.0	174.9	418.0	4356.2	57.9	88.0	129.3	2640.4

Table B 17: Seasonal Rainfall, Observedflow and Evaporation Data in Mahaweli Ganga

Maha Season				Yala Season		
Water Years	Thiessen Rainfall (mm)	Observedflow (mm)	Evaporation (mm)	Thiessen Rainfall (mm)	Observedflow (mm)	Evaporation (mm)
1949/1950	869.66	626.28	444.10	1674.75	1073.21	432.00
1950/1951	835.11	547.05	437.20	2088.37	1522.36	438.90
1951/1952	1274.66	828.70	450.70	1935.17	1410.85	425.40
1952/1953	985.57	605.21	455.50	1268.75	856.56	420.60
1953/1954	1179.54	743.91	461.30	1599.95	894.76	414.80
1954/1955	1284.40	805.69	472.20	1937.84	1283.96	403.90
1955/1956	639.34	477.63	432.00	1776.76	1141.38	444.10
1956/1957	964.19	648.11	438.90	1408.51	871.31	437.20
1957/1958	1438.81	1023.35	425.40	1301.57	834.98	450.70
1958/1959	957.17	705.07	420.60	2053.76	1271.76	455.50
1959/1960	986.37	676.70	414.80	1965.47	1208.83	461.30
1960/1961	1118.25	858.19	403.90	1595.66	1055.79	472.20
1961/1962	817.57	518.16	444.10	1600.26	1087.74	432.00
1962/1963	947.50	650.83	437.20	1275.57	711.44	438.90
1963/1964	1110.68	844.30	450.70	1517.84	860.98	425.40
1964/1965	800.80	550.68	455.50	1586.55	1048.87	420.60
1965/1966	1053.17	682.30	461.30	1144.74	566.29	430.00
1966/1967	1066.29	686.59	472.20	1064.91	491.09	468.10
1967/1968	1361.10	912.59	432.00	2373.43	1503.42	504.70
1968/1969	876.50	568.86	438.90	1674.00	963.45	473.90
1969/1970	1158.66	629.99	425.40	1391.27	758.26	507.40
1970/1971	1092.60	762.90	420.60	1966.10	1187.39	502.30
1971/1972	722.09	607.75	430.00	1807.26	1003.13	513.00
1972/1973	1209.21	1008.59	468.10	1247.48	638.17	476.00
1973/1974	1042.69	566.90	504.70	2135.07	1519.57	440.20
1974/1975	819.30	561.72	473.90	1966.05	1139.72	434.60
1975/1976	1103.87	936.30	507.40	946.74	417.66	393.20
1976/1977	872.39	516.45	502.30	1635.33	949.35	410.00
1977/1978	1144.35	765.83	513.00	2267.99	1445.71	391.20
1978/1979	1138.46	1015.36	476.00	1984.93	1041.90	413.80

Table B 18: Rainfall Average by Thiessen and Arithmetic Mean method in Mahaweli Ganga

Water Years	Arithmetic Mean Method (mm/year)	Thiessen Average Method (mm/year)
1949/50	2579.45	2544.41
1950/51	2948.57	2923.48
1951/52	3234.99	3209.83
1952/53	2218.40	2254.31
1953/54	2685.23	2779.49
1954/55	3219.73	3222.24
1955/56	2406.62	2416.10
1956/57	2387.70	2372.70
1957/58	2761.21	2740.37
1958/59	2971.87	3010.94
1959/60	2950.40	2951.84
1960/61	2745.59	2713.92
1961/62	2438.47	2417.82
1962/63	2229.57	2223.07
1963/64	2663.57	2628.52
1964/65	2389.23	2387.35
1965/66	2196.10	2197.91
1966/67	2138.07	2131.20
1967/68	3767.20	3734.53
1968/69	2553.77	2550.49
1969/70	2545.83	2549.92
1970/71	3072.90	3058.70
1971/72	2495.70	2529.35
1972/73	2390.77	2456.69
1973/74	3165.70	3177.76
1974/75	2766.88	2785.35
1975/76	2027.73	2050.61
1976/77	2492.50	2507.72
1977/78	3381.07	3412.34
1978/79	3088.10	3123.39

Appendix-C

Parameter Optimization results

Table C 1: Parameter Optimization of Coarser Resolution for Kalu Ganga at Ellagawa

SC/C	0.1	0.2	0.5	0.6	0.7	0.8	0.9	1	1.1	1.2	1.3	1.4	1.5	1.9	2
sc100	0.693	0.629	0.469	0.427	0.398	0.376	0.363	0.362	0.376	0.397	0.427	0.456	0.477	0.541	0.552
sc200	0.670	0.607	0.450	0.410	0.378	0.356	0.340	0.343	0.359	0.386	0.419	0.454	0.487	0.591	0.604
sc300	0.636	0.573	0.413	0.372	0.338	0.314	0.299	0.303	0.321	0.351	0.384	0.423	0.463	0.603	0.624
sc400	0.609	0.543	0.377	0.333	0.297	0.271	0.255	0.259	0.280	0.308	0.344	0.385	0.432	0.600	0.629
sc500	0.599	0.529	0.350	0.303	0.262	0.232	0.216	0.219	0.240	0.268	0.308	0.352	0.403	0.591	0.624
sc600	0.604	0.532	0.340	0.287	0.240	0.205	0.185	0.185	0.206	0.236	0.277	0.325	0.378	0.579	0.615
sc700	0.617	0.545	0.345	0.289	0.237	0.193	0.166	0.158	0.181	0.213	0.254	0.303	0.356	0.565	0.606
sc800	0.631	0.559	0.357	0.298	0.245	0.199	0.165	0.145	0.164	0.197	0.238	0.285	0.338	0.552	0.596
sc900	0.645	0.574	0.372	0.312	0.257	0.209	0.172	0.153	0.160	0.188	0.225	0.271	0.322	0.538	0.585
sc1000	0.659	0.588	0.388	0.327	0.271	0.221	0.184	0.163	0.167	0.188	0.221	0.261	0.309	0.525	0.575
sc1100	0.673	0.602	0.404	0.343	0.288	0.237	0.198	0.177	0.176	0.194	0.220	0.257	0.302	0.512	0.565
sc1200	0.687	0.617	0.419	0.359	0.304	0.255	0.214	0.191	0.187	0.201	0.222	0.255	0.298	0.500	0.554
sc1300	0.700	0.630	0.435	0.375	0.321	0.272	0.232	0.207	0.200	0.209	0.227	0.256	0.294	0.492	0.545
sc1400	0.713	0.644	0.450	0.391	0.338	0.290	0.249	0.223	0.213	0.217	0.233	0.258	0.293	0.486	0.537
sc1500	0.726	0.658	0.465	0.407	0.354	0.307	0.267	0.239	0.227	0.228	0.240	0.261	0.293	0.480	0.531
sc1600	0.740	0.672	0.479	0.422	0.370	0.323	0.283	0.255	0.241	0.239	0.247	0.266	0.294	0.476	0.526
sc1700	0.753	0.685	0.493	0.437	0.386	0.339	0.299	0.271	0.255	0.250	0.255	0.271	0.297	0.471	0.521
sc1800	0.765	0.698	0.507	0.451	0.401	0.355	0.315	0.285	0.268	0.261	0.264	0.275	0.300	0.467	0.517
sc1900	0.777	0.710	0.520	0.465	0.415	0.370	0.330	0.299	0.281	0.272	0.272	0.281	0.303	0.464	0.513
sc2000	0.789	0.722	0.533	0.479	0.430	0.384	0.344	0.312	0.294	0.283	0.281	0.287	0.306	0.461	0.509

Table C 2: Parameter Optimization of Coarser Resolution for Mahaweli at Morape

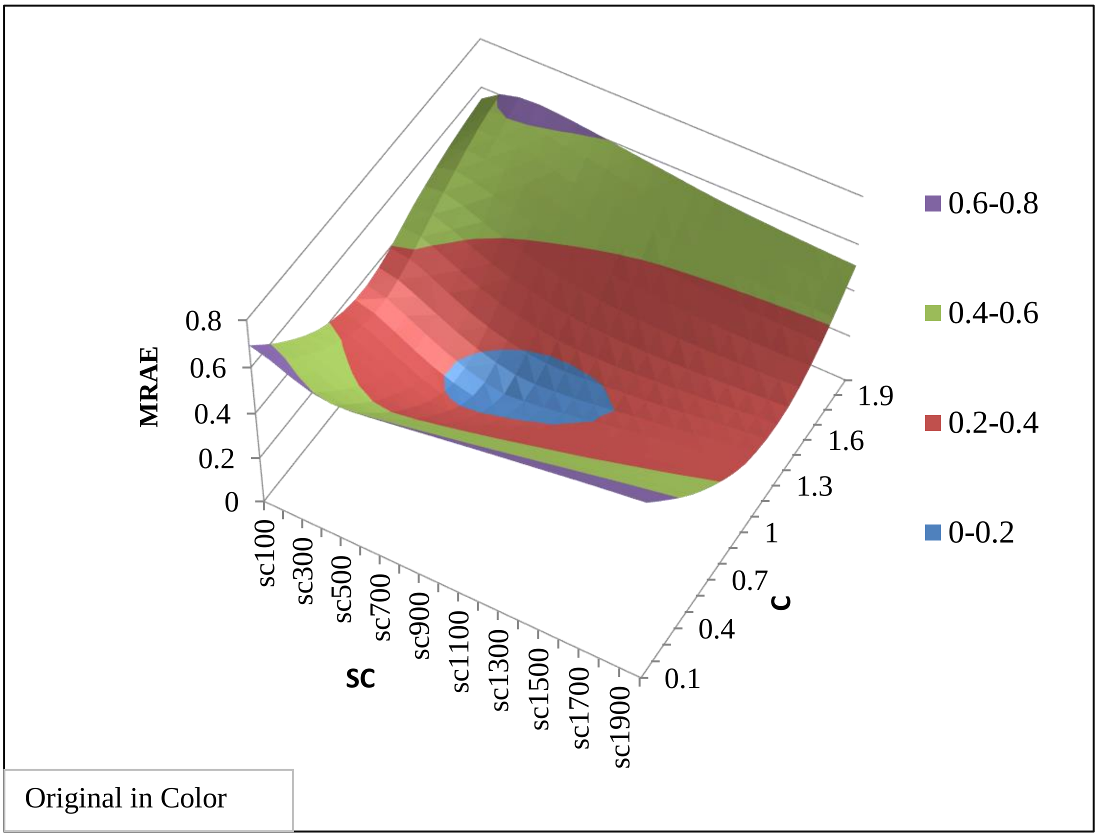
SC/C	0.4	0.5	0.6	0.8	0.9	1	1.1	1.2	1.3	1.4	1.5	1.6	1.8	1.9	2
sc100	0.628	0.589	0.558	0.512	0.505	0.502	0.502	0.506	0.509	0.517	0.530	0.542	0.571	0.581	0.590
sc200	0.623	0.582	0.544	0.489	0.476	0.470	0.470	0.472	0.481	0.497	0.520	0.552	0.606	0.623	0.634
sc300	0.588	0.543	0.501	0.440	0.424	0.416	0.417	0.422	0.434	0.456	0.492	0.530	0.593	0.618	0.637
sc400	0.554	0.504	0.459	0.391	0.374	0.364	0.364	0.372	0.388	0.417	0.458	0.497	0.571	0.601	0.626
sc500	0.523	0.471	0.424	0.349	0.329	0.317	0.318	0.329	0.349	0.383	0.423	0.465	0.547	0.583	0.615
sc600	0.499	0.444	0.395	0.315	0.290	0.277	0.277	0.292	0.315	0.351	0.393	0.436	0.526	0.567	0.604
sc700	0.484	0.426	0.374	0.289	0.259	0.244	0.244	0.259	0.286	0.323	0.365	0.412	0.508	0.552	0.593
sc800	0.479	0.418	0.362	0.269	0.236	0.216	0.217	0.232	0.261	0.298	0.343	0.392	0.491	0.538	0.582
sc900	0.480	0.416	0.357	0.257	0.220	0.195	0.195	0.210	0.239	0.278	0.325	0.376	0.476	0.525	0.571
sc1000	0.486	0.420	0.357	0.252	0.210	0.181	0.176	0.192	0.222	0.263	0.310	0.362	0.463	0.513	0.562
sc1100	0.494	0.425	0.362	0.252	0.207	0.174	0.162	0.177	0.208	0.250	0.298	0.349	0.451	0.504	0.554
sc1200	0.502	0.433	0.368	0.254	0.208	0.173	0.152	0.169	0.198	0.240	0.287	0.338	0.441	0.495	0.546
sc1300	0.509	0.441	0.376	0.258	0.210	0.175	0.154	0.163	0.191	0.231	0.278	0.329	0.433	0.487	0.539
sc1400	0.517	0.449	0.383	0.264	0.215	0.179	0.158	0.162	0.188	0.225	0.271	0.321	0.426	0.480	0.532
sc1500	0.524	0.456	0.391	0.271	0.221	0.184	0.163	0.164	0.186	0.220	0.265	0.314	0.419	0.472	0.526
sc1600	0.531	0.464	0.399	0.279	0.229	0.190	0.169	0.168	0.186	0.217	0.260	0.309	0.413	0.466	0.520
sc1700	0.531	0.464	0.399	0.279	0.229	0.190	0.169	0.168	0.186	0.217	0.260	0.309	0.413	0.466	0.520
sc1800	0.545	0.479	0.414	0.298	0.247	0.207	0.183	0.179	0.189	0.215	0.253	0.300	0.402	0.456	0.509
sc1900	0.553	0.487	0.423	0.307	0.257	0.216	0.191	0.184	0.192	0.215	0.250	0.296	0.398	0.451	0.504
sc2000	0.560	0.495	0.431	0.317	0.266	0.226	0.198	0.190	0.196	0.216	0.249	0.293	0.393	0.447	0.499

