APPLICATION OF
'abcd' MONTHLY WATER BALANCE MODEL
FOR KALU GANGA AND GIN GANGA BASINS
AND ITS APPLICATION POTENTIAL FOR
WATER RESOURCES INVESTIGATION

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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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May 2018

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. Also, I hereby grant to University of Moratuwa the non-exclusive right to reproduce and distribute my thesis, in whole or in part in print, electronic or other medium. I retain the right to use this content in whole or part in future works (such as articles or books).

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Dulan Nalaka Gunasekara Date

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

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Dr. R. L. H. L. Rajapakse Date

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ABSTRACT

Application of 'abcd' monthly water balance model for Kalu Ganga and Gin Ganga basins and its application potential for water resources investigation

Only a limited number of mathematical models have been developed currently in Sri Lanka for water resources management purposes in Kalu and Gin River basins which predominantly provide water for the water supply schemes, irrigation and mini hydropower schemes. The developed models contain either a large number of parameters which increase the model complexity or less number of parameters which increase the amount of details in a parameter thus compromising the simulation accuracy. Based on available case studies, it is sufficient to have three to five parameters to reproduce most of the information in a hydrological record in monthly models for humid regions. Therefore, the “abcd” model which is a monthly lump hydrological model with four parameters was selected for the present research for the investigation of water resources in Kalu and Gin river basins considering Ellagawa and Thawalama sub catchments.

For the corresponding watersheds, precipitation, streamflow and evaporation data were collected for the past 30 years and checked by visual comparison, single and double mass curve analysis and annual water balance budget to ensure data reliability, consistency and to identify suitable data periods for model calibration and validation. For Gin River, a 25 years data period was used, while 20 years of data were selected for Kalu River basin. For the model evaluation, Mean Ratio of Absolute Error (MRAE) was used as the objective function while Nash Sutcliff Efficiency coefficient was used for the comparison purposes. In addition, visual inspection of flow simulation with respect to the observed flow, annual water balance and flow duration curves were used for the model performance evaluation. The optimized a, b, c, and d parameters for Thawalama and Ellagawa watersheds are 0.961, 1066, 0.003, 0.813 and 0.998, 1644, 0.013, 0.741, respectively. The MRAE for the calibration of Thawalama and Ellagawa watersheds are 0.21 and 0.26, respectively while obtaining 0.23 and 0.43 for the validation which show satisfactory results. In both watersheds, low flows have been slightly over estimated while very high flows have been underestimated. But a balanced distribution of simulated flow results can be observed in intermediate flows. Comparatively high dispersion of simulation results can be observed in Ellagawa watershed than Thawalama watershed. In case of parameter sensitivity, parameter “a” and “b” are the most sensitive while parameter “d” is having the lowest sensitivity.

As model outputs, monthly and annual variation of groundwater discharge, direct runoff, soil moisture storage and groundwater storage of the watersheds were obtained. For the overall discharge of both watersheds, the contribution from groundwater is very low. Therefore, the “abcd” hydrologic model can be recommended to use for streamflow simulations and water resources investigations in monthly temporal resolution for the watersheds which are having similar characteristics with parameter values in the ranges of a (0.961-0.998), b (1066-1644), c (0.003-0.013) and d (0.813-0.741).

Key words: ‘abcd’ model, monthly water balance model, parameter sensitivity, water resources investigation

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LIST OF ABBREVIATIONS

Abbreviation	Description
IPCC	Intergovernmental Panel on Climate Change
MSL	Mean Sea Level
P_t	Monthly precipitation
E_t	Actual evapotranspiration,
R_t	Recharge to groundwater storage,
QU_t	Upper zone contribution to runoff
XU_t	Upper soil zone soil moisture storage at the current time step
XUt_{-1}	Upper soil zone soil moisture storage at the previous time step
MRAE	Mean Ratio of Absolute Error
MSE	Mean Square Error
NSE	Nash Sutcliffe efficiency
SC	Field capacity of the catchment
WMO	World Meteorological Organization
EOt	Evapotranspiration opportunity
Rt	Groundwater Recharge
XLt	Soil moisture storage in ground water compartment after recharging
QL_t	Discharge from ground water compartment
Q_t	Total stream flow
PE	Potential Evapotranspiration
FAO	Food and Agriculture Organization
Kc	Crop coefficient
Cp	Pan Co-efficient
RE_m	Relative Maximum Error
SI	Sensitivity Index

1 INTRODUCTION

1.1 General

Considerable amount of uncertainties will be there over the future water demand and availability of water, which will be a challenge for the water management planners. Climate change and its potential hydrological effects are dominantly contributing to this uncertainty (Middelkoop et al., 2001; Xu & Singh, 2004). According to the second assessment of the Intergovernmental Panel on Climate Change (IPCC), increasing concentrations of greenhouse gases in the atmosphere will lead to increase the global average temperature by between 1.0 and 3.5 degrees Celsius over the forthcoming century (Intergovernmental Panel on Climate Change [IPCC], 2007). This will affect the hydrological cycle and cause changes in precipitation and evapotranspiration (Middelkoop et al., 2001). In addition to the climate change impacts, the land use of the catchments would be changed with the urbanization which can affect the runoff coefficient, evapotranspiration and groundwater recharge. All these changes will in turn affect the water availability and runoff and thus may affect the flow regimes of rivers. This alarms the water managers to establish a systematic method to investigate water resources in a basin for effective water management.

For the research, two wet zone watersheds of Sri Lanka were used, which are Ellagawa watershed of Kalu Ganga and Thawalama watershed of Gin Ganga. The Kalu Ganga, which originates in the central hills of Sri Lanka, flows through Ratnapura and Horana and falls into the Indian Ocean at Kalutara with a total length of about 100 km and catchment area of 2,690 km^2. From the starting point of the river to Rathnapura town, the bed of the river stretch has a narrow formation with high banks in both sides, having a drop from 2250 m MSL to 14 m MSL. The river basin lies entirely within the wet zone of the country and average annual rainfall in the basin is 4,040 mm with ranging from 6,000 mm in mountainous areas and 2,000 mm in the low plain areas. The elevation at Ellagawa is about 105 m MSL which is the point of interest of the watershed under this study. The Gin ganga originates from the mountainous region in Southern side of Sinharaja forest, Gongala in Deniyaya having an elevation of over

1300 m MSL, and flows through Tawalama, Neluwa and Agaliya and falls into sea at Gintota, Galle. The basin area of Gin ganga is 932 km^2 with an estimated average annual rainfall of around 3,290 mm. The elevation at Thawalama is about 94.0 m MSL.

According to the land use maps of Survey Department, Sri Lanka which was updated in 2003, the Ellagawa watershed consist of 18% homestead gardens, 20% coconut cultivations, 25% rubber cultivations, 15% unclassified forest area 8% tea while the Thawalama watershed consist of 9% homestead gardens, 9% coconut cultivations, 5% rubber cultivations and 34% unclassified forest area and 11% scrub lands which are main land uses. With the development of road network and transport facilities in those catchments, the rubber lands, coconut lands, unclassified forests, tea states and scrub lands are being converted into residential and commercial land use. This increasing trend of urbanization and deforestation can adversely affect the groundwater storage and deplete the aquifer recharging which can be reflected in the river flow specially in dry months. In both rivers, it may exist a considerable baseflow component because both rivers fall in wet zone of Sri Lanka. Rapid changing of land use pattern and high rate of application of agrochemicals and fertilizers have significantly affected the raw water quality of Gin Ganga (Wijesiri, Chaminda & Silva, 2015). This situation will be aggravated in dry months due to the increment of concentration of pollutants.

Both rivers play a significant role in supplying water for the domestic, industrial and irrigation usages in respective watersheds. The pipe born water supply system for Galle city is totally dependent on the water resources of Gin Ganga (Wijesiri et al., 2015) while Kalu Ganga provides water for number of water supply schemes (eg. Kandana and Kethhena, etc.) which supplies water for most of the areas of Kalutara district. With the urbanization, the demand goes up for pipe-borne water and this will lead to commission more water supply schemes and to increase the capacity of existing ones.

There are number of mini hydropower plants developed in both watersheds of Kalu Ganga and Gin Ganga which play a key role in supplying electricity to rural areas. For example, Erathna Mini Hydropower Project in Kalu Ganga and Pitadeniya, and Vidullanka Hydropower plants in Gin Ganga watersheds can be highlighted.

For the operation capacity estimations of public water supply schemes and mini hydropower projects, it is important to have a flow simulation model which can be used to develop accurate flow duration curves and to predict the operation performances even under catchment modifications. Therefore, any selected model should have a model structure which represents the soil moisture and groundwater compartments with optimum number of parameters with relatively less complexity and in an appropriate temporal resolution.

Currently in Sri Lanka, only a limited number of mathematical models have been developed for Kalu and Gin river basins. Wijesekera (2000) had applied a mathematical model for Gin ganga, based on Sugawara's tank model concept with 3 layer linear tank structure which has 6 parameters. The three layers represent surface storage, intermediate storage and groundwater storage which represent the whole system, but the model has become complex with large number of parameters. Wickramaarachchi, Ishidaira, and Wijayaratna (2012) have applied a distributed hydrological model which is called as the University of Yamanashi Distributed Hydrological Model with Block-wise use of TOPMODEL and Muskingum-Cunge method (YHyM/BTOPMC) for Gin ganga. The model simulation results had adequately represented the main hydrological characteristics of Gin ganga watershed including runoff volume, base flow and soil moisture states of the catchment. Even though the heterogeneity of the basin is highly represented in distributed models, it is quite limited in usage due to the requirement of large amount of data which are scarce and difficulties in data acquiring due to various organizational constraints and the requirement of modelling skills. Kahndu (2015) and Sharifi (2015) have applied two parameter model developed by Xiong and Guo (1999) in monthly temporal resolution for Thawalama and Ellagawa watersheds of Gin Ganga and Kalu Ganga, respectively, for the evaluation of climate change impacts and water resources. This model is simple and consists of only one compartment having two parameters namely transformation of time scale (C) and field capacity (SC) which represents the soil moisture. But this model does not consist of any parameters regarding the groundwater storage or discharge which will be important in flow simulation under droughts. Kanchanamala, Herath, and Nandalal (2016) have applied a mathematical lump model by using HEC-HMS for Kalu ganga at Rathnapura considering different number of sub catchments. But dividing the sub catchments will make the model complex in the application and additionally it needs the skill of handling the HEC-HMS software in case of practical applications.

Generally, the temporal resolution of the model is selected according to the purpose to be served. Monthly water balance models are advantageous in comparing with daily models if the intended application output is related to monthly, seasonal or annual temporal resolution. Other than that, according to Wang et al. (2011), monthly water balance models have low computational cost than daily models, because it requires only monthly data, which is cheaper than daily data even in Sri Lanka and readily available. For water resources investigations, snowmelt simulations, climate change impact assessments, flow forecasting and for water project designs monthly models have been used successfully (Xu & Singh, 1998). In the selection of an appropriate model, it is very important to select a model which is having an optimum number of parameters. According to Xu and Singh (1998), it is sufficient to have three to five parameters to reproduce most of the information in a hydrological record in monthly models for humid regions. But for arid or semi-arid regions, more complex model structure has to be used with large number of parameters.

Lumped rainfall-runoff models are popular among hydrologists, due to their simplicity in application by generalizing the heterogeneity of the catchment. One of the important principles in developing lump models is to use less number of parameters as possible which can reflect the regime characteristics which change with land use and installation facilities of water management (Thomas, 1981).

Therefore, the ‘abcd’ model, which is a monthly lump hydrological model of having four parameters, was selected for the present research for the investigation of water resources in Kalu and Gin river basins at Ellagawa and Thawalama, respectively. This model was first developed by Harold A. Thomas Jr. in 1981 under the report of “Improved Methods for National Water Assessment" (Thomas, 1981). The model structure consists of two main compartments, called soil moisture compartment and groundwater compartment. Each compartment is equipped with two parameters, where two of them represent runoff characteristics of the catchment while the other two parameters represent groundwater flow. The inputs of the model are monthly precipitation and potential evapotranspiration while the outputs of the model are monthly runoff (direct and indirect), soil moisture, and groundwater storage (Thomas, 1981). In addition, the other main advantage of the model is the computational simplicity, since it is developed in spreadsheet format using MS Excel.

1.2 Problem statement

Currently Kalu Ganga and Gin Ganga watersheds are vulnerable to intermittent floods and droughts and this situation has aggravated mainly with the land use change, rapid urbanization and climate change impacts which have affected adversely on the water supply schemes, mini hydropower plants and agriculture. Therefore, it is a timely need to manage the water resources in Kalu Ganga and Gin Ganga watersheds in an efficient manner without leading to any water deficits for the above crucial water requirements.

In Sri Lankan context, hydrologic models are not very much used as in other countries in water resources investigation, planning and management, which poses a risk for the future of water resources management. By this time, there are no monthly lump hydrologic models developed for Gin and Kalu river basins, which incorporate optimum number of parameters and a model structure to represent the soil moisture and groundwater. Therefore, it is a timely need to develop an appropriate hydrologic model which can simulate the stream flow specially under moderate and low flow conditions in monthly temporal scale to investigate the water resources in Kalu and Gin river basins.

1.3 Objectives/Specific objectives

1.3.1 Objective

The overall objective of the research is to develop, calibrate and validate a hydrologic model which can be used to simulate specially moderate and low flow conditions in Kalu Ganga and Gin Ganga at Ellagawa and Thawalama watersheds, respectively, to investigate the water resources availability for sustainable management of water resources in the Wet Zone basins of Sri Lanka.

1.3.2 Specific objectives

1. Select a monthly hydrologic model which can represent the system with optimum number of parameters to investigate the water resources of selected watersheds
2. Hydrological data checking and selection of a data set for the study
3. Develop, calibrate and validate the selected hydrologic model
4. Sensitivity analysis of model parameters
5. Demonstrate the applicability of the selected model for the water resources investigation in the selected watersheds
6. Derive recommendations and directions for future studies

2 LITERATURE REVIEW

2.1 Introduction

In the selection of an appropriate hydrologic model for water resources investigation of Ellagawa and Thawalama watersheds, it is very important to study on the types of the hydrologic models available with their various usages, required optimum number of model parameters, and selection of an appropriate temporal resolution and data period. After selecting the model, structure of the model, behavior of the parameters, model inputs, limitations and its applications in different regions of the world, have to be studied. In application of the model for the respective watersheds, model calibration and validation criteria must be identified to check the model performance for the considered objectives. Selection of initial values and identification of warm up period for the model is also important in the modelling process which needs to be studied under literature review.

2.2 Hydrologic model classification

According to Chow, Maidment, and Mays (1988), hydrologic models can be categorized into two main categories called physical models and abstract models. The physical models represent the real-world scenarios in a reduced scale while the abstract models represent the systems in terms of a set of equations which link the input and output variables. These variables may be a function of space, time and randomness. Considering this randomness, the abstract models can be categorized into two types called deterministic and stochastic. The deterministic models do not consider randomness while the stochastic models consider randomness. Although, almost all the hydrologic phenomena consist of randomness, it is considered in modeling only if it is pronounced. The deterministic models are further categorized as lumped and distributed according to spatial variation. The lump models are spatially averaged models without considering the spatial variation while the distributed models consider the variables as a function of space dimensions. The stochastic models are further classified considering spatial variation as space independent and space correlated, considering inter influence on different spatial points on the random variables. All the deterministic models can be further categorized as steady flows and unsteady flows considering the variation of flow in a particular point with respect to the time while categorizing the stochastic models as time independent and time correlated considering the interdependency of events. Further according to Chow et al.(1988), practical modeling usually considers only one or two sources of variations though five sources of variations (randomness, three space dimensions, time) are existed.

There are number of classifications other than the above classification. For example, according to Gayathri, Ganasri, and Dwarakish (2015), models can be classified based on the input parameters and the extent of physical principles applied in the model, as static and dynamic models considering time factor and as empirical, conceptual and physically based models. The empirical models are also called black box models, which are highly data driven and valid only within the boundary of a given domain. The conceptual models are also known as gray box models, which include semi empirical equations with a physical basis and parameters are derived by using field data and calibration. The physically based models are also called white box models or mechanistic models and it is a mathematically idealized representation of the real phenomenon.

2.3 Monthly water balance models , its usage and required number of model parameters

Monthly water balance models are extensively used to identify the water availability, watershed characteristics, water resources management and to evaluate the hydrologic consequences of climate change. The main practical reasons for using monthly water balance models are, for the water resources planning and prediction of effects of climate change, monthly stream flow discharges may be adequate and the abundance of monthly hydro climatological data. For humid regions, it is sufficient to use a model which has been formulated with three to five parameters to represent most of the hydrological information in the catchment. But for arid and semi-arid regions, relatively complex models with ten to fifteen parameters may be used (Xu & Singh, 1998). According to Thomas, Marin, and Brown (1983), approximately four to six parameters are needed to define the parameters adequately for a catchment and the parameters need not to have the conventional meanings of hydrologic variables.

In comparing monthly water balance models with daily water balance models, monthly water balance models are advantages if the main interest of the application is monthly, seasonal, or annual stream flow volume. Subsequently, monthly water balance models have low computational cost, because it requires only monthly data (Wang et al., 2011). In addition to the above facts, model complexity has to be increased when increasing the dryness index and decreasing the time scale (Atkinson, Woods, & Sivapalan, 2002).

According to Xu & Singh (1998), monthly water balance models are generally used for reconstruction of the hydrology of watersheds, climatic change impacts assessments, and evaluation of the seasonal and geographical patterns of water supply and irrigation demand.

2.4 Aggregated/ Lumped water balance models

According to Thomas (1981), one of the main important principles in developing lumped models is the usage of limited number of parameters which represent the regime characteristics which can change with the land use and installation facilities of water management.

2.5 Data period for monthly water balance models

Selection of the data length is one of the most important decision-making points in climatological studies. In the analysis of time series, hydro climatologists are concentrating on differences in 30-year normals along the whole period of records. Therefore the period of 30-year is assumed to be long enough for a valid mean statistic (Kahya & Kalaycı, 2004).

But some studies demonstrate that, there will not be a considerable change in the performance of the model even though the calibration period increases more than 10 years. By using “abcd” monthly water balance model, a comprehensive study had been carried out by using 241 non-snow catchments in the United States to check whether it will change the model performance when the calibration data period is increased. For this, altogether 40 years of monthly data had been used from 1951-1990. In that study, the model was calibrated first by using 10 years monthly data from 1951 to

1960. Then the model was validated for the data period of 10 years, from 1981 to 1990. Out of the above selected catchments 53% of catchments were classified as good for a set criterion, while 35% of catchments were classified as good in the validation. The same procedure was done increasing the calibration period for two decades (1951-1970) and for three decades (1951-1980) separately and validated for the period from 1981 to 1990 as previous. As a result of this study, it had been found that only 52% and 50% of the catchments were classified as good respectively in calibration while having 37% and 40% as good in validation. This indicates that there is only a small improvement in model performance in case of increasing data period in calibration (Martinez & Gupta, 2010).

In addition to this study, lot of monthly modelling work had been done successfully even with less data periods than 30 years as follows. For the application of "abcd" monthly water balance model for three selected basins of the United States, 17 years data period was used by Al-Lafta, Al-Tawash, and Al-Baldawi (2013), using 10 years for the calibration and 7 years for the verification. In the development of 79 monthly water balance models for Belgium Burma and China by Vandewiele, Xu, and Win (1992), different data periods had been used which varies between 5 to 35 years. Out of these 79 catchments, 71 catchments had been modeled by using less than 20-year data period. For the application of two parameter monthly water balance model for 70 sub catchments in China, Xiong and Guo (1999) had used less than 20 year data period for 17 catchments, 20~25 year data period for 38 catchments, 25~30 year data period for 13 catchments and greater than 30 year data period for only 2 catchments.

In addition to the above, some modelers had used higher data periods than 30 years in monthly water balance modelling. As an example, Alley (1984) had used 50 years of monthly data for the investigation of various monthly water balance models in New Jersey, USA.

By reviewing above facts, it can be concluded that there will not be a considerable change in model performance even increasing the data period more than 10 years in the model calibration. And further, most of the modelers have not followed a specific data length to develop their monthly models.

2.6 Parameter sensitivity analysis

According to Hamby (1994), sensitivity analysis is done in mathematical modelling for following reasons;

- ❖ To determine which parameters, require additional research to improve and enhance the knowledge base, to reduce output uncertainty
- ❖ To identify, which parameters are not significant and can be eliminated from the model
- ❖ To determine which inputs, contribute most to output variability
- ❖ To identify which parameters are mostly correlated with the output
- ❖ To identify the consequences of changing a given input parameter when the model is in production use

There are large number of ways of conducting a sensitivity analysis. For example, differential sensitivity analysis, one at a time sensitivity measures, factorial design, sensitivity index (SI), importance factors, subjective sensitivity analysis, scatter plots, importance index, relative deviation method, relative deviation ratio, Pearson’s r, rank transformation etc. But in comparing different methods it may not produce identical results (Iman & Helton, 1988). Therefore, the method needs to be selected according to the requirement.

Considering the objective of our research and the simplicity of usage, Sensitivity Index (SI) was selected to identify the overall sensitivity of parameters while using “one at a time sensitivity measures” to identify the local sensitivity of parameters.

- One at a time sensitivity measures

Conceptually the easiest way of carrying out a sensitivity analysis is varying one parameter while keeping others fixed (Hamby,1994). A sensitivity ranking can be obtained by increasing each parameter by a given percentage while leaving all others constant and quantifying the change in model output. This type of analysis has been referred to as a 'local' sensitivity analysis (Crick, Hill, & Charles, 1987), since it only addresses sensitivity relative to a point estimated but not for the entire parameter distribution.

- Sensitivity Index (SI)

One of the other simple methods of determining parameter sensitivity is to calculate the output percentage difference when varying one input parameter from its minimum value to its maximum value which is called the Sensitivity Index (SI) (Hoffman & Gardner, 1983; Bauer & Hamby, 1991).

$$\text{Sensitivity Index (SI)} = (D_{max} - D_{min}) / (D_{max}) \qquad (12)$$

where D_{min} and D_{max} represent the minimum and maximum output values, respectively, resulting from varying the input over its entire range.

2.7 The "abcd" monthly water balance model

2.7.1 Introduction

This model was first developed by Harold A. Thomas Jr. in 1981 under the report of "Improved Methods for National Water Assessment". According to the report, the model consists of four parameters, out of which two of them representing runoff characteristics of the catchment while the other two parameters representing groundwater flow. The inputs of the model are monthly precipitation and potential evapotranspiration or pan evaporation and the outputs of the model are monthly runoff (direct and indirect), soil moisture, and ground water storage (Thomas, 1981).

The advantage of the "abcd" model is the more realistic representation of infiltration by facilitating for the stream flow even under low soil moisture conditions (Martinez & Gupta, 2010).

2.7.2 The "abcd" model structure

According to Thomas (1981), Martinez and Gupta (2010) and Al-Lafta et al., (2013) the model structure of the ‘abcd’ model is as shown in Figure 2-1. In the model, parameter ‘a’ reflects the propensity of runoff to occur before the soil is fully saturated (Thomas et al., 1983). The parameter ‘b’ is the upper limit on the sum of actual evapotranspiration and soil moisture storage in a given month.