Table C 3: Parameter Optimization at Finer Resolution for Kalu Ganga a Ellagawa

MRAE	sc650	sc700	sc750	sc800	sc850	sc900	sc950
0.6	0.286	0.289	0.293	0.298	0.305	0.312	0.320
0.65	0.260	0.262	0.266	0.271	0.277	0.284	0.291
0.7	0.236	0.237	0.240	0.245	0.250	0.257	0.264
0.75	0.214	0.213	0.216	0.221	0.226	0.232	0.238
0.8	0.197	0.193	0.195	0.199	0.203	0.209	0.214
0.85	0.184	0.178	0.178	0.181	0.184	0.189	0.194
0.9	0.173	0.166	0.163	0.165	0.168	0.172	0.178
0.95	0.169	0.158	0.152	0.153	0.156	0.160	0.164
1	0.171	0.158	0.149	0.145	0.148	0.153	0.158
1.1	0.193	0.181	0.171	0.164	0.160	0.160	0.163
1.2	0.224	0.213	0.204	0.197	0.190	0.188	0.187
1.3	0.264	0.254	0.246	0.238	0.231	0.225	0.222
1.4	0.314	0.303	0.294	0.285	0.278	0.271	0.265

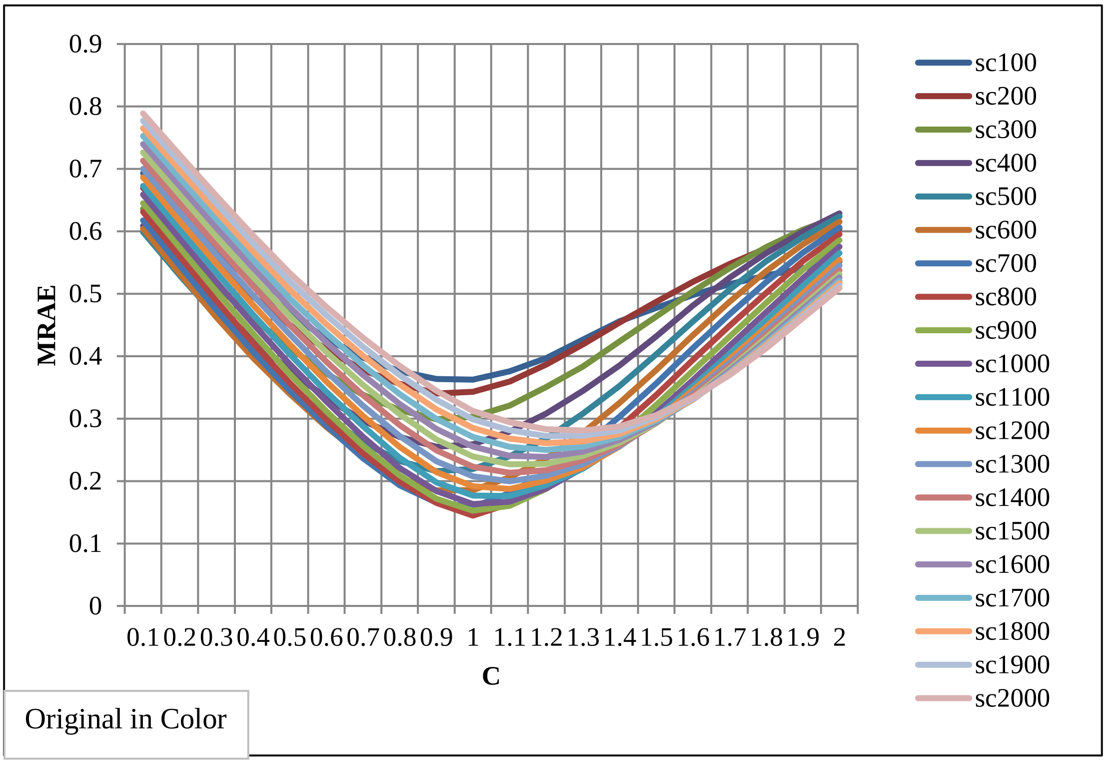
Table C 4: Parameter Optimization at Finer Resolution for Mahaweli at Morape

C/SC	sc1050	sc1100	sc1150	sc1200	sc1250	sc1300	1350
0.9	0.208	0.207	0.207	0.208	0.208	0.210	0.212
0.95	0.190	0.189	0.189	0.189	0.190	0.191	0.192
1	0.177	0.174	0.173	0.173	0.174	0.175	0.177
1.05	0.168	0.164	0.161	0.161	0.161	0.162	0.164
1.1	0.168	0.162	0.156	0.152	0.152	0.154	0.155
1.15	0.174	0.168	0.162	0.157	0.154	0.154	0.155
1.2	0.184	0.177	0.173	0.169	0.165	0.163	0.162
1.25	0.197	0.191	0.186	0.182	0.179	0.176	0.174
1.3	0.215	0.208	0.203	0.198	0.194	0.191	0.190



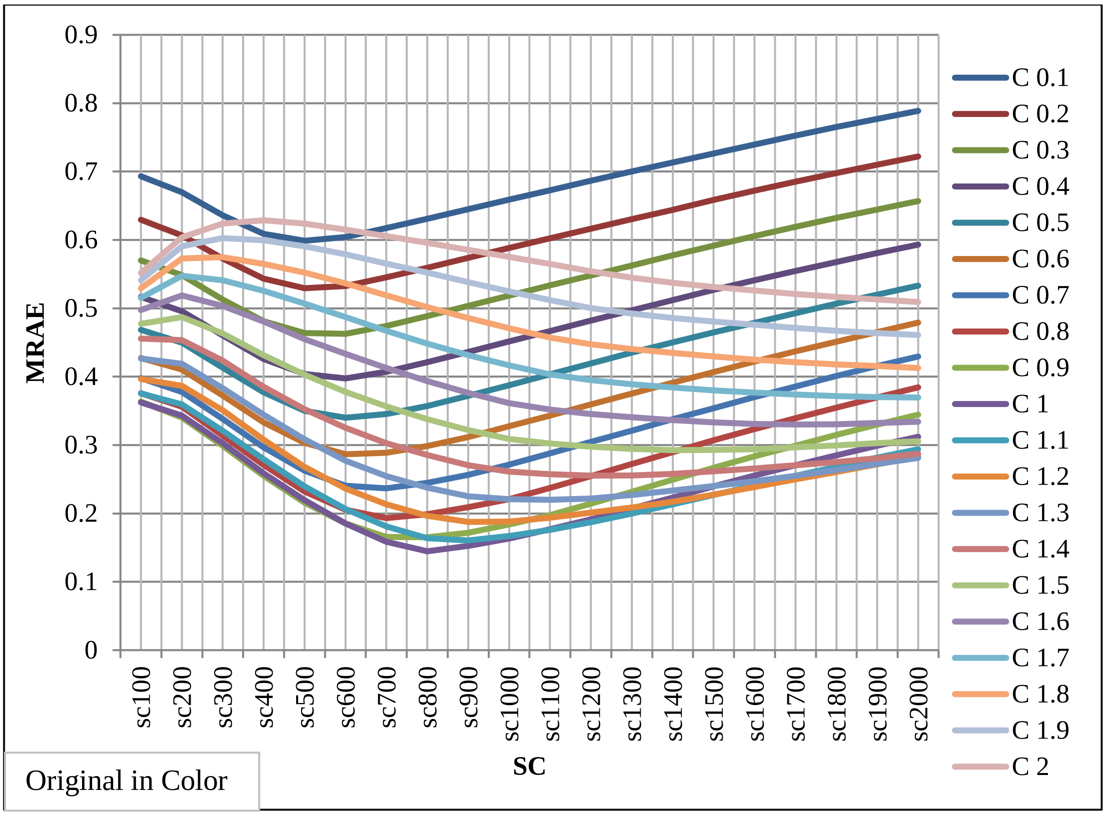
Original in Color

Figure C 1: Coarser Resolution Surface for Kalu Ganga at Ellagawa



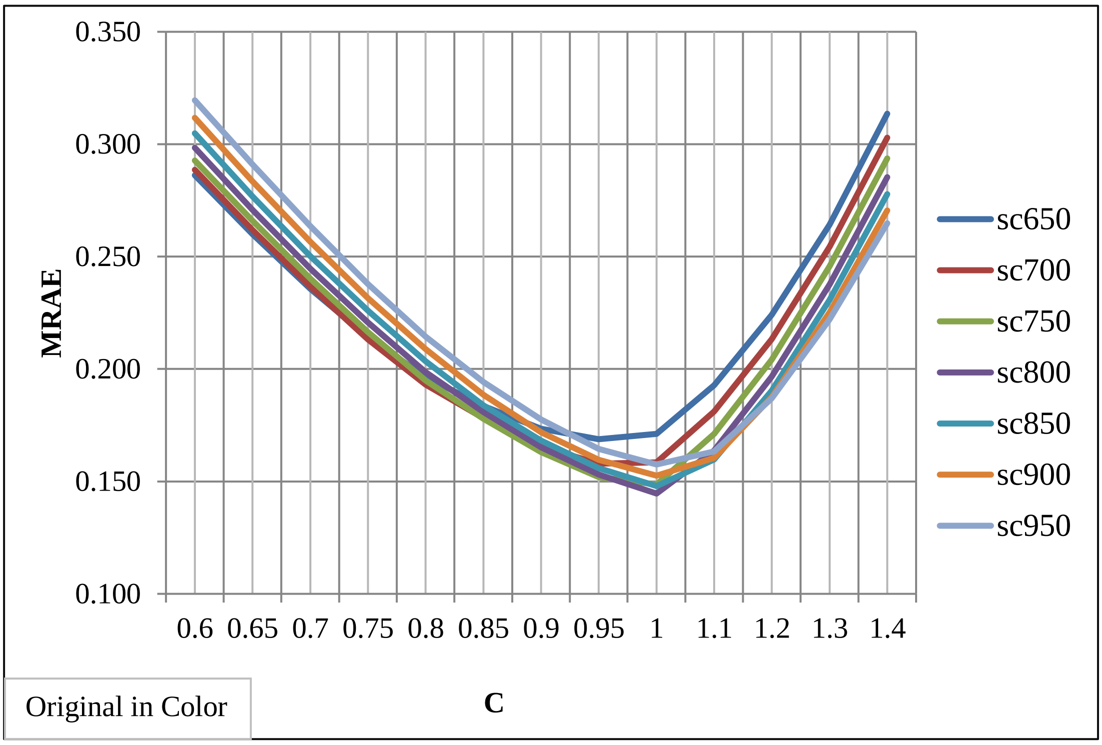
Original in Color

Figure C 2: Coarser Resolution Optimization of Parameter C for Kalu Ganga at Ellagawa