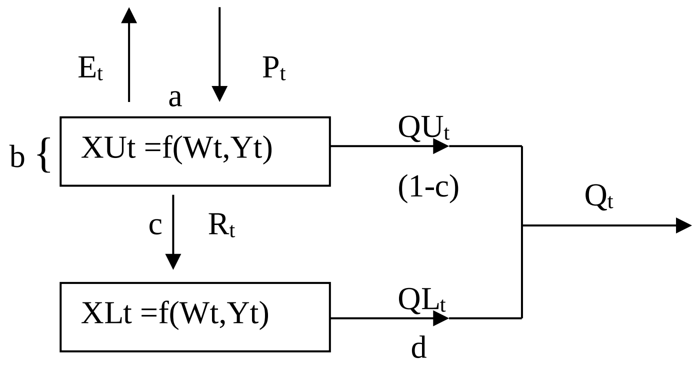

Figure 2-1: The "abcd" model structure

This parameter reflects the ability of the catchment to hold water within the upper soil horizon. The parameter ‘c’ controls the water input to the aquifers . The reciprocal of the parameter ‘d’ is equal to the average groundwater residence time (Al-Lafta et al., 2013).

By applying the continuity equation for the upper moisture zone;

$$P_t - E_t - R_t - QU_t = \Delta XU = XU_t - XU_{t-1} \qquad (1)$$

Where; P_t - Monthly precipitation

E_t - Actual evapotranspiration,

R_t - Recharge to groundwater storage,

QU_t - Upper zone contribution to runoff

XU_t and XUt_{-1} - Upper soil zone soil moisture storage at the current and previous time steps

The above expression can be rearranged as;

$$(P + XU_{t-1}) = (Et + XU_t) + QU_t + R_t, \qquad (2)$$

where $(P + XU_{t-1})$ is the available water (WA_t) while ($E_t + XU_t$) is the evapotranspiration opportunity (EO_t)

EO_t can be expressed as a nonlinear function of WA_t as;

$$\mathrm{EOt(WAt)} = \frac{\mathrm{WAt+b}}{\mathrm{2a}} - \sqrt{\left(\frac{\mathrm{WAt+b}}{\mathrm{2a}}\right)^2 - \frac{\mathrm{WAt.b}}{\mathrm{a}}} \qquad (3)$$

The nonlinear relationship between E_t, EO_t, and PE_t can be written as,

$$E_t = EO_t \cdot \{1 - \exp(-PE_t / b)\}. \qquad (4)$$

Considering the water availability for runoff as $(WA_t - EO_t)$

Upper zone contribution to runoff,

$$QU_t = (1 - c) \cdot (WA_t - EO_t) \tag{5}$$

Ground water recharge;

$$R_t = c \cdot (WA_t - EO_t) \tag{6}$$

Soil moisture storage in ground water compartment after recharging;

$$XL_t = (XL_{t-1} + R_t) \cdot (1 + d)^{-1} \tag{7}$$

The discharge from ground water compartment can be written as;

$$QL_t = d \cdot (XL_t) \tag{8}$$

The total stream flow can be written as;

$$Q_t = QU_t + QL_t \tag{9}$$

2.7.3 Application of "abcd" model

According to Thomas (1981), the "abcd" model was initially applied as a monthly water balance model. Later the model was applied under different time scales as seasonal, monthly and annual, and the results were examined for "reasonableness" and consistency. According to the results, it was shown that, the model performs better under annual time scale (Thomas et al., 1983). But the "abcd" model had been applied successfully in monthly time scale for 3 basins in United states according to Al-Lafta et al. (2013) and 764 basins according to Martinez and Gupta (2010).

In the application of the model, it is not necessary to separate the direct and indirect runoff of the observed flow even though the model has two compartments for storage of water in aquifers and in sub soil. The availability of data related to soil moisture and ground water will make easy to determine the parameters of the model but even without those data the model can be fitted (Thomas, 1981).

According to Lafta et al. (2013), it was found that the "abcd" model does not perform well in regions dominated by snow without appropriate modifications in the model structure and further, it was observed that the model shows an intermediate level of performance in mild climates (warm and humid). Martinez and Gupta (2010) has addressed the effect of snow successfully by doing appropriate modifications to the "abcd" model structure.

2.7.4 Potential Evapotranspiration (PE) for the model

Potential evapotranspiration is one of the main inputs for the ‘abcd’ model. There are number of models available to calculate the potential evapotranspiration. Thomas (1981) had used pan evaporation method as the potential evapotranspiration method for the firstly developed ‘abcd’ model. Other than the pan evaporation method, temperature based methods, radiation based methods and combination methods are available to estimate the potential evapotranspiration. Hargreaves Method and Thornthwaite Method are examples for the temperature based methods while Turc Method and Priestly-Taylor Method are examples for the radiation based methods. Under combination methods, FAO Penman-Monteith Method can be elaborated which has been proposed by the International Commission for Irrigation and Drainage and Food and Agriculture Organization of the United Nations as a standard method for estimating reference evapotranspiration.(Nikam, Kumar, Garg, Thakur, & Aggarwal, 2014) .

Since the pan evaporation data is readily available for the study area and the method is more straight forward, it was used as the potential evaporation estimation method for the study.

2.7.4.1 Pan Evaporation model of Doorenbos and Pruitt (1975)

The potential evapotranspiration can be expressed in terms of pan evaporation and pan co-efficient as,

$$PE = Cp\,(E_{pan}) \tag{10}$$

This Cp can be expressed as,

$$Cp = Kp \times Kc \tag{11}$$

Kp is the pan coefficient which can be taken as 0.8 on average, for the common Class A pan. Kc is the crop coefficient which is dependent on the type of vegetation and growth stage (Brutsaert, 2013). The Kc values given in the crop evapotranspiration guidelines for computing crop water requirements-FAO Irrigation and Drainage Paper

56, by Allen, Pereira, Raes, and Smith (1998) was used for the calculation of a weighted Kc value considering various land uses in both watersheds.

2.7.5 The “abcd" model parameters from literature

In the calibration of the "abcd" model, it is very important and convenient to have initial values for the parameters for a good start and to check the reliability of the estimated parameter values. According to Vandewiele et al. (1992); Alley (1984) and Martinez, Gupta (2010), and Lafta et al. (2013) for various catchments which does not have snow fall, it was found that the four parameters (a,b,c,d) have different values as shown in Table 2-1.

Table 2-1: The a,b,c,d parameters form previous studies

Reference	**Vandewiele et al. (1992)**		**Lafta et al. (2013)**	**Alley (1984)**		**Martinez and Gupta, (2010)**	
No of Basins	79		2	10		127	
Parameter	Range	Mean	Mean	Range	Mean	Range	Mean
a	0.96–0.999	0.986	0.994	0.975–0.999	0.992	0.873–0.999	0.977
b	260–1900	475	700	14–50	30	133–922	393
c	0.04–0.70	0.270	0.1	0.01–0.46	0.16	0–1	0.229
d	0.0003–0.415	0.11	0.03	0.07–1.0	0.26	0–1	0.35

2.8 Parameter optimization

Wijesekera (2000) recommends that even though the mathematical indicators help to identify the best fit, it is important to look at the water balance, time series of estimates with respect to the observed rainfall and duration curves to select the best parameter set for the particular catchment.

2.9 Objective functions

2.9.1 Applications of different objective functions by different modelers

According to the Kruse, Boyle, and Base (2005), there are three main concerns of hydrologists to evaluate hydrologic model performance. They are, to provide a quantitative estimate on the model's capability of forecasting the past and future behavior of catchments, to provide a mechanism to evaluate the improvements to the modelling approach by different means and to compare the current modelling work with the previous study results.

For the evaluation of the watershed model performance, different objective functions had been used by different modelers.

Martinez and Gupta (2010) had used Nash–Sutcliffe efficiency (NSE) as the model evaluation criteria for the application of "abcd" monthly water balance model for 764 catchments in the United States. In the model evaluation, if the NSE value is between 1.00~0.75, it was considered as good while considering values between 0.75~0.67 as acceptable, 0.67~0.59 as poor and the values less than 0.59 as bad.

Lafta et al. (2013) had used Mean Squared Error (MSE) as the evaluation criteria to evaluate model performance of "abcd" model for the St. Johns river catchment, Kickapoo river catchment and Leaf river catchment in the United States. The corresponding MSE values for calibration and validation for the St. Johns River catchment and Leaf River catchment are 5.31 & 6.68 and 7.14 & 8.25, respectively. The "abcd" model had not performed well for the Kickapoo river catchment, since the catchment is dominated by snow.

Wijesekera and Rajapakse (2014) had used Mean Ratio of Absolute Error (MRAE) for the calibration and validation of water balance model for Aththanagalu Oya basin in Sri Lanka. The achieved MRAE values for calibration and validation were 0.66 and 0.7 respectively which are not generally considered as appropriate values for a good fit. Further, NSE, Correlation coefficient and R^2 were used for the comparison purpose.

Xiong and Guo (1999) had used NSE, Relative Error (RE) and Relative Maximum Error (RE_m) as objective functions for the evaluation of two- parameter monthly water balance model.

Wijesekera (2000) had used Mean Ratio of Absolute Error (MRAE) as the objective function to evaluate the model performance for Gin Ganga and gained values between 0.2-0.4 as MRAE values for the calibration and verification.

Perera and Wijesekera (2011) have used Mean Ratio of Absolute Error (MRAE) as the objective function for the evaluation of model performance developed for the sub basins of Kalu Ganga, Kelani Ganga and Attanagalu Oya in Sri Lanka. The obtained MRAE values were 0.44, 0.30 and 0.90, respectively for the three sub basins.

According to Gupta, Kling, Yilmaz, and Martinez (2009), MSE and the NSE are the most commonly used objective functions for calibration and validation of hydrological models. But in Sri Lankan context, MRAE also can be considered as famous as an objective function in the modelling of high, medium and low flows.

2.9.2 Evaluation of objective functions

Generally, most of the efficiency criteria had been formulated with the difference between observed value and the simulated value at each time step and by normalizing it with the variability of the relevant observations at each time step. To prevent cancelling out the errors due to opposite signs, when taking the summation of differences between observed and simulated discharge, absolute or the squared errors have been taken in to consideration. This has led to high emphasis on larger errors while neglecting smaller errors. The larger errors are generally associated with high flows which will lead to fitting peak flows of the hydrographs in calibration rather fitting to low flows which may represent base flow (Krause et al., 2005).

2.9.2.1 Nash–Sutcliffe efficiency (NSE)

Nash–Sutcliffe efficiency criteria has been defined as one minus the sum of the squired difference between the observed and simulated values of stream flow at each time step, normalized by the variance of the observed values for the time period under consideration (Nash & Sutcliff, 1970).

$$E = 1 - \frac{\sum_{i=1}^{n}(Oi - Pi)^2}{\sum_{i=1}^{n}(Oi - Om)^2} \tag{13}$$

The range of E can vary between 1.0 and $-\infty$. The condition E=1 indicates the perfect fit while minus values indicates that the mean value of the observed values will be more representative than the model. According to Legates and McCabe (1999), the main disadvantage in NSE is the overestimation of larger values in the time series while neglecting the low flow values.

In runoff predictions, this leads to an overestimation of the model performance at peak flows while underestimation during low flow conditions. Therefore Nash-Sutcliffe is not very sensitive during low flow periods (Krause et al., 2005).

2.9.2.2 Mean Ratio Absolute Error (MRAE)

Mean Ratio Absolute Error have been defined as below;

$$MRAE = \frac{1}{n}\left[\sum \frac{|Yobs - Ycal|}{Yobs}\right] \tag{14}$$

This efficiency criteria indicates, the degree of matching of observed and calculated stream flow hydrographs and gives an average relative error of model output with reference to a given observed stream flow (Wijesekera, 2000).

Further, by using MRAE as the objective function for the model evaluation of Gin Ganga, Wijesekera (2000) has shown that MRAE can be used successfully to evaluate the model performance for high, medium and low stream flows. At the modelling of two low lying urban watersheds in the Greater Colombo area of Sri Lanka, Wijesekera and Ghanapala (2003) had used MRAE as the model evaluation criteria to match high, medium and low flows successful.

2.9.2.3 Relative Error (RE)

Relative error (RE) is defined as the volumetric fit between the observed runoff series and the simulated series, which is expected to close to zero for a good simulation (Xiong & Guo, 1999).

$$\mathrm{RE} = \sum(\mathrm{Qobs} - \mathrm{Qsim}) / \sum \mathrm{Qobs} \; \mathrm{X} \; 100\% \qquad (15)$$

2.9.2.4 Ratio of Absolute Error to Mean (RAEM)

This objective function indicates the ratio between observed and calculated discharge with respect to the mean of the observed flows. Therefore, it is obvious that RAEM will not be reliable when the mean of the observed values is not properly representing the flow data series. But this objective function had been recommended by WMO guidelines and used by Priyani (2016) for the comparison purpose along with MRAE in her study for Kalu Ganga basin.

$$\mathrm{RAEM} = \frac{1}{\mathrm{n}} \left[\sum \frac{|\mathrm{Yobs} - \mathrm{Ycal}|}{\overline{\mathrm{Yobs}}} \right] \qquad (16)$$

The summary of the above evaluation of objective functions has been shown in terms of their performance for high, moderate and low flows considering different model applications as shown in Table 2-2.

Since "abcd" model has a separate groundwater compartment which facilitates to simulate the base flow which stands as a requirement to model low and moderate flows in dry periods, and the model application is for water resources planning and management, MRAE is much suitable as the objective function in this study along with NSE for comparison.

Table 2-2 - Evaluation of objective functions

Objective function	Performance	Relevant Literature
NSE	Very good in high flows, Poor in medium in low flows	Research publication by Xiong & Guo, (1999) had showed that NSE can be used for Peak flow estimation. But, sometimes overestimation of the model performance during peak flow could occur (Legates and McCabe ,1999).
MRAE	Very good for high, medium and low flows	Study carried out by Wijesekera & Ghnanapala, 2003; Wijesekera, 2000 shows that the MRAE can be used well for high, medium and low flows matching.
RE	Good for high, medium and low flows	Xiong & Guo, 1999 had used RE along with NSE successfully in evaluating the model performance
RAEM	Good for high, medium and low flows	Not commonly used in the modelling studies, Priyani (2016) had used successfully

2.10 Warm up period and initial values for soil moisture and groundwater storage for water balance models

Since ‘abcd’ model has a soil moisture compartment and a ground water compartment in the model structure, initial values are needed for the initial soil moisture content and groundwater storage.

Initialization bias occurs when a model is started in an unrealistic state which needs modifications for the initial value and generally this occurs in non-terminating simulations, but it can also take place in terminating simulations (Hoad, Robinson, & Davies, 2008). According to Robinson (2004), there are five main methods for dealing with initialization bias as follows;

1. Run-in model for a warm-up period until it reaches a realistic condition (steady state for nonterminating simulations). Delete data collected from the warm-up period.

2. Set initial conditions in the model so that the simulation starts in a realistic condition.
3. Set partial initial conditions then warm-up the model and delete warm-up data.
4. Run model for a very long time making the bias effect negligible.
5. Estimate the steady state parameters from a short transient simulation run (Sheth-Voss, Willemain, & Haddock, 2005).

In hydrological modelling, calculation of warm up period is important. Robinson (2004) has categorized the available methods in calculating warm up period in to five main categories as below;

1. Graphical methods – Truncation methods that involve visual inspection of the time-series output and human judgement.
2. Heuristic approaches – Truncation methods that provide (simple) rules for determining when to truncate the data series, with few underlying assumptions.
3. Statistical methods – Truncation methods that are based upon statistical principles.
4. Initialization bias tests – Tests for whether there is any initialization bias in the data. They are therefore, not strictly methods for obtaining the truncation point but they can be adapted to do so in an iterative manner or can be used in combination with the above truncation methods to ascertain whether they are working sufficiently.
5. Hybrid methods – A combination of initialization bias tests with truncation methods to determine the warm-up period.

According to Xiong and Guo (1999), the initial value for soil moisture (S_0) has some effect on the model performance and it will be more important in cases where the data period is less. For the two parameter model, 150-200 mm value had been taken as S(0) and it had been re-estimated by using the mean value of the soil water content values in the positions of having same rank of the cycle. Xiong and Guo (1999) had considered the cycle period as one year and estimated the S(0) as ;

$$S(0) \approx \sum_{j=1}^{m} S(j \times 12)/m \qquad (17)$$

where m is the number of years of the calibration data series, i.e. m = Nc/12, Nc is the number of months in the calibration period. If the cycle period is one year, the values of S(12), S(24), S(36) etc. cannot be very much different.

At the first development of “abcd” monthly water balance model, Thomas (1981) had assumed trial values as initial values for the soil moisture and ground water with a tentative a,b,c and d parameter set and routed the system over 8 cycles until the initial soil moisture and ground water storages attained a quasi-steady state.

By studying the above literature, it is apparent that different modelers had used different methods to handle the warm up period and initial moisture content in modelling exercise. For this study, considering the first method of Robinson (2004), the model will be routed for number of cycles until the soil moisture and ground water storages are achieved the quasi-steady state by using arbitrary values as initial values.

2.11 Rainfall interpolation method

There are number of rainfall interpolation methods available. According to Mahalingam, Deldar, and Vinay (2015), Kriging Ordinary method is highly suitable for rainfall interpolation in comparison with Inverse Distance Weighting (IDW), Natural Neighbor, Spline and Trend methods. But in this study, Thiessen polygon method had not been taken for comparison which is very famous among hydrologists in Sri Lanka.

In the development of daily YHyM/BTOPMC distributed model for Gin Ganga basin, Wickramaarachchi et al. (2012) had used the Thiessen polygon method for the spatial distribution of rainfall data in the basin. Therefore, considering the simplicity and its validity for water balance modelling, Thiessen polygon method was used as the rainfall interpolation method in this research.

2.12 Literature review summary

Out of the different types of hydrologic models in the model classification, a lump model was selected for the study. The applicability of hydrologic models under different temporal resolutions were studied and monthly resolution was selected for the research. Considering the objectives of the research, ‘abcd’ model was selected which is a lump monthly model having four parameters. The model structure and the function of the parameters were identified in detail by reviewing different applications of the ‘abcd’ model. Pan Evaporation Model of Doorenbos and Pruitt (1975) was selected as the calculation method of potential evapotranspiration which is one of the inputs, considering the availability of pan evaporation data relevant to the selected catchments. For the interpolation of rainfall, Thiessen polygon method was selected considering its simplicity in application and wide usage among hydrologists in Sri Lanka even for distributed hydrologic models. In the model application, as initial values of soil moisture and ground water, arbitrary values can be used as used in the two parameter model application by Xiong and Guo (1999) and in the “abcd” model by Thomas (1981). When the arbitrary values are used for initial soil moisture and ground water storages, warm up period has to be handled, not affecting the model performance. For that, model can be run for number of cycles until it reaches the quasi-steady state as Thomas (1981) had done in applying “abcd” model by incorporating one of the methods proposed later by Robinson (2004). For the parameter optimization, MRAE was selected as the objective function, considering it’s suitability for the performance evaluation specially in moderate and low flow regimes and wide range of applications among Sri Lankan hydrologists.

3 METHODOLOGY AND MATERIALS

3.1 Methodology brief

The research problem was identified by conducting a background study on the current modelling practices in Sri Lanka for Kalu and Gin river basins and the main objective was defined based on those information and findings. The selection of the watersheds was achieved mainly by considering the data availability and the possibility of high water demand in future, with the urbanization and risk of water deficits in wet zone of Sri Lanka due to the climate change and catchment modifications. The specific objectives were defined benchmarking the overall objective, by showing the intermediate milestones that must be passed to achieve the overall objective.

After finalizing the objectives, literature survey was conducted following the identification of the key aspects to be studied according to the defined specific objectives. First, an appropriate lump monthly model with appropriate number of parameters was selected based on the literature review, considering the research question, time constraints, data availability, cost and model simplicity. For the selected model, a further refined literature survey was carried out to find an appropriate data period for the data collection. Subsequently, the literature survey was conducted to select an appropriate objective function to evaluate the model performance and a suitable method for the calculation of potential evapotranspiration. In addition, previous modelling work related to 'abcd' model was studied, and model parameter ranges were identified which were helpful in model calibration and parameter sensitivity analysis. The literature regarding model warm up period was studied to set the initial soil moisture and groundwater storages for the model.

The data collection was undertaken considering the input requirements of the model and checked by using recommended methods. The data set was divided into two sets, as old half for calibration and the latest half for validation and the "abcd" hydrologic model was developed and checked, accordingly. The initial parameters were selected by using the values in the literature. Then the model was calibrated and validated by using appropriate data sets and parameter sensitivity analysis was conducted by using the methods identified in the literature review. Relevant water resources investigation applications were identified, and the applicability of the model was demonstrated for water resources investigation.