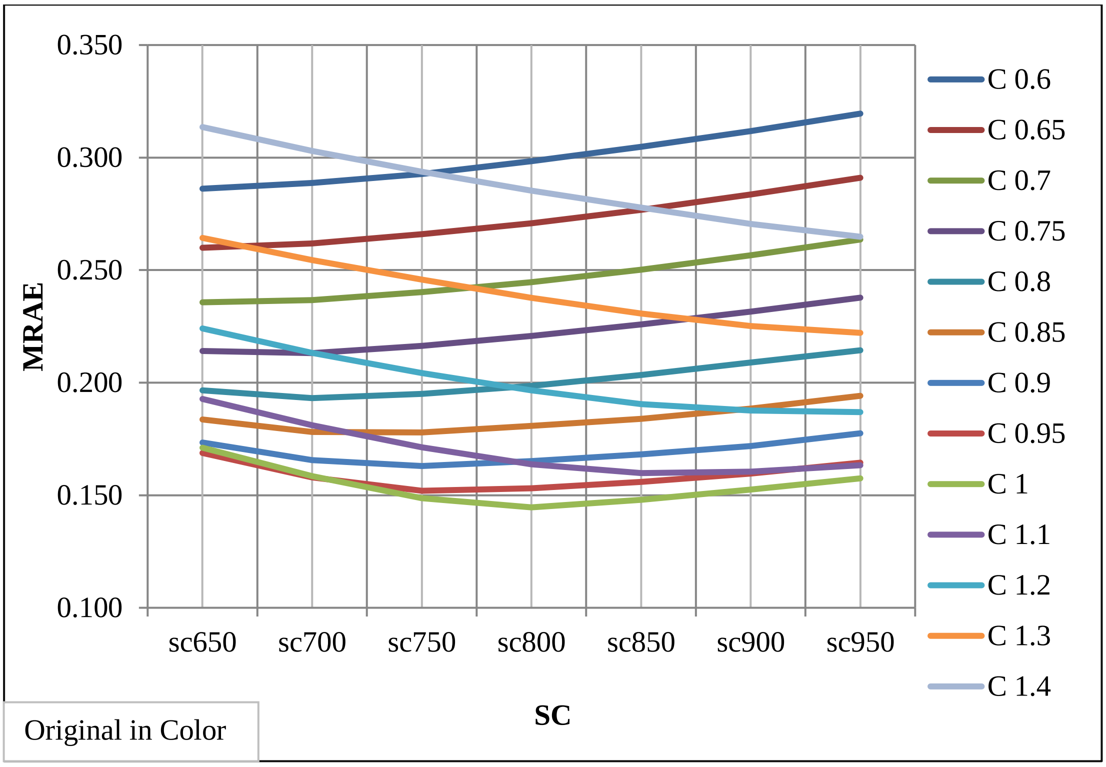
Original in Color

Figure C 3: Coarser Resolution Optimization of Parameter SC in Kalu Ganga at Ellagawa



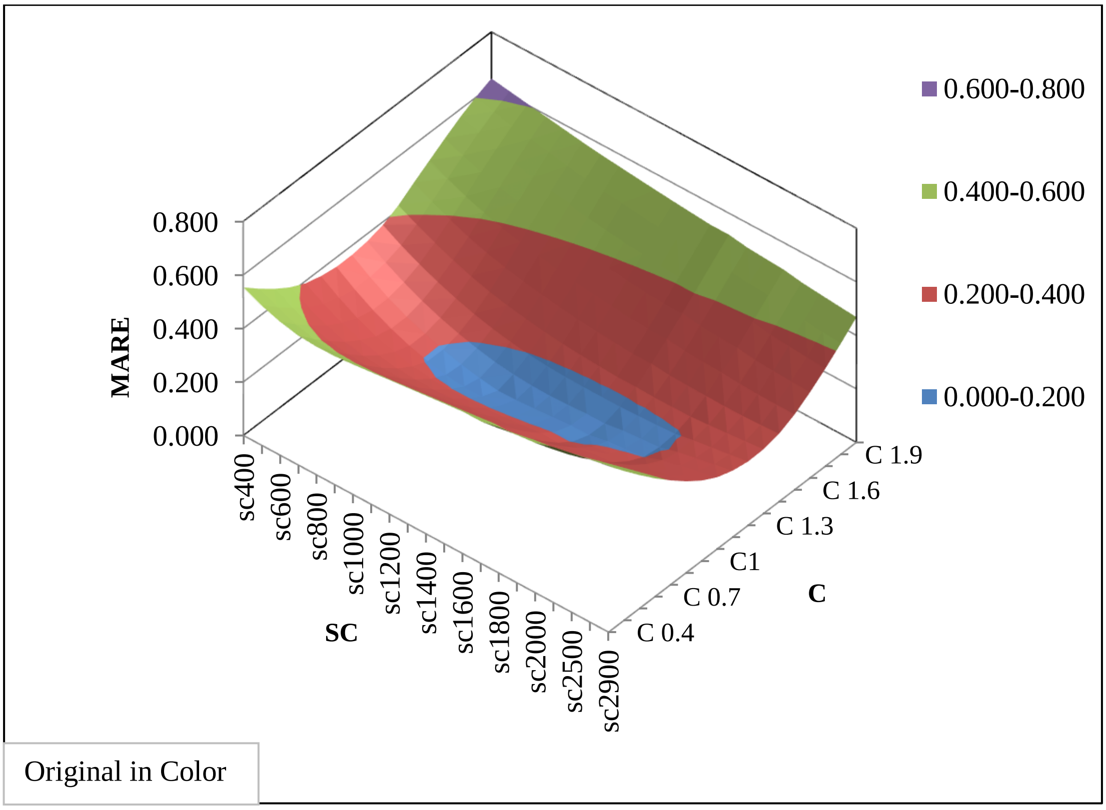
Original in Color

Figure C 4: Optimization of Parameter C at Finer Resolution for Kalu Ganga at Ellagawa



Original in Color

Figure C 5: Optimization of Parameter SC at Finer Resolution for Kalu Ganga at Ellagawa



Original in Color

Figure C 6: Coarser Resolution Surface for Mahaweli Ganga at Morape

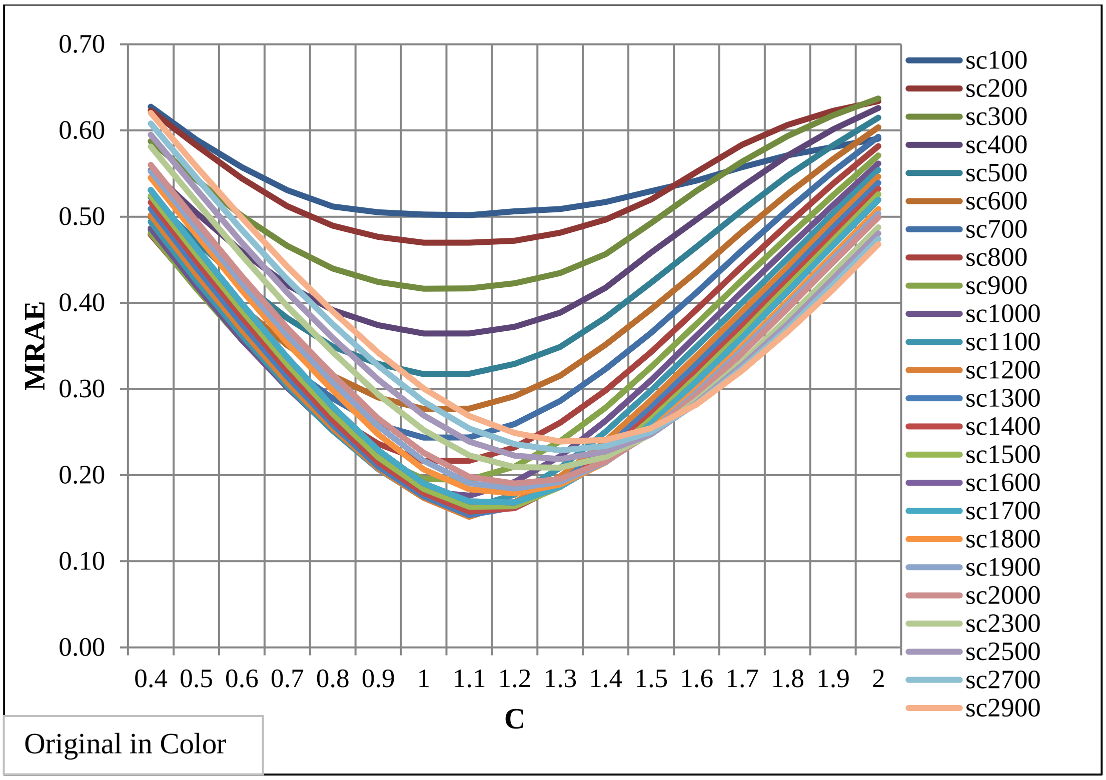


Figure C 7: Coarser Resolution Optimization of Parameter C for Mahaweli Ganga at Morape

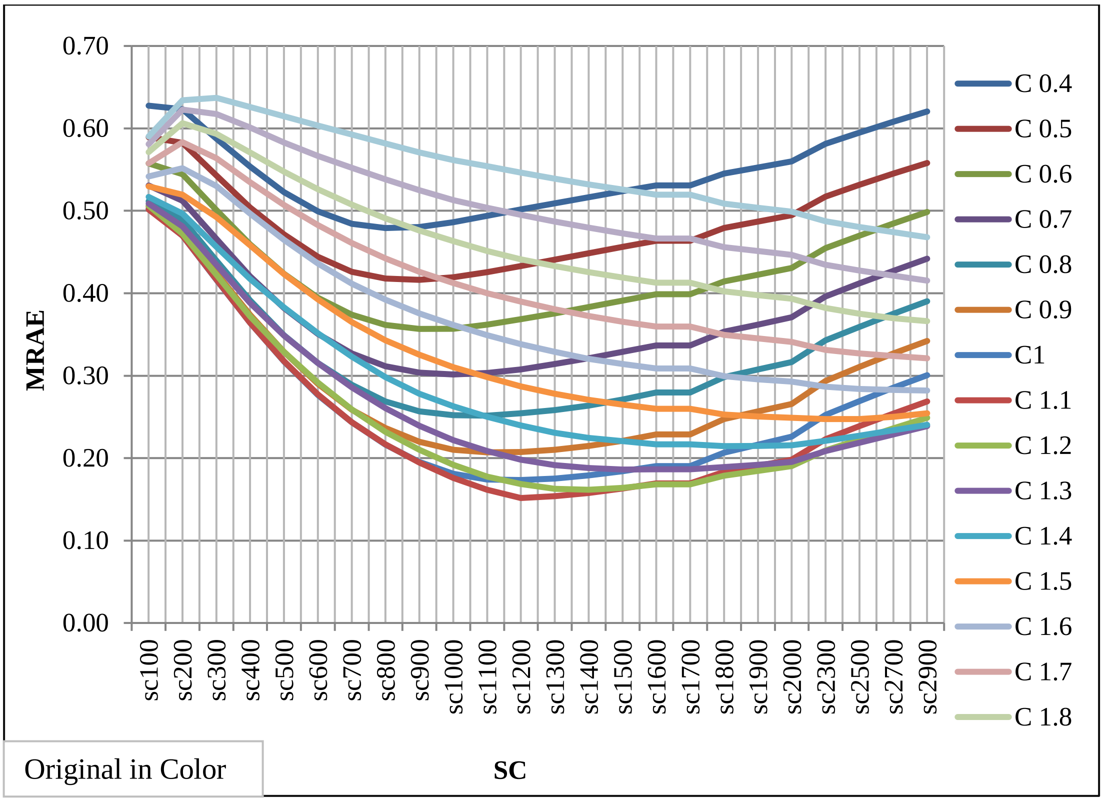


Figure C 8: Coarser Resolution Optimization of Parameter SC for Mahaweli Ganga

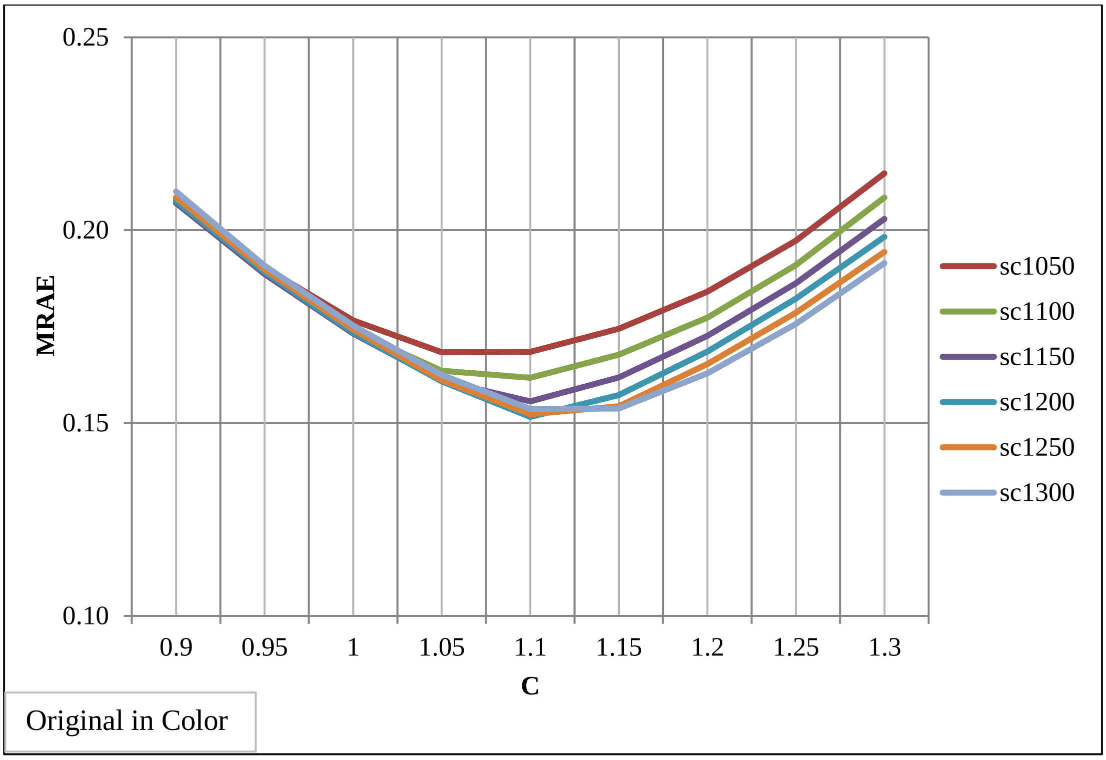


Figure C 9: Optimization of Parameter C at Finer Resolution for Mahaweli Ganga at Morape