3.2 Methodology flow chart

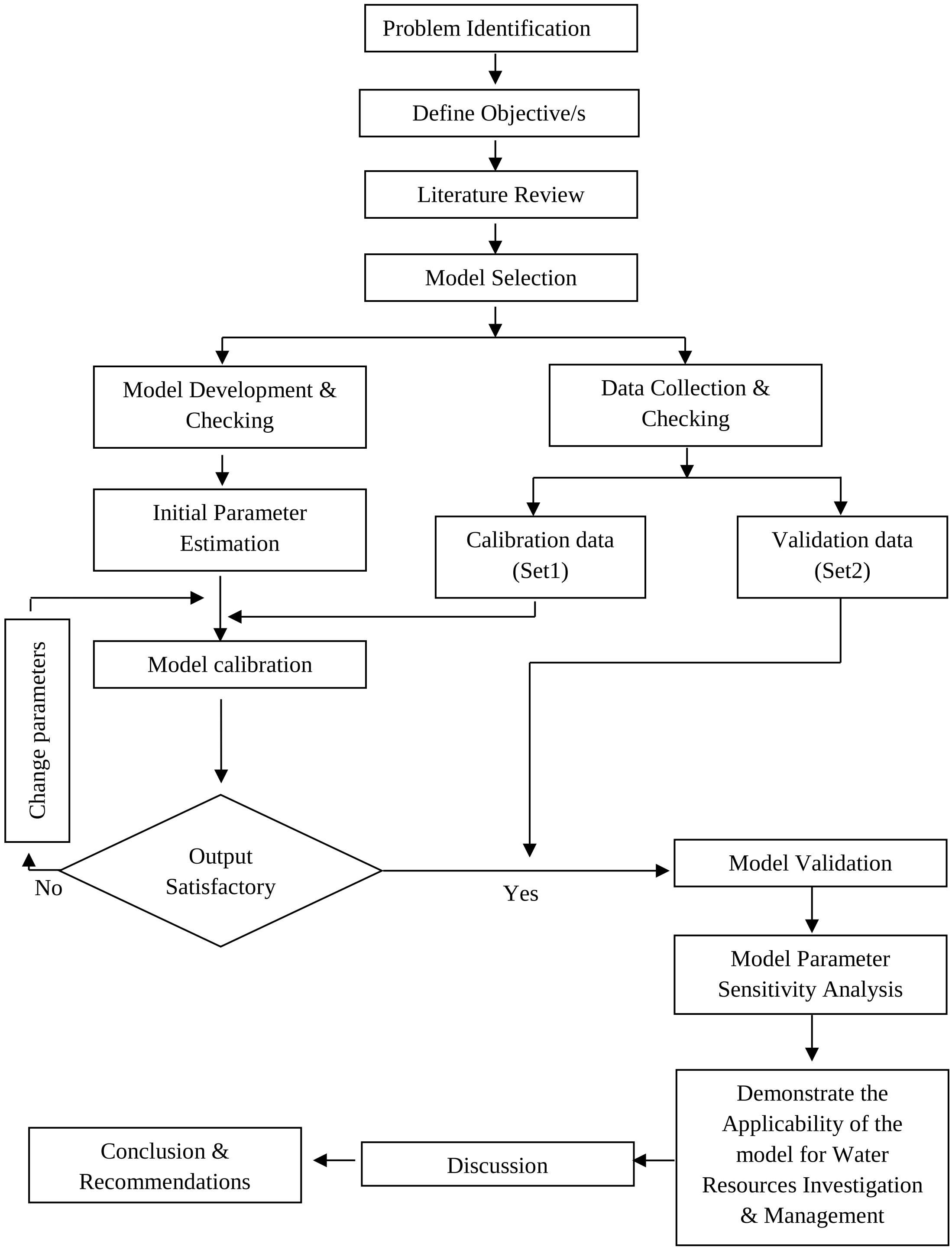

Figure 3-1: Methodology flow chart

3.3 Study sites

3.3.1 Ellagawa watershed

Ellagawa watershed is a sub watershed of Kalu Ganga basin which has been shown in Figure 3-2, which is about 1383 km^2 in size and situated in Rathnapura district bordering the Kelani Ganga basin from North and Walawe Ganga basin from East and Gin Ganga basin from South. The selected watershed is in wet climatic zone of Sri Lanka. The major soil type of the watershed is Red-Yellow Podzolic while having a hilly, rolling terrain type. The Average temperature of the watershed is about 27 ^{o}C.

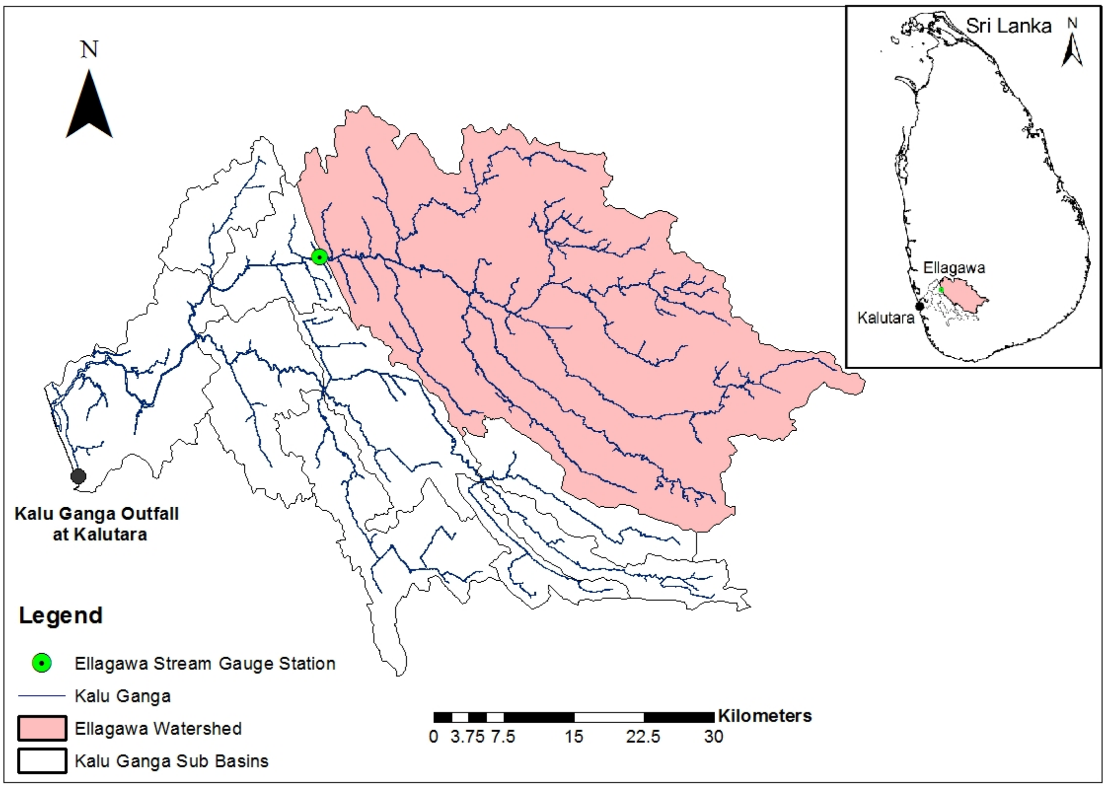

Figure 3-2: Ellagawa watershed and stream network

The details regarding the administrative boundaries and the stream networks has been shown in Table 3-1 .

Table 3-1: Summary of Ellagawa Watershed

Kalu Ganga Basin (km^2)	2784
Watershed at Ellagawa (km^2)	1383
Province	Western Province
District	Rathnapura
Main Stream Length (km)	428
Drainage Density (km/km^2)	0.3

According to the latest land use maps which has been updated by Survey Department of Sri Lanka in 2003, the Ellagawa watershed contains 25% rubber cultivations, 20% coconut cultivations, 15% forest, 17% homesteads /gardens and other land uses as shown in Figure 3-3 and Table 3-2.

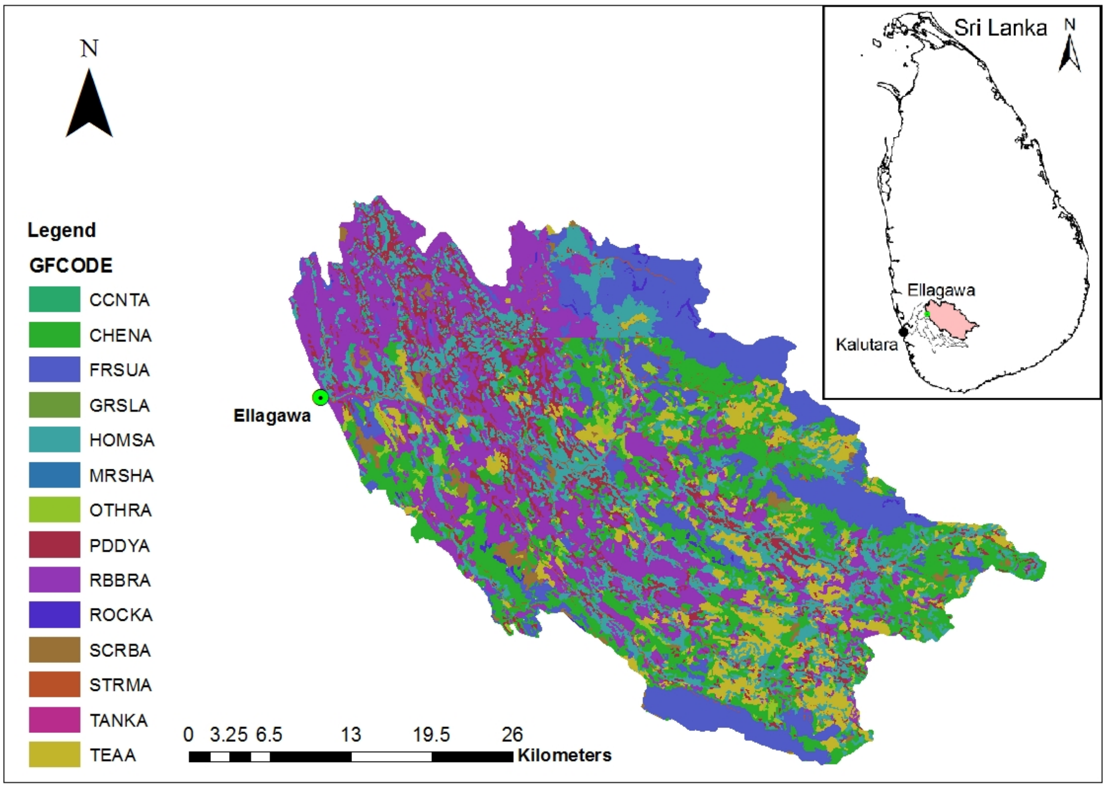

Figure 3-3: Land use of Ellagawa Watershed at Kalu Ganga

Table 3-2: Land use Details of Ellagawa Watershed

#	GF Code	Land use type	Area (km^2)	Area (%)
1	CCNTA, CHENA	Coconut	281.306	20.342
2	FRSUA	Forest-Unclassified	217.173	15.704
3	GRSLA	Grass Land	1.198	0.087
4	HOMSA	Homesteads/Garden	248.403	17.963
5	MRSHA	Marsh	0.222	0.0160
6	OTHRA	Other Cultivation	26.657	1.928
7	PDDYA	Paddy	94.169	6.810
8	RBBRA	Rubber	350.140	25.319
9	ROCKA	Rock	5.782	0.418
10	SCRBA, TANKA	Scrub land	21.707	1.570
11	STRMA	Stream	19.153	1.385
12	TEAA	Tea	116.980	8.459
Total			1382.89	100%

3.3.2 Thawalama watershed

Thawalama watershed is a sub watershed of Gin Ganga basin (Figure 3-4) which is about 360 km^2 in size situated in Galle and Matara districts bordering Kalu Ganga basin from North and Nilwala Ganga basin from South. The selected watershed is in wet climatic zone of Sri Lanka. The major soil type of the watershed is Red-Yellow Podzolic while having a hilly, rolling terrain type. The Average temperature of the watershed is about 28 ˚C. The other details regarding the administrative boundaries and the stream networks have been shown in Table 3-3.

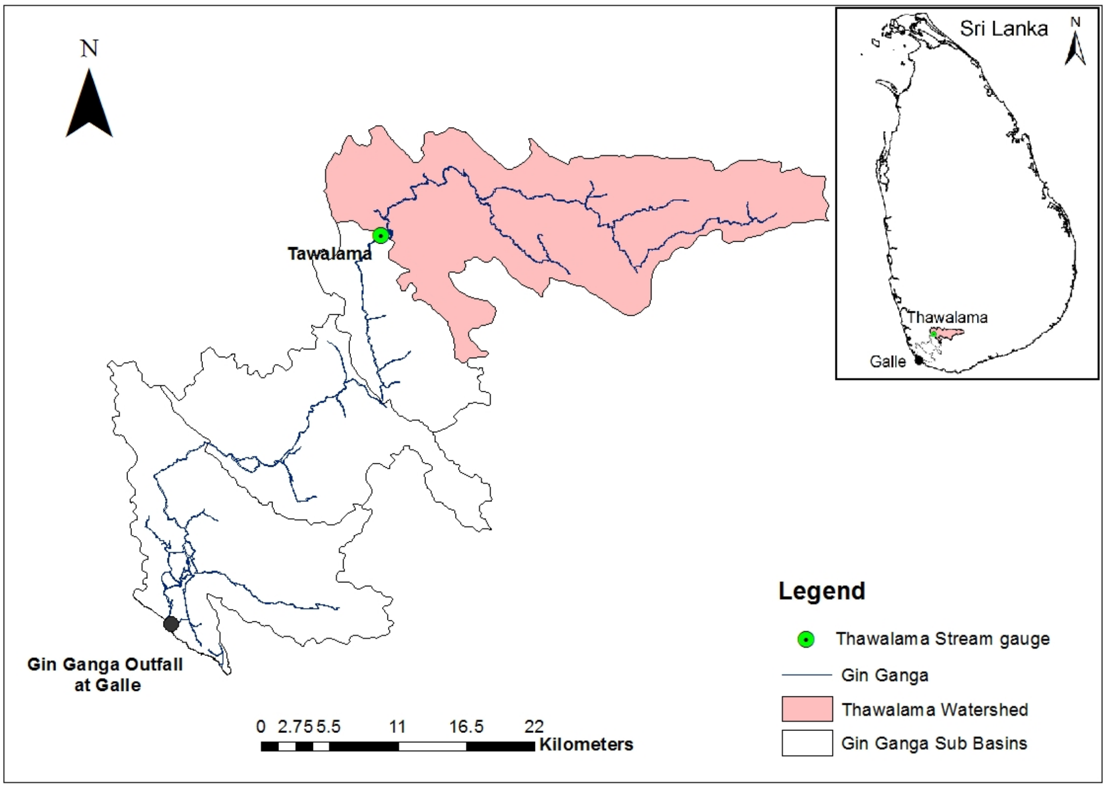

Figure 3-4: Thawalama watershed and stream network

According to the latest land use maps which has been updated by Survey Department of Sri Lanka in 2003, the Thawalama watershed contains 34% unclassified forests, 25% tea cultivations, 11% scrub lands, 8% homesteads /gardens and other land uses as shown in Figure 3-5 and Table 3-4.