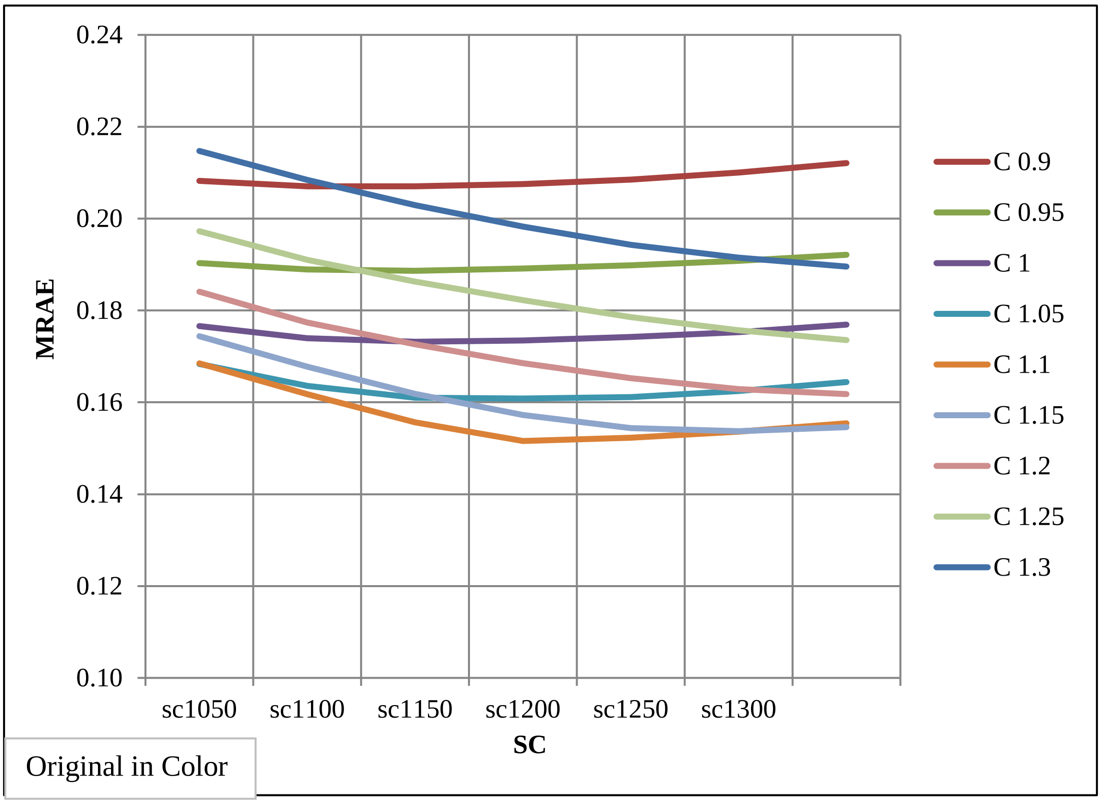
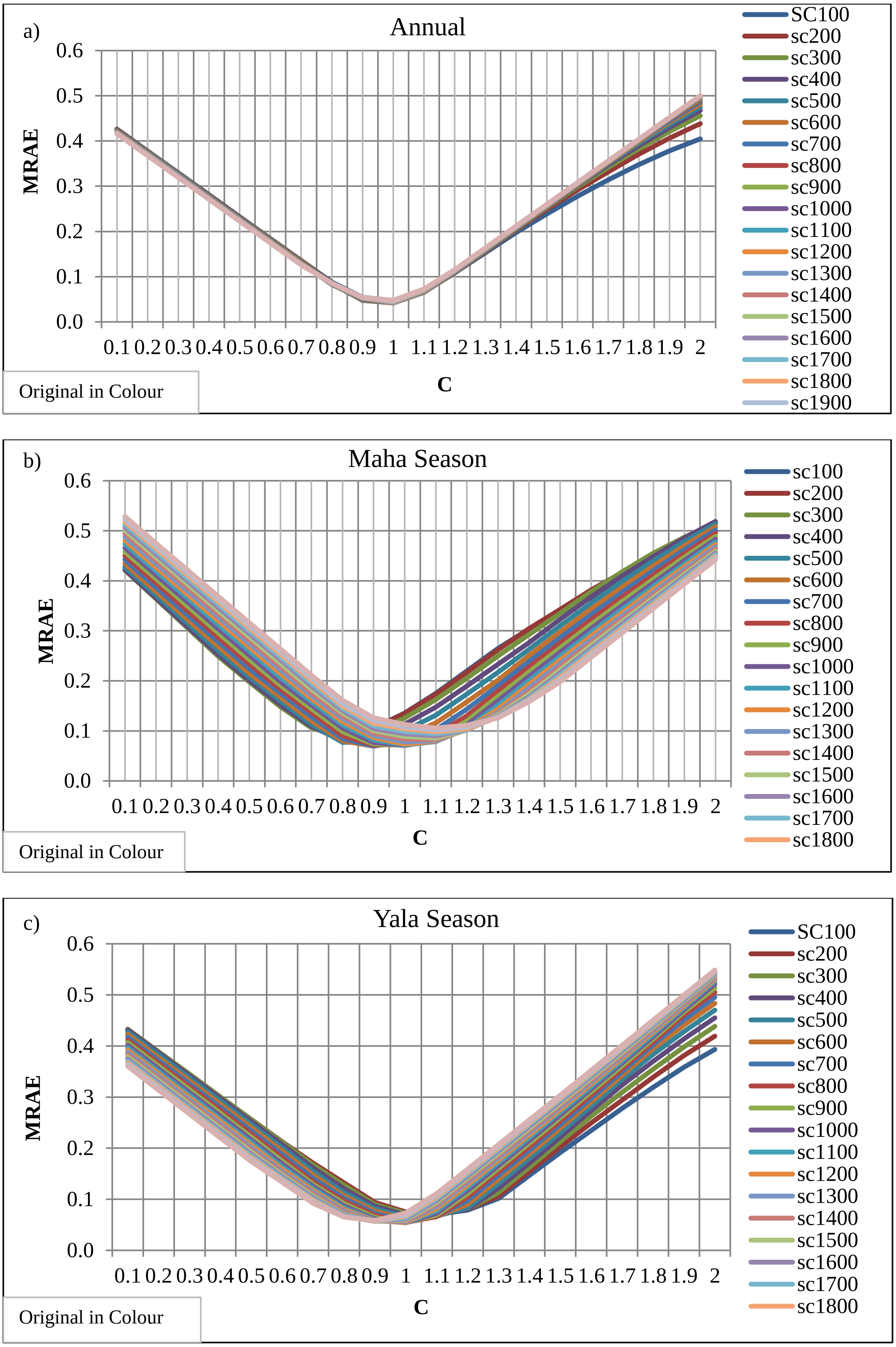


Figure C 10: Optimization of Parameter SC at Finer Resolution for Mahaweli Ganga at Morape

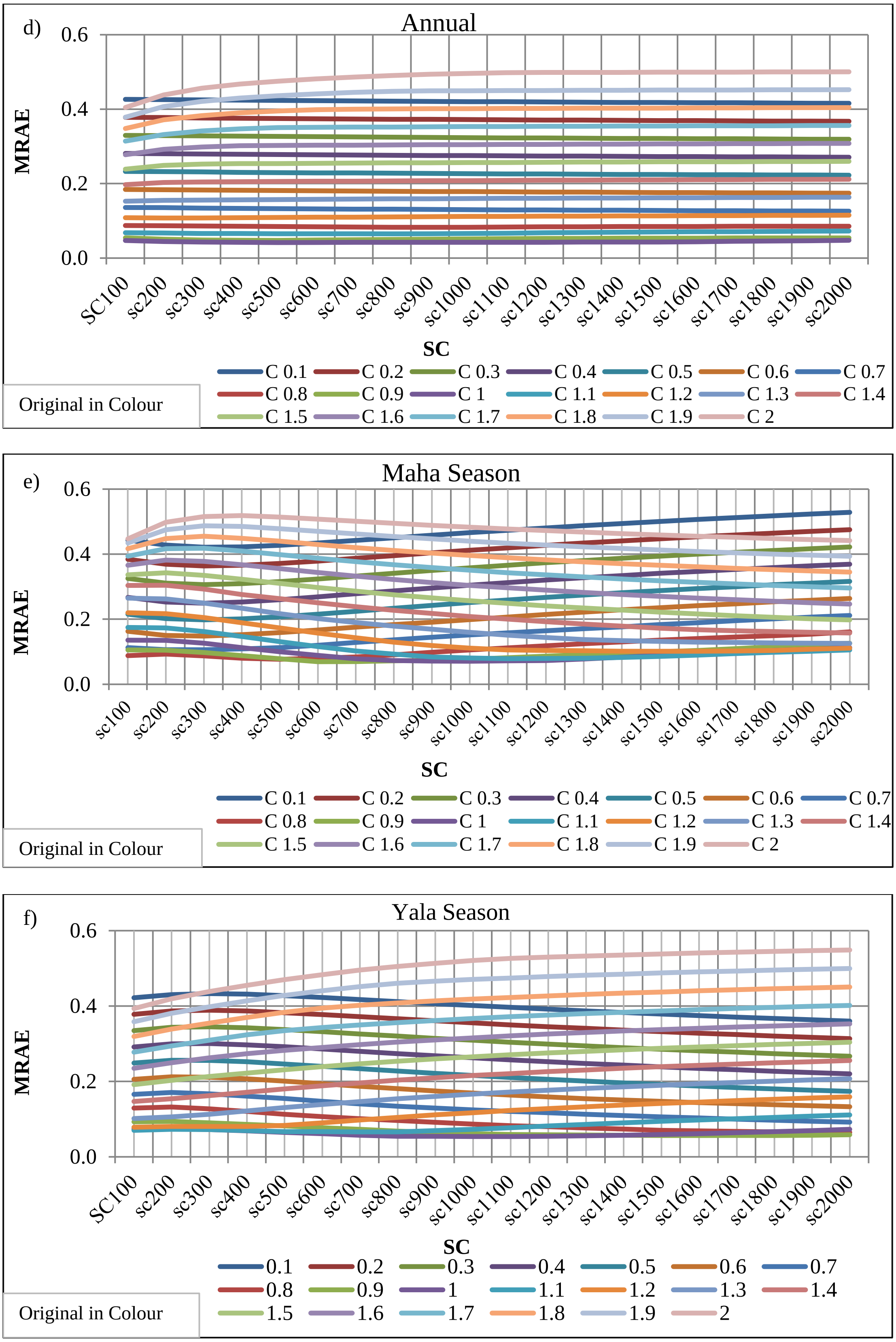


Original in Colour

Original in Colour

Original in Colour

Figure C 11: Optimization of Parameter C in Annual and Seasonal time scale for Kalu Ganga (a-c)



Original in Colour

Original in Colour

Original in Colour

Figure C 12: Optimization of Parameter SC in Annual and Seasonal time scale for Kalu Ganga (d-f)