Table 3-3: Summary of Thawalama watershed

Gin Ganga Basin (km^2)	924
Watershed at Thawalama (km^2)	360
Province	Southern Province
District	Galle and Matara
Main Stream Length (km)	74
Drainage Density (km/sqkm)	0.2

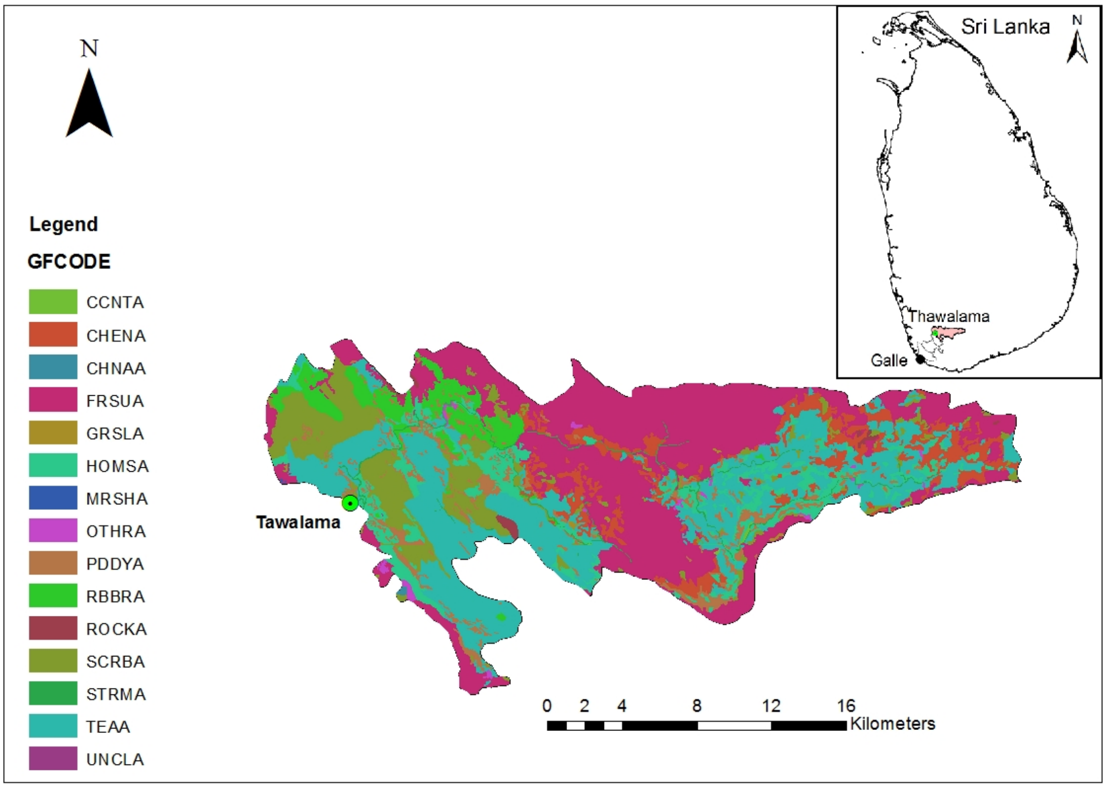

Figure 3-5: Land use in Thawalama watershed at Gin Ganga

Table 3-4: Land Use Details of Thawalama Watershed

#	GF Code	Land use type	Area (km^2)	Area (%)
1	CCNTA, CHENA, CHNAA	Coconut	31.276	8.687
2	FRSUA	Forest-Unclassified	122.799	34.106
3	GRSLA	Grass Land	0.501	0.139
4	HOMSA	Homesteads/Garden	31.396	8.720
5	MRSHA	Marsh	0.049	0.014
6	OTHRA	Other Cultivation	1.881	0.522
7	PDDYA	Paddy	18.383	5.106
8	RBBRA	Rubber	18.575	5.159
9	ROCKA	Rock	1.635	0.454
10	SCRBA	Scrub land	39.830	11.062
11	STRMA	Stream	3.978	1.105
12	TEAA	Tea	89.736	24.923
13	UNCLA	Unclassified	0.007	0.002
Total			360.046	100%

3.4 Data collection

Data collection regarding rainfall, evaporation and stream flow was done complying the guidelines of World Meteorological Organization (WMO), from the Department of Meteorology and Department of Irrigation of Sri Lanka which are the responsible state organizations to maintain the data bases of above data. For the demarcation of sub watershed at Thawalama, in Gin Ganga basin and Ellagawa at Kalu Ganga basin, the basin maps developed by Department of Agrarian Services Development were used.

3.4.1 Data collection for Ellagawa watershed

For the study, five rain gauge stations were selected, namely Keragala, Galature Estate, Rathnapura, Alupola Group and Wellandura Estate which are located inside the Ellagawa watershed as shown in Figure 3-6. The selected evaporation station is Rathnapura which is also located inside the watershed and Ellagawa is the stream gauge location which is the point of interest for the demarcation of watershed. The main criteria of selection of the stations were the availability of data for the selected period and the location with respect to the watershed. The selected period for data checking was 1980 October to 2010 September (30 years).

Table 3-7 summarizes the location details of the gauging station data. The general details of the Ellagawa watershed, data resolutions & data sources and the station density verses WMO guidelines have been shown in Table 3-5 and Table 3-6, respectively.

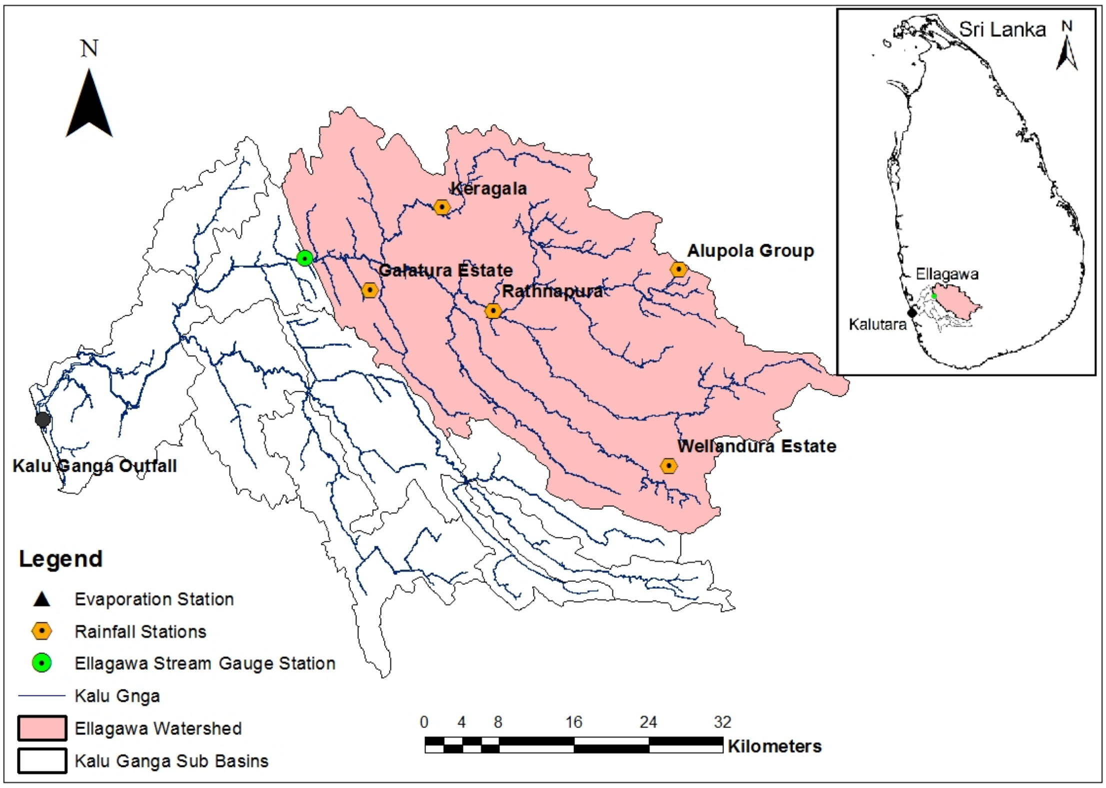

Figure 3-6: Ellagawa Watershed and Gauging Stations

Table 3-5: Data Sources and resolutions for Ellagawa Watershed at Kalu Ganga

Data Types	**Temporal Resolution**	**Spatial Resolution (km^2/station)**	**Data Period**	**Source**
Rainfall	Monthly	276.6	1980-2010	Dept. of Meteorology
Evaporation	Monthly	1383	1980-2010	Dept. of Meteorology
Stream flow	Monthly	1383	1980-2010	Dept. of irrigation
Topo maps	N/A	1:50000	Updated 2003	Dept. of Survey
Land Use	N/A	1:50000	Updated 2003	Dept. of Survey

Table 3-6: Distribution of Gauging Stations at Ellagawa Watershed at Kalu Ganga

Gauging Station	**Number of Stations**	**Station density (km^2/station)**	**(WMO , 2009) (km^2/station)**
Rainfall	5	276.6	575
Stream flow	1	1383	1875
Evaporation	1	1383	-

Table 3-7: Rainfall, Streamflow and Evaporation Gauging Station Details of Ellagawa Watershed

Station	Location Coordinates		District
	Longitude	Latitude	
Rainfall Stations			
Alupola Group	80° 34' 48" N	06° 43' 12" E	Rathnapura
Galatura Estate	80° 16' 48" N	06° 42' 00" E	Rathnapura
Rathnapura	80° 24' 00" N	06° 40' 48" E	Rathnapura
Wellandura Estate	80° 34' 12" N	06° 31' 48" E	Rathnapura
Keragala	80° 21' 00" N	06° 46' 48" E	Rathnapura
Stream flow Stations			
Ellagawa	80° 13' 00" N	06° 43' 53" E	Kalutara
Evaporation Station			
Rathnapura	80° 24' 00" N	06° 40' 48" E	Rathnapura

3.4.2 Data collection for Thawalama watershed

For the study, four rain gauge stations were selected, Kudawa, Dependene Group, Anningkanda and Millewa Estate which are located outside the watershed except Anningkanda as shown in Figure 3-7. The selected evaporation station is Rathnapura which is also located outside of the watershed and Thawalama is the stream gauge location which is the point of interest for the demarcation of watershed. The main criteria of selection of the stations were the availability of data for the selected period and the location with respect to the watershed. The selected period for data checking was 1980 October to 2011 September (31 years).

Table 3-10 summarizes the location details of the gauging station data. The data resolutions, data sources and the station density verses WMO guidelines have been shown in Table 3-8 and Table 3-9, respectively.

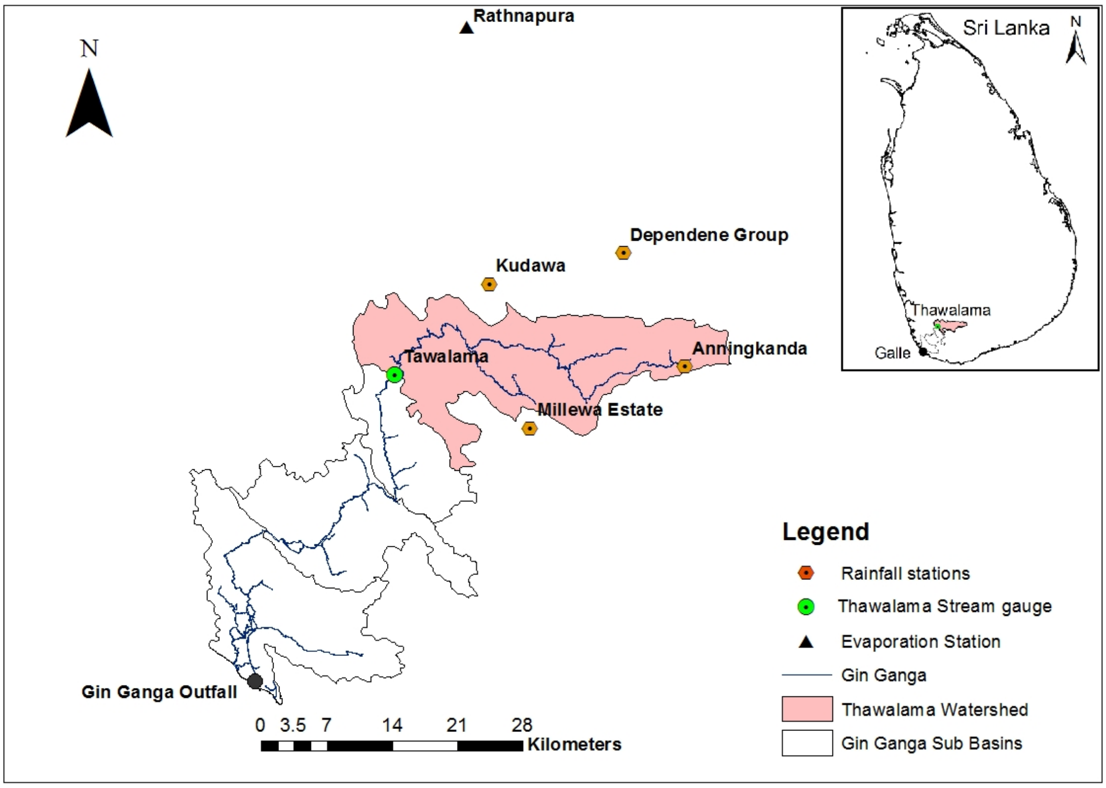

Figure 3-7: Thawalama Watershed and Gauging Stations

Table 3-8: Data Sources and resolutions for Thawalama Watershed in Gin Ganga

Data Types	**Temporal Resolution**	**Spatial Resolution (km^2/station)**	**Data Period**	**Source**
Rainfall	Monthly	90	1980-2011	Dept. of Meteorology
Evaporation	Monthly	360	1980-2011	Dept. of Meteorology
Stream flow	Monthly	360	1980-2011	Dept. of irrigation
Topo maps	N/A	1:50000	Updated 2003	Dept. of Survey
Land Use	N/A	1:50000	Updated 2003	Dept. of Survey

Table 3-9:Distribution of Gauging Stations at Thawalama Watershed at Gin Ganga

Gauging Station	**Number of Stations**	**Station density (km^2/station)**	**WMO Standards (km^2/station)**
Rainfall	4	90	575
Stream flow	1	360	1875
Evaporation	1	360	-

Table 3-10:Rainfall, Stream flow and Evaporation Station Details of Thawalama Watershed

Station	Location Coordinates		District
	Longitude	Latitude	
Rainfall Stations			
Kudawa	80° 25' 12" N	06° 25' 48" E	Rathnapura
Dependene Group	80° 33' 00" N	06° 27' 36" E	Rathnapura
Anningkanda	80° 36' 36" N	06° 21' 00" E	Matara
Millewa Estate	80° 27' 36" N	06° 17' 24" E	Matara
Stream flow Stations			
Thawalama	80° 19' 50" N	06° 20' 33" E	Galle
Evaporation Station			
Rathnapura	80° 24' 00" N	06° 40' 48" E	Rathnapura

3.5 Thiessen averaged rainfall

Thiessen polygon method was selected as the rainfall interpolation method based on the findings of the literature review. Thiessen polygons were drawn by using Arc GIS as shown in Figure 3-8 and Figure 3-9 for each rain gaging stations for corresponding watersheds in Kalu Ganga and Gin Ganga to calculate the Thiessen weights as shown in Table 3-11 and Table 3-12.

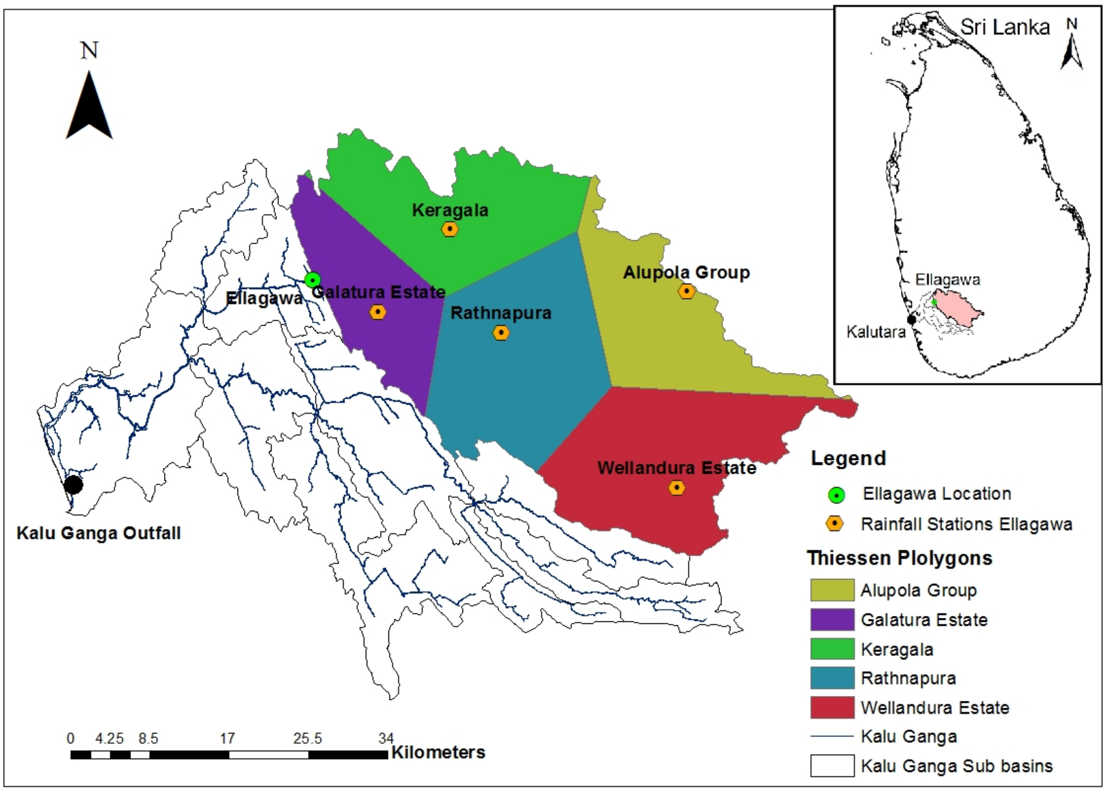

Figure 3-8: Thiessen Polygons for Rainfall Stations- Ellagawa Watershed

Table 3-11: Thiessen polygon Area and Weights for Ellagawa Watershed

Rain Gauge Station	Thiessen Area (km^2)	Thiessen Weight
Alupola Group	236.568	0.171
Galatura Estate	192.500	0.139
Rathnapura	339.982	0.246
Wellandura Estate	333.080	0.241
Keragala	280.757	0.203

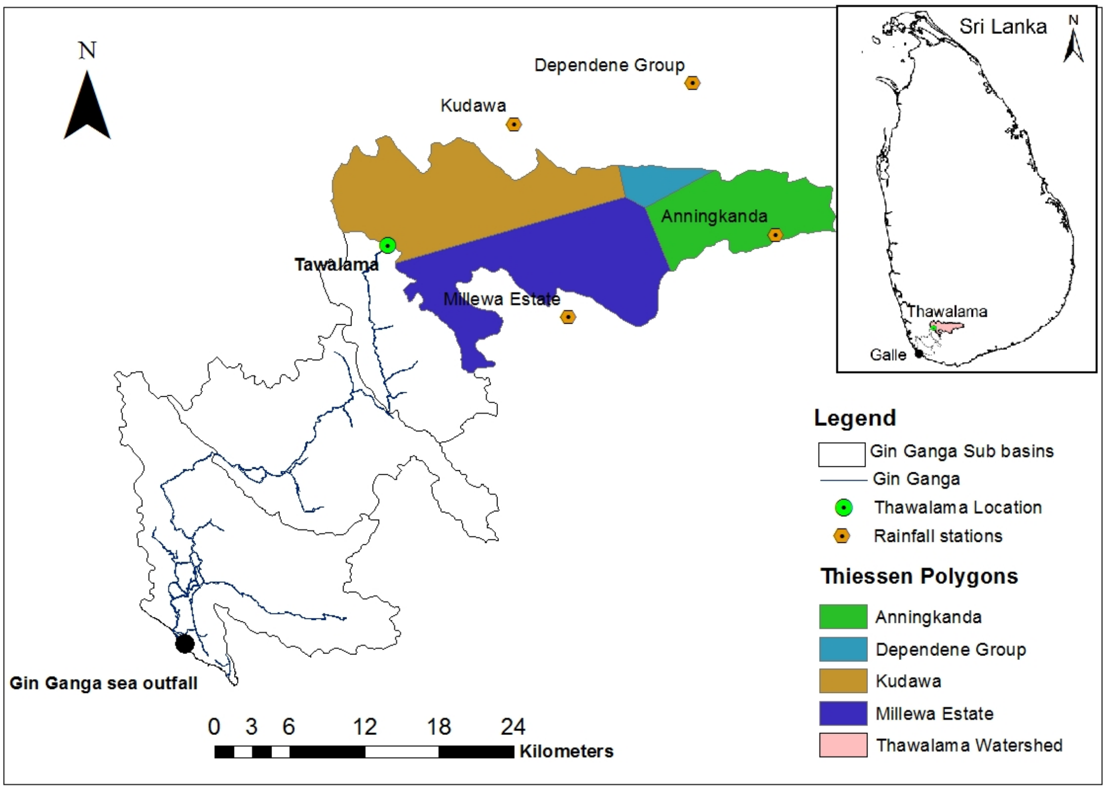

Figure 3-9: Thiessen Polygons for Rainfall Stations-Thawalama Watershed

Table 3-12: Thiessen Polygon Area and Weights for Thwalama Watershed

Rain Gauge Station	Thiessen Area (km^2)	Thiessen Weight
Kudawa	134.895	0.375
Dependene Group	14.882	0.041
Anningkanda	75.988	0.211
Millewa Estate	134.280	0.373

3.6 Data checking

3.6.1 General

For the considered data period in both Gin Ganga and Kalu Ganga, rainfall data, streamflow data and pan evaporation data were checked by using standard data checking methods. Under data checking, visual data checking, missing data identification and filling, consistency check, annual water balance, seasonal water balance, runoff coefficient check were performed.