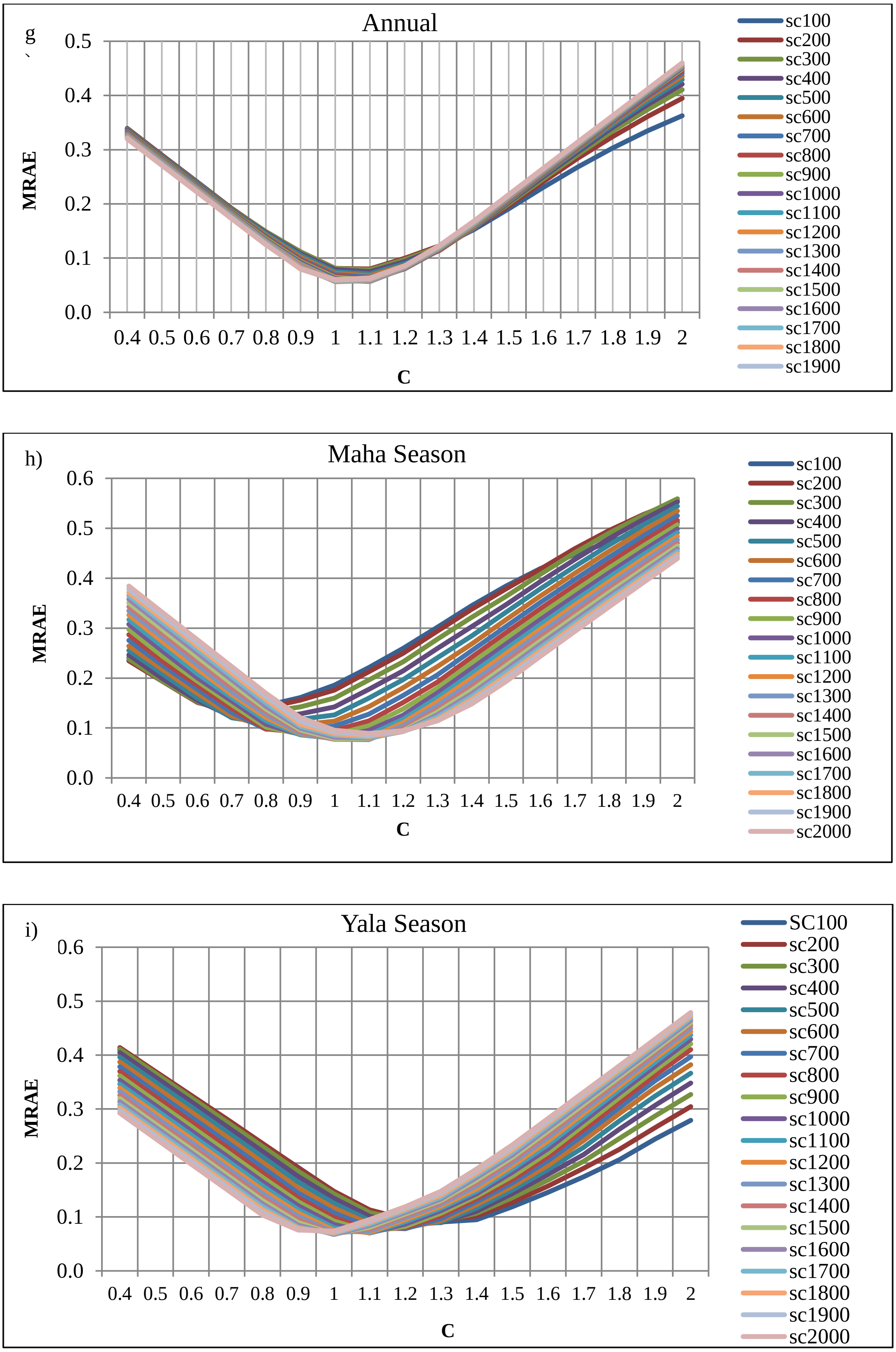


Figure C 13: Optimization of Parameter C in Annual and Seasonal time scale for Mahaweli Ganga (g-i)

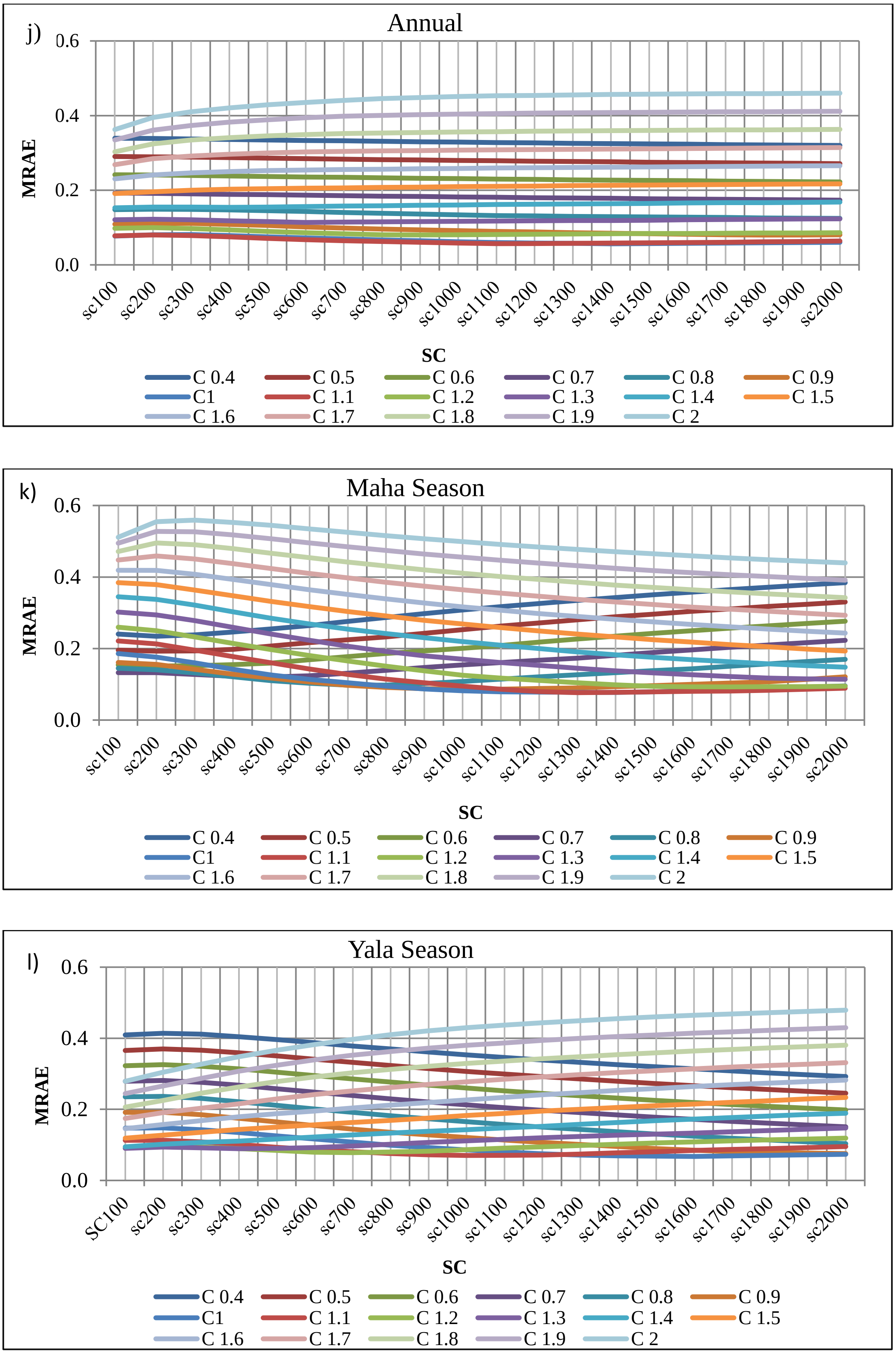


Figure C 14: Optimization of Parameter SC in Annual and Seasonal time scale for Mahaweli Ganga (j-l)

Appendix-D

Calibration and verification Results

Table D 1: Estimated and Observed flow of Kalu Ganga in Annual and seasonal time scale

Year	Calibration Period						Year	Verification Period					
	Annal		Maha Season		Yala Season			Annal		Maha Season		Yala Season	
	Estimated flow (mm)	Observed flow (mm)	Estimated flow (mm)	Observed flow (mm)	Estimated flow (mm)	Observed flow (mm)		Estimated flow (mm)	Observed flow (mm)	Estimated flow (mm)	Observed flow (mm)	Estimated flow (mm)	Observed flow (mm)
1983-84	3162.2	3049.6	1550.2	1423.1	1612.0	1626.4	1998-99	2902.2	2784.5	1126.0	1115.2	1776.2	1669.3
1984-85	2554.5	2653.7	977.1	1081.4	1577.4	1572.4	1999-00	2049.5	2094.5	1029.6	1028.0	1019.8	1066.5
1985-86	2592.6	2646.1	1215.4	1349.6	1377.2	1296.5	2000-01	1249.4	1243.0	640.4	685.7	609.0	557.3
1986-87	1980.6	2038.2	921.9	923.3	1058.7	1114.9	2001-02	1656.4	1694.9	780.8	774.9	875.7	920.0
1987-88	3664.5	3689.0	1211.3	1309.4	2453.2	2379.6	2002-03	2629.5	2550.9	951.9	832.6	1677.6	1718.3
1988-89	2609.1	2687.8	621.0	699.2	1988.1	1988.6	2003-04	1506.3	1486.5	430.4	395.1	1075.9	1091.4
1989-90	1983.8	2060.9	948.4	879.6	1035.3	1181.3	2004-05	1641.1	1655.5	790.8	705.5	850.4	950.0
1990-91	2040.5	1988.6	1000.0	922.6	1040.5	1066.0	2005-06	2157.2	1949.2	1063.1	952.9	1094.0	996.3
1991-92	1972.8	2198.7	686.8	698.6	1286.0	1500.1	2006-07	1835.8	1836.0	757.2	733.5	1078.6	1102.6
1992-93	2232.5	2144.6	870.1	892.6	1362.4	1252.0	2007-08	2510.2	2497.4	1010.0	1058.3	1500.2	1439.0
1993-94	2222.1	2417.5	1304.4	1380.8	917.7	1036.7	2008-09	1421.6	1511.9	561.9	565.8	859.7	946.1
1994-95	3025.3	3009.7	947.2	1026.5	2078.1	1983.3	2009-10	2001.8	1886.6	541.0	533.7	1460.8	1352.9
1995-96	2131.5	2315.8	702.7	877.3	1428.8	1438.4	2010-11	2150.8	2089.2	1076.4	979.8	1074.5	1109.4
1996-97	2017.8	1936.3	588.9	573.6	1429.0	1362.6	2011-12	1639.7	1559.3	611.6	632.0	1028.1	927.3
1997-98	3030.2	2854.1	1341.3	1272.7	1688.9	1581.4	2012-13	2840.3	2413.7	1360.3	1247.2	1480.0	1166.5

Table D 2: Estimated and Observed flow of Mahaweli Ganga in Annual and seasonal time scale

Year	Calibration Period						Year	Verification Period					
	Annal		Maha Season		Yala Season			Annal		Maha Season		Yala Season	
	Estimated flow (mm)	Observed flow (mm)	Estimated flow (mm)	Observed flow (mm)	Estimated flow (mm)	Observed flow (mm)		Estimated flow (mm)	Observed flow (mm)	Estimated flow (mm)	Observed flow (mm)	Estimated flow (mm)	Observed flow (mm)
1949/50	1672.7	1699.5	634.0	626.3	1038.7	1073.2	1964/65	1676.5	1599.5	624.4	550.7	1052.1	1048.9
1950/51	2067.1	2069.4	536.2	547.0	1530.9	1522.4	1965/66	1050.9	1248.6	530.4	682.3	520.5	566.3
1951/52	2260.0	2239.5	851.0	828.7	1409.0	1410.9	1966/67	1026.8	1177.7	642.2	686.6	384.5	491.1
1952/53	1425.8	1461.8	604.9	605.2	820.9	856.6	1967/68	2378.7	2416.0	871.7	912.6	1507.0	1503.4
1953/54	1823.4	1638.7	715.2	743.9	1108.2	894.8	1968/69	1440.0	1532.3	557.9	568.9	882.1	963.5
1954/55	2305.8	2089.7	896.3	805.7	1409.5	1284.0	1969/70	1386.8	1388.2	680.1	630.0	706.8	758.3
1955/56	1562.9	1619.0	435.1	477.6	1127.8	1141.4	1970/71	1910.9	1950.3	715.5	762.9	1195.4	1187.4
1956/57	1544.7	1519.4	695.2	648.1	849.5	871.3	1971/72	1687.6	1610.9	594.6	607.8	1093.0	1003.1
1957/58	1942.3	1858.3	1033.7	1023.3	908.7	835.0	1972/73	1516.8	1646.8	916.8	1008.6	600.0	638.2
1958/59	1836.0	1976.8	620.4	705.1	1215.6	1271.8	1973/74	2037.7	2086.5	526.7	566.9	1511.0	1519.6
1959/60	1766.9	1885.5	554.6	676.7	1212.3	1208.8	1974/75	1753.7	1639.4	473.8	499.7	1279.8	1139.7
1960/61	1628.1	1914.0	657.8	858.2	970.2	1055.8	1975/76	1280.6	1354.0	880.1	936.3	400.4	417.7
1961/62	1467.9	1605.9	433.1	518.2	1034.8	1087.7	1976/77	1366.6	1465.8	473.5	516.5	893.1	949.3
1962/63	1224.2	1362.3	658.2	650.8	566.0	711.4	1977/78	2216.8	2211.5	748.9	765.8	1467.9	1445.7
1963/64	1745.7	1705.3	757.4	844.3	988.3	861.0	1978/79	2051.9	2017.1	941.4	975.2	1110.5	1041.9

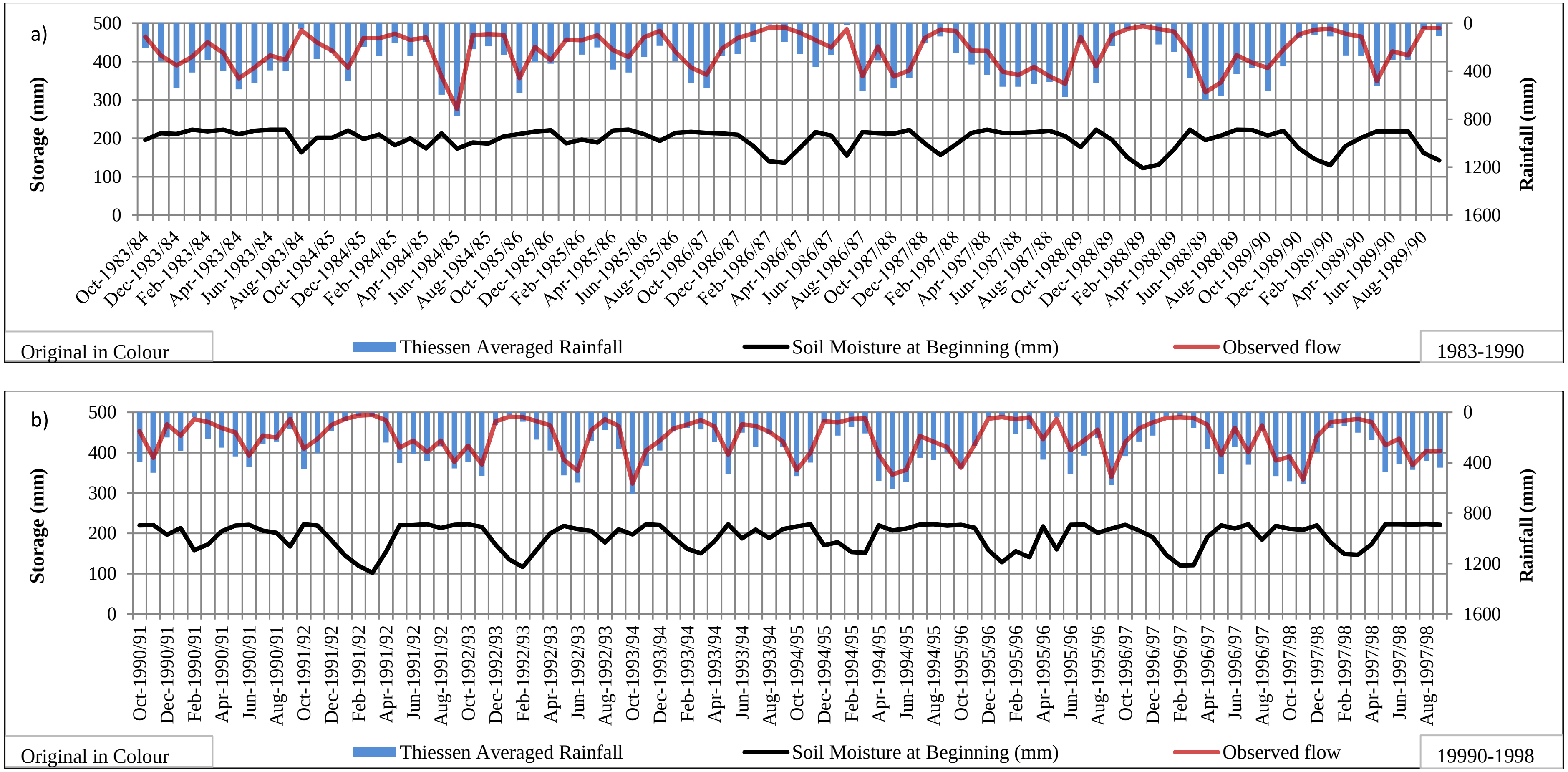


Figure D 1: Simulated Soil water content in Calibration period of Kalu Ganga (a-b)

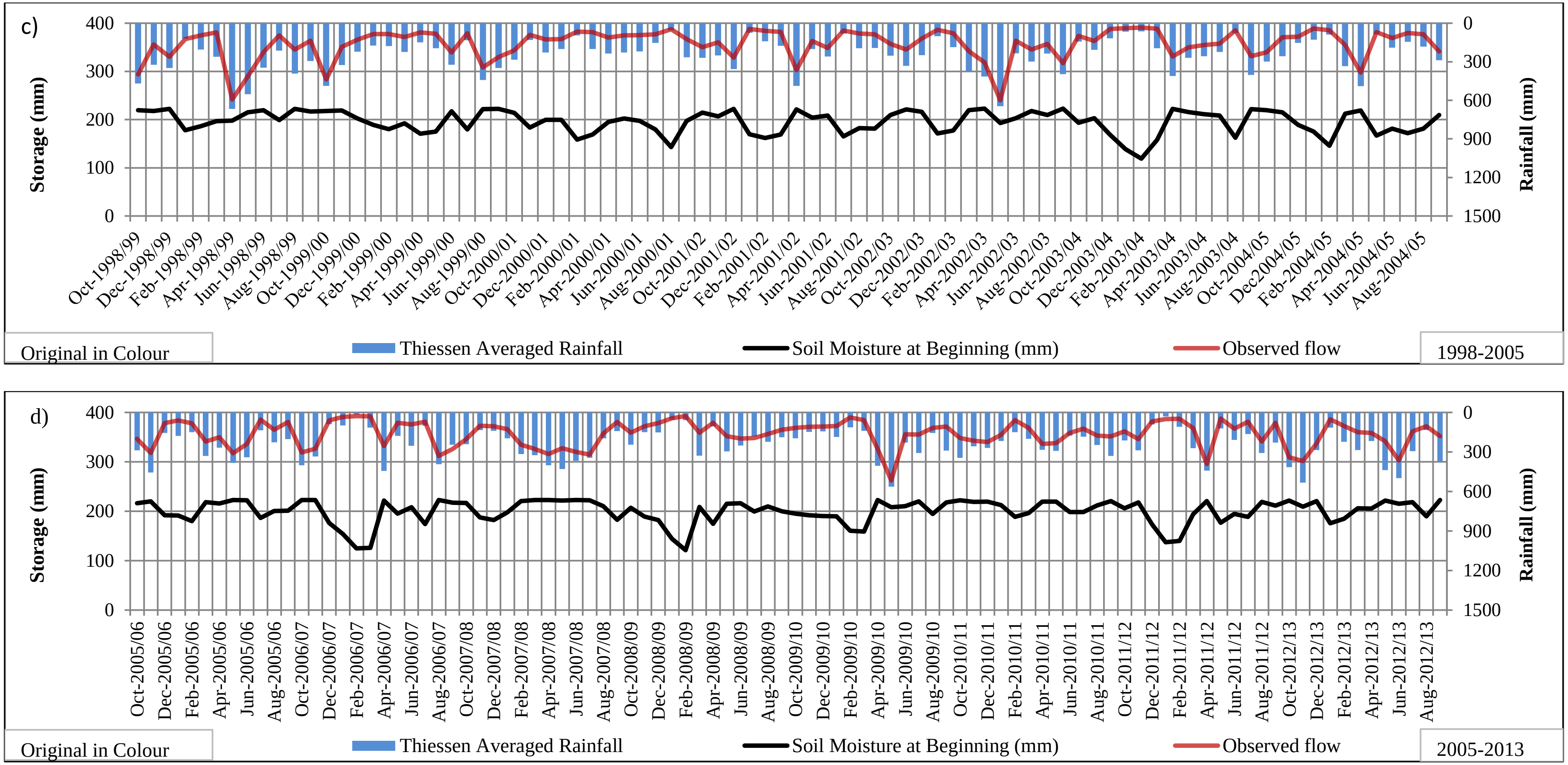


Figure D 2: Simulated Soil water content in Verification period of Kalu Ganga (c-d)

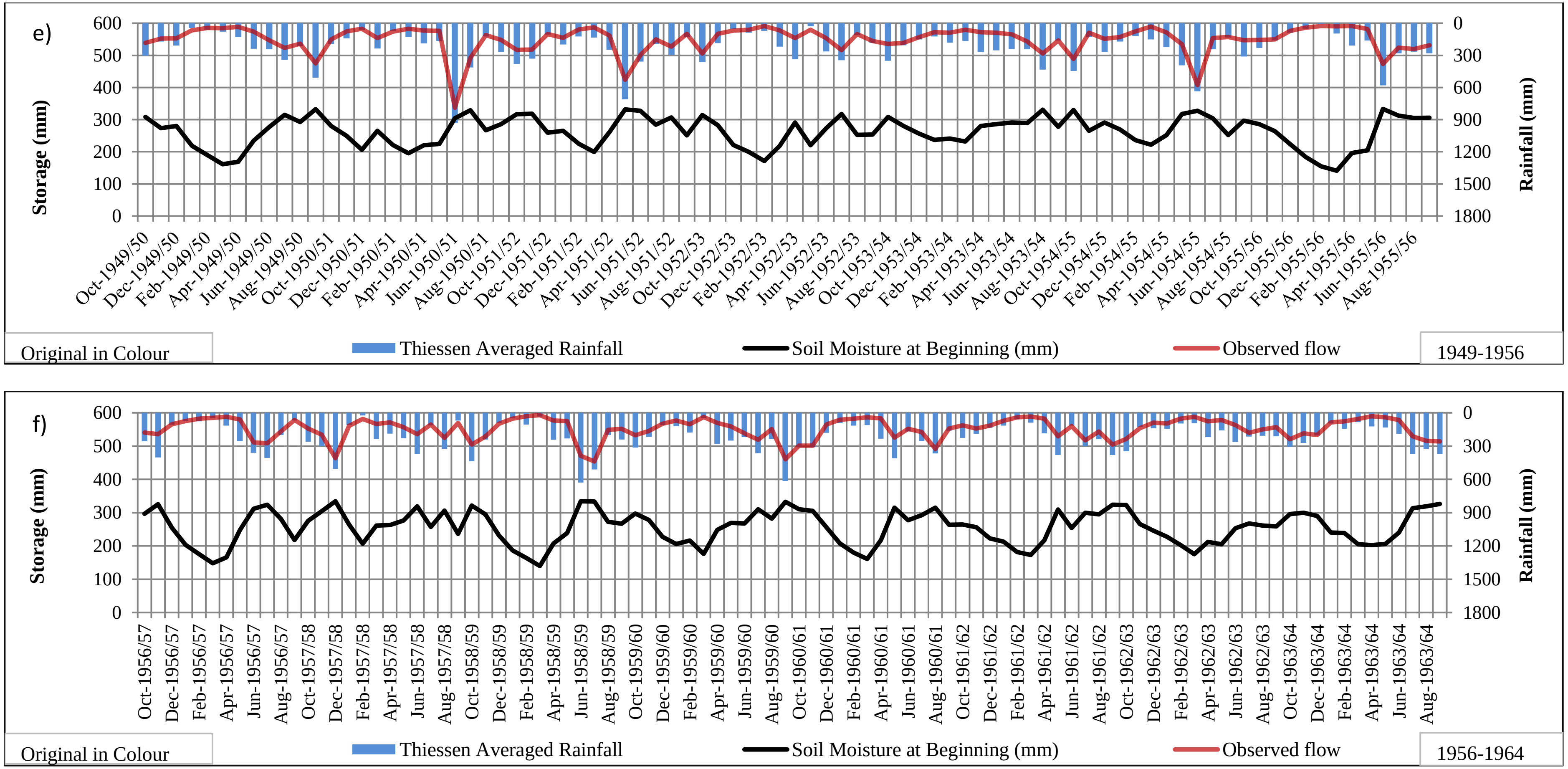


Figure D 3: Simulated Soil water content in Calibration period of Mahaweli Ganga (e-f)

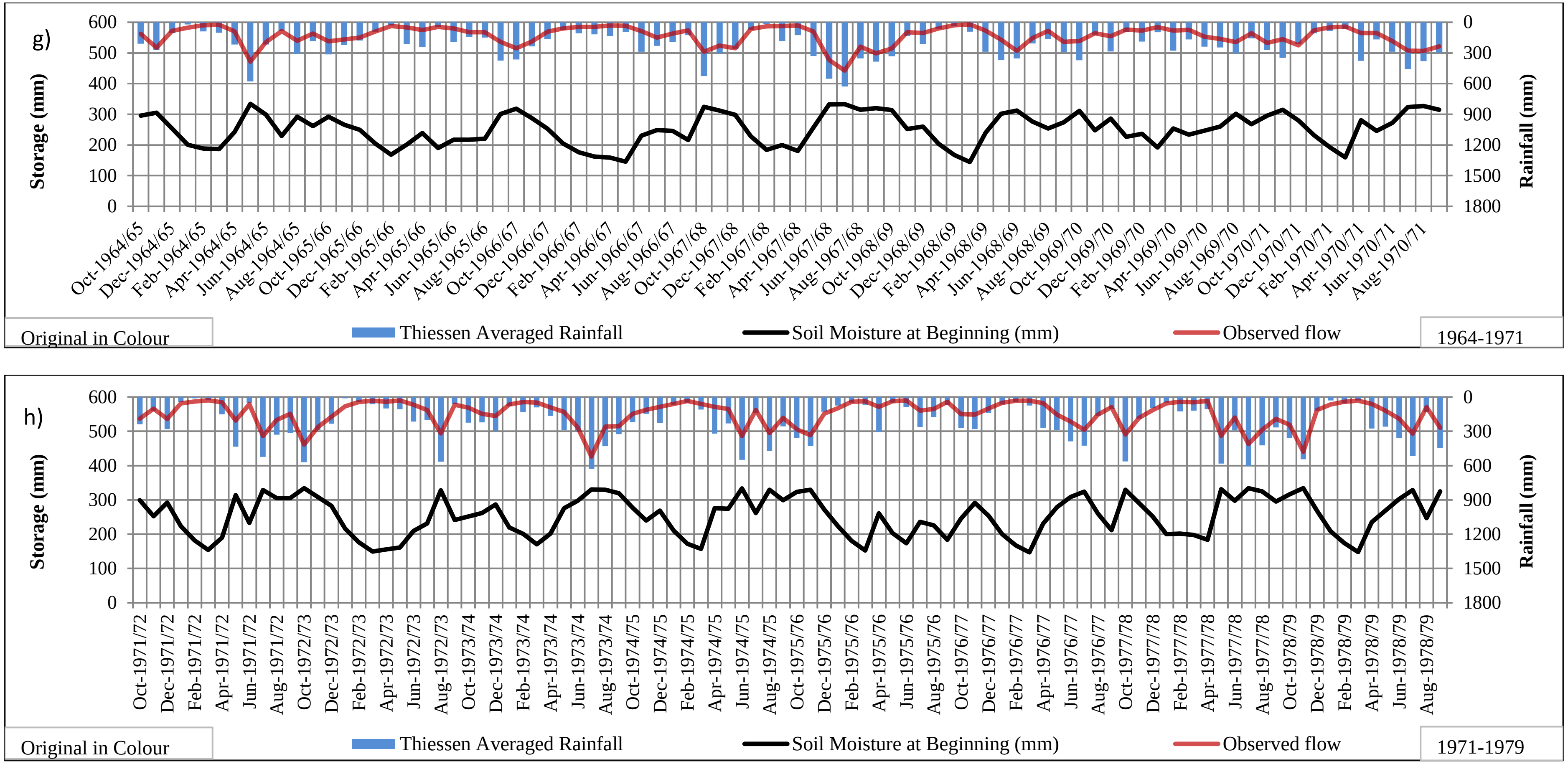
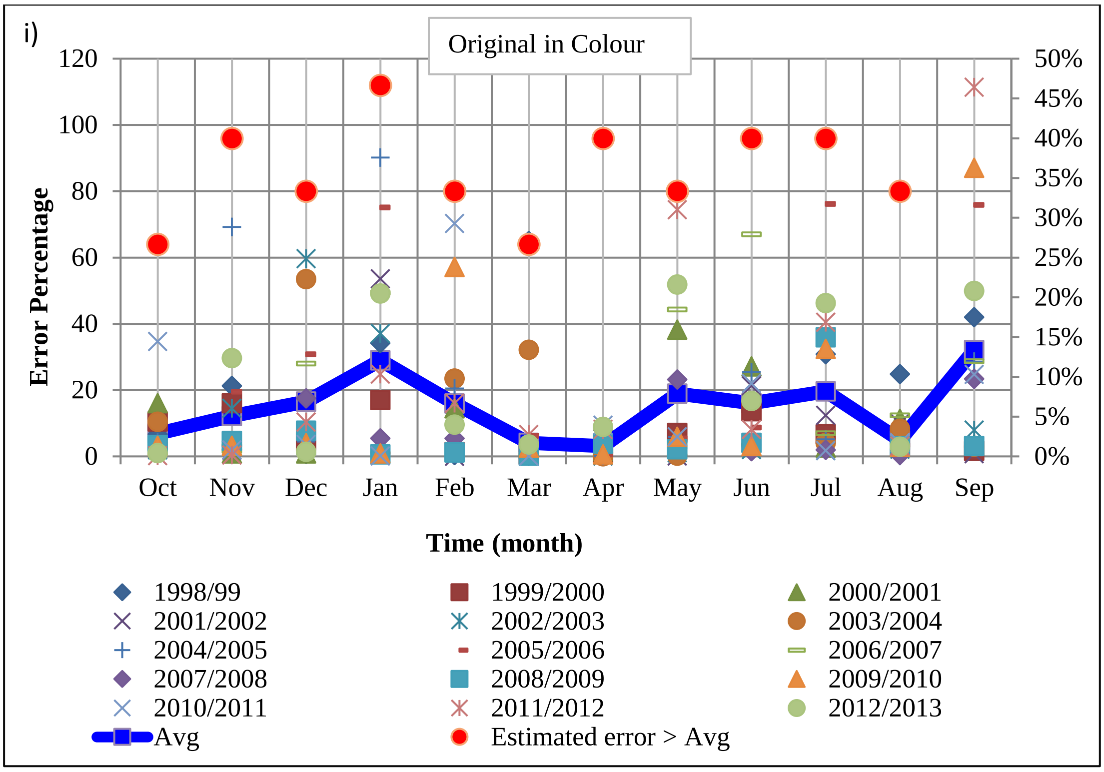


Figure D 4: Simulated Soil water content in Verification period of Mahaweli Ganga (g-h)



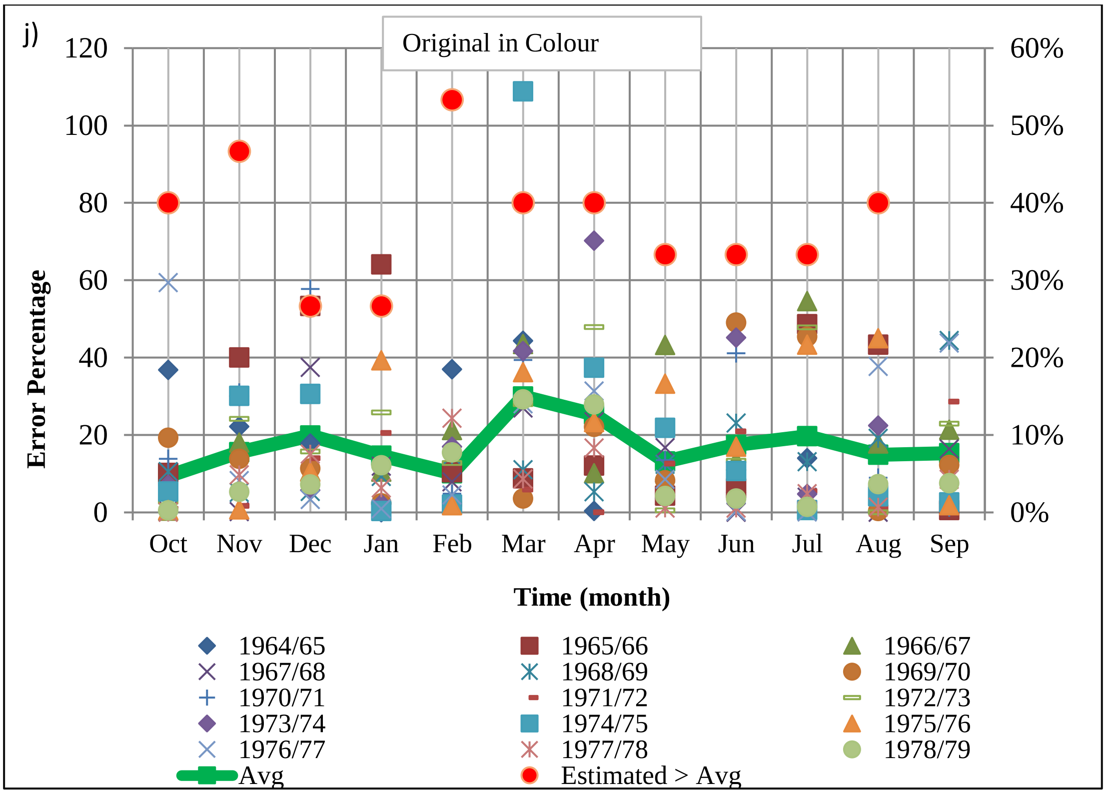


Figure D 5: Simulated Error during Verification of Kalu Ganga and Mahaweli Ganga (i-j)

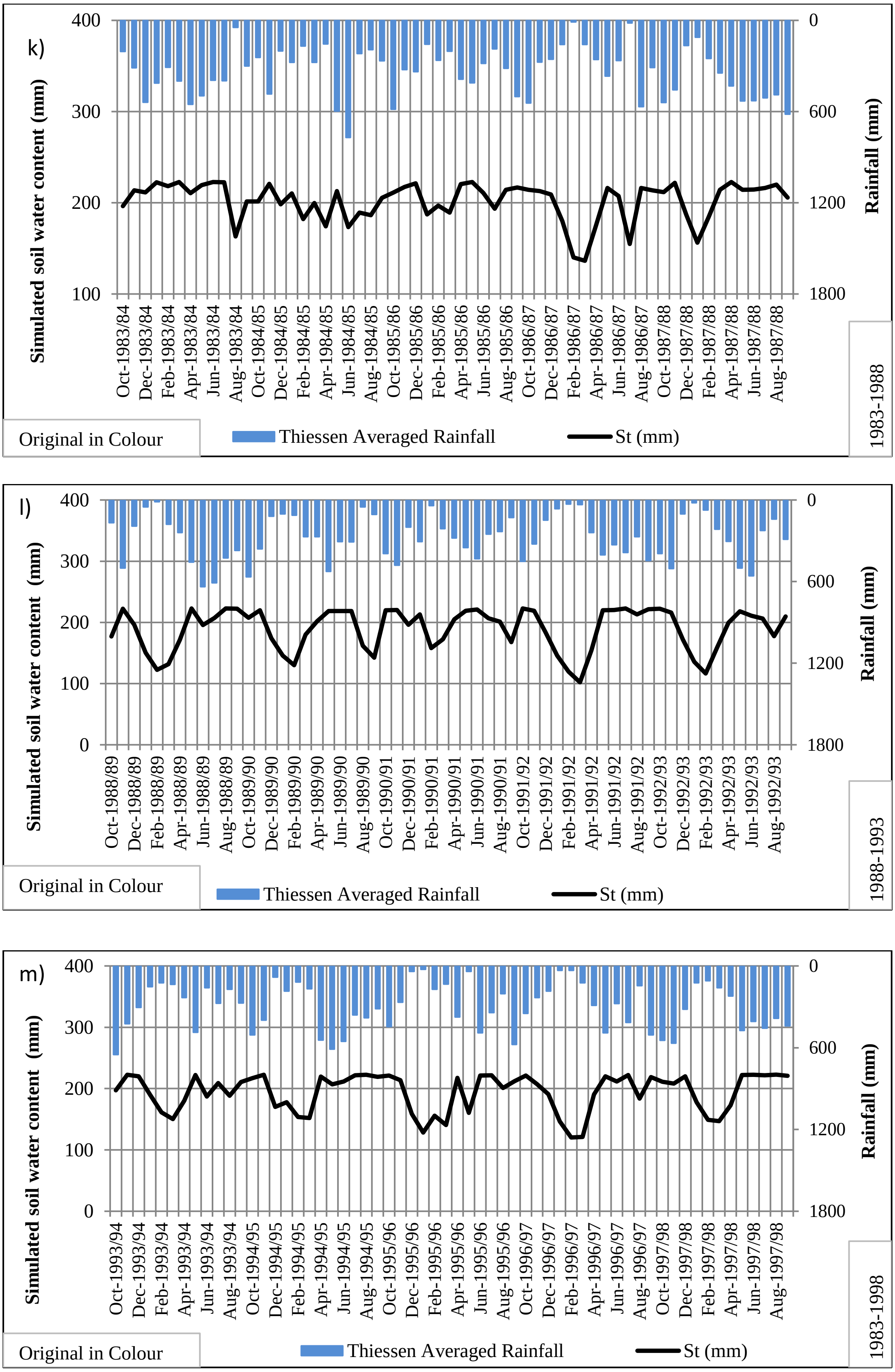


Figure D 6: Simulated Soil water content in Calibration period of Kalu Ganga (k-m)

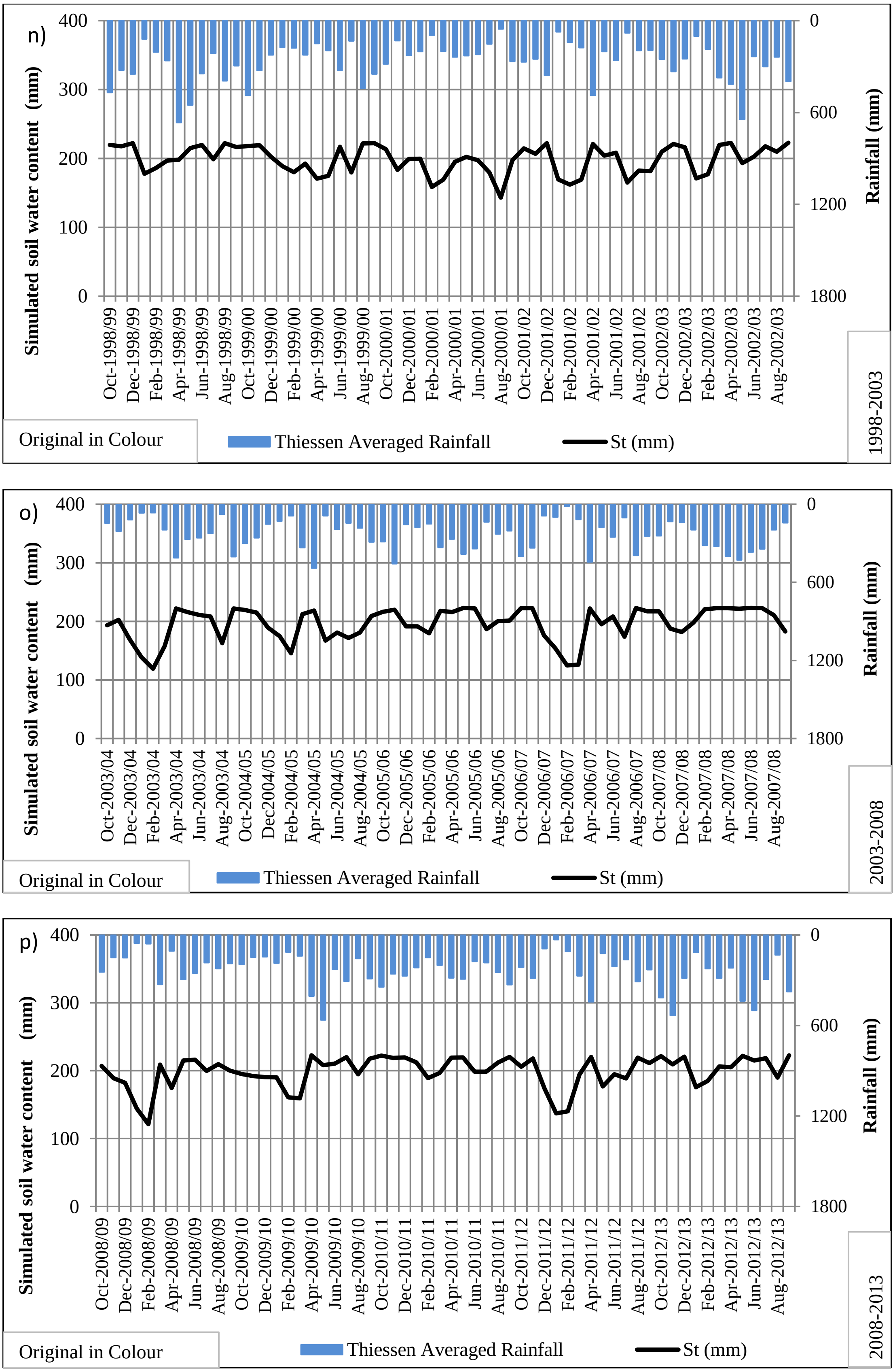


Figure D 7: Simulated Soil water content in Verification period of Kalu Ganga (n-p)

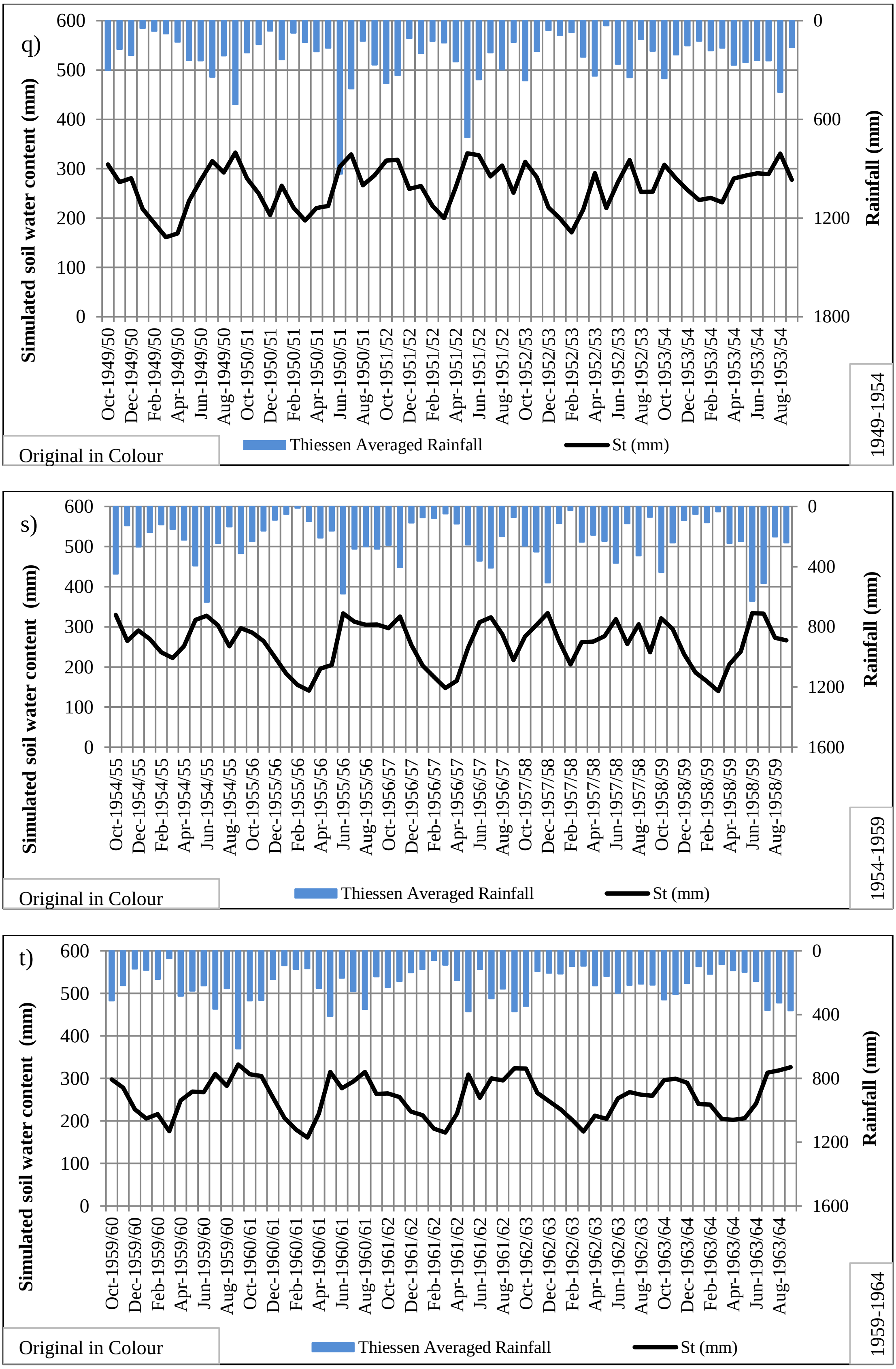


Figure D8: Simulated Soil water content in Calibration period of Mahaweli Ganga (q-t)

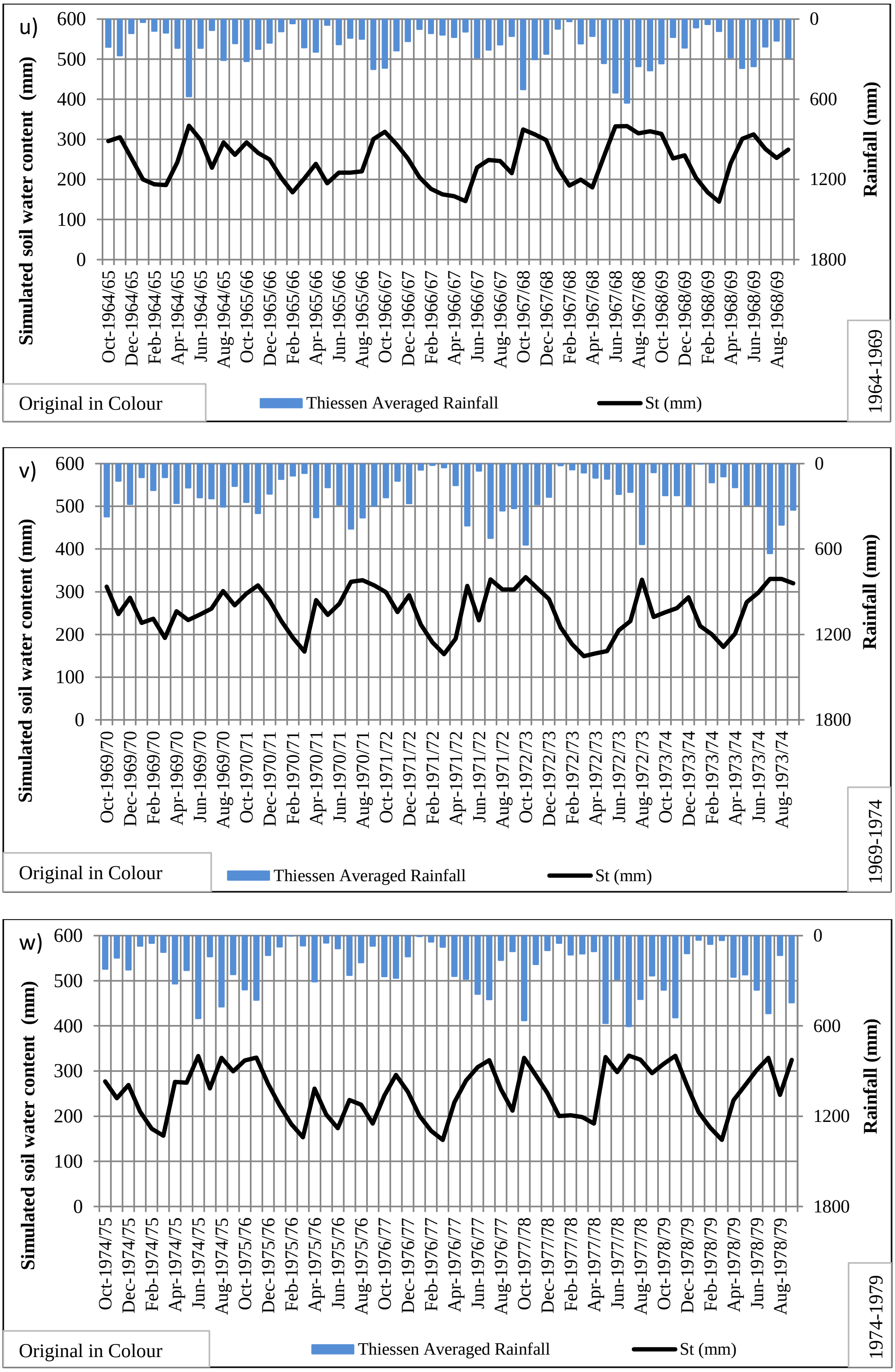


Figure D 9: Simulated Soil water content in verification period of Mahaweli Gang (u-w)