3.6.2 Visual data checking

The main purpose of visual data check is to check the response of the flow to the rainfall which is considered as the most important aspect in water balance modelling. Following procedure was followed in visual data checking;

❖ First, the rainfall data set was checked for the quantity of missing values. According to the general consensus, the missing data quantity should be less than 10% of total values for a considered station. Under Table 3-13 and Table 3-14, the missing data percentages for the two watersheds have been summarized and it shows that in all the stations, missing data percentages are less than 10%.

Table 3-13: Summary of Missing Values - Ellagawa Watershed

Station	Number of missing values	Missing values as a % of total values (total-12x30=360)
Rain Gauging Station		
Alupola Group	0	0.0
Galatura Estate	2	0.6
Rathnapura	0	0.0
Wellandura Estate	19	5.3
Keragala	16	4.4
Stream Gauging Station		
Ellagawa	1	0.3
Pan Evaporation Station		
Rathnapura	6	1.7

Table 3-14: Summary of Missing values- Thawalama Watershed

Station	Number of missing values	Missing values as a % of total values (total-12x31=372)
Rain Gauging Station		
Kudawa	12	3.2
Dependene Group	5	1.3
Anningkanda	4	1.1
Millewa Estate	6	1.6
Stream Gauging Station		
Thawalama	1	0.3
Pan Evaporation Station		
Rathnapura	6	1.6

❖ The Thiessen averaged rainfall verses observed stream flow was plotted by neglecting the months of having missing data for preliminary inspection of the streamflow response. It was observed that the stream flow shows a good response for the rainfall except for very few months.

❖ The missing rainfall data were filled by using liner regression method, in such a way to satisfy the R^2 value of the linear relationship is greater than 0.5. The missing values of stream flow and pan evaporation were filled by using the monthly averages of total data period.

❖ After filling the missing data, Thiessen averaged rainfall was calculated for respective months and the visual check was done in monthly basis, to check the response of the stream flow which has been shown in Figure A-2.1 and Figure A-2.2 in Appendix A and Figure B-2.1 and Figure B-2.2 in Appendix B for Ellagawa and Thawalama watersheds respectively. By that poor responses were identified and highlighted in corresponding figures.

❖ Since, some poor responses were observed in monthly temporal resolution, annual stream flow was plotted against annual Thiessen averaged rainfall to check the visual response in annual temporal resolution as shown in Figure 3-10 and Figure 3-11.

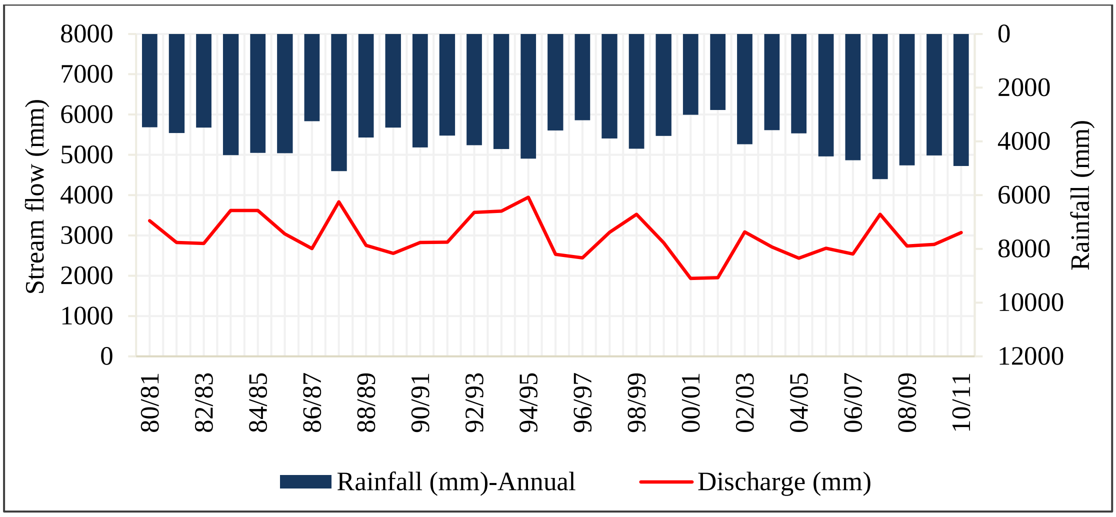

Figure 3-10: Annual Comparison of Rainfall and Streamflow-Gin Ganga

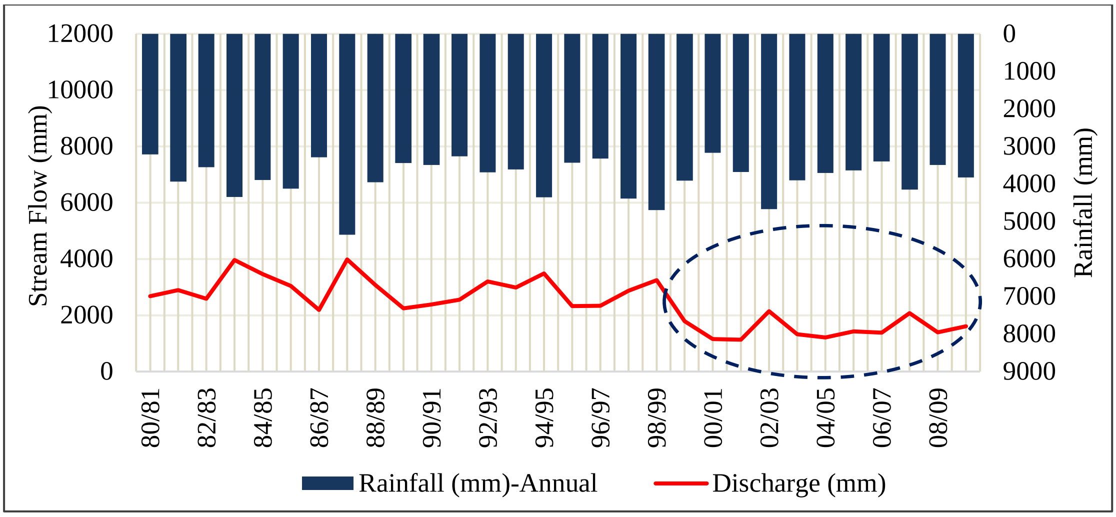

Figure 3-11: Annual Comparison of Rainfall and Streamflow-Kalu Ganga

According to the annual visual check of annual stream flow data, a sudden reduction of flow was observed in Ellagawa stream flow data from year 2000 onwards as shown in Figure 3-10. But within that period a reduction of rainfall was not observed. Appropriate response in stream flow was observed in Gin river data.

3.6.3 Co-relation between the stream flow and rainfall data

The correlation between observed stream flow and Thiessen averaged rainfall was checked for Gin Ganga and Kalu Ganga in monthly basis as shown in Figure 3-12 and Figure 3-13. The got R^2 values were 0.6655 and 0.5777, respectively, which showed an acceptable correlation since R^2 is greater than 0.5.

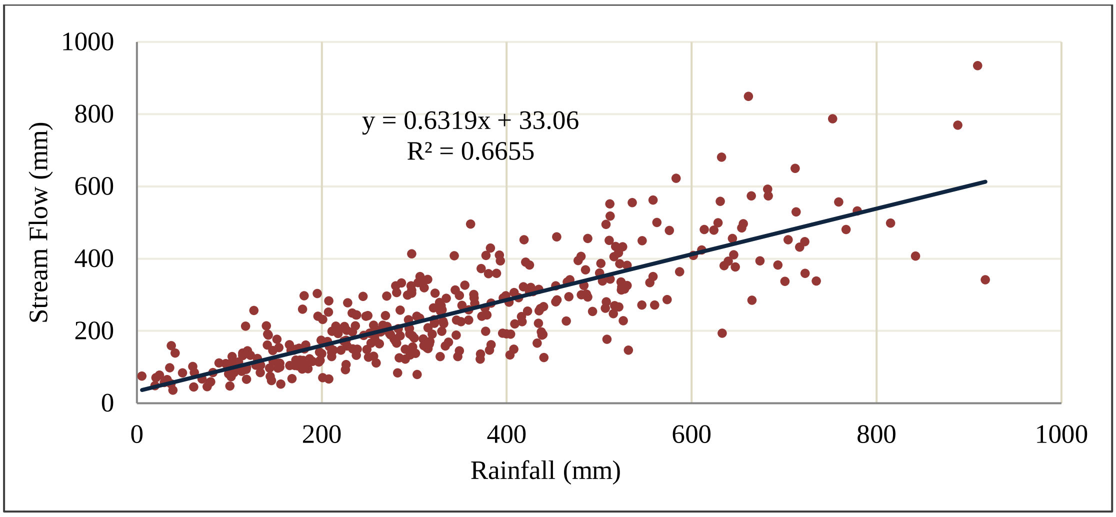

Figure 3-12: Correlation between monthly observed stream flow and Rainfall-Gin Ganga

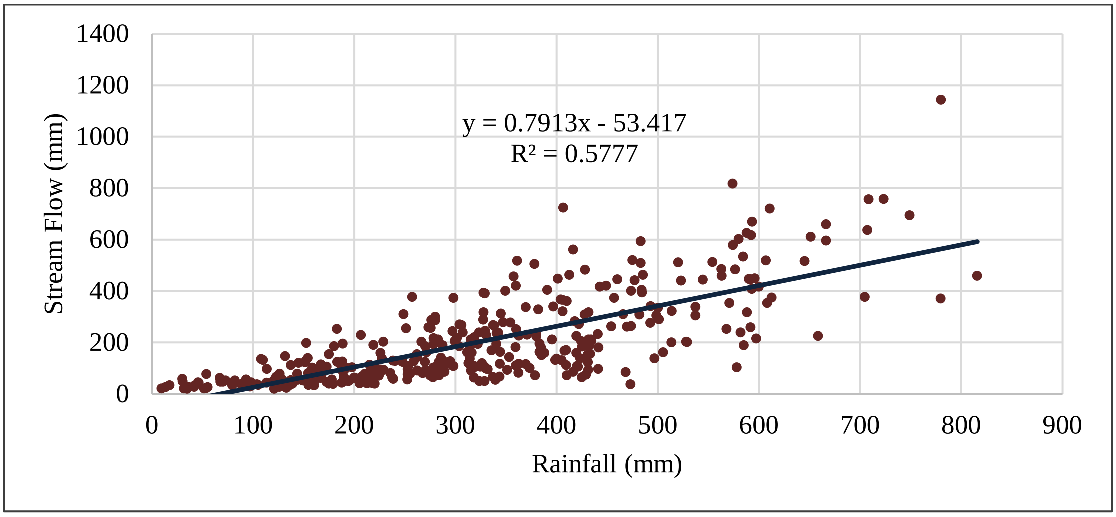

Figure 3-13: Correlation between monthly observed streamflow and Rainfall- Kalu Ganga

Further, a monthly visual comparison was done in annual basis to check whether is there any unrealistic variation of rainfall, streamflow and pan evaporation as shown in Figure A-2.3 and Figure B-2.3 in Appendix A and Appendix B, respectively. But for both watersheds, considerable unrealistic variations were not found.

3.6.4 Single mass curve analysis

Single mass curve analysis was carried out for the rainfall, stream flow and evaporation data considering the consistency in annual cycles, which is the same concept of linear regression, which is used successfully to estimate the missing rainfall (Sharifi, 2015; Caldera, Piyathisse, & Nandalal, 2016).

3.6.4.1 Single mass curve analysis for rainfall data

Single mass curves were plotted for all the rainfall stations in one graph to check the consistency of rainfall data and to observe the relative variation as shown in Figure 3-14 and Figure 3-16 for Ellagawa and Thawalama watersheds. Further, the consistency was checked in the Thiessen averaged rainfall data as shown in Figure 3-15 and Figure 3-17, since it will directly affect the monthly water balance.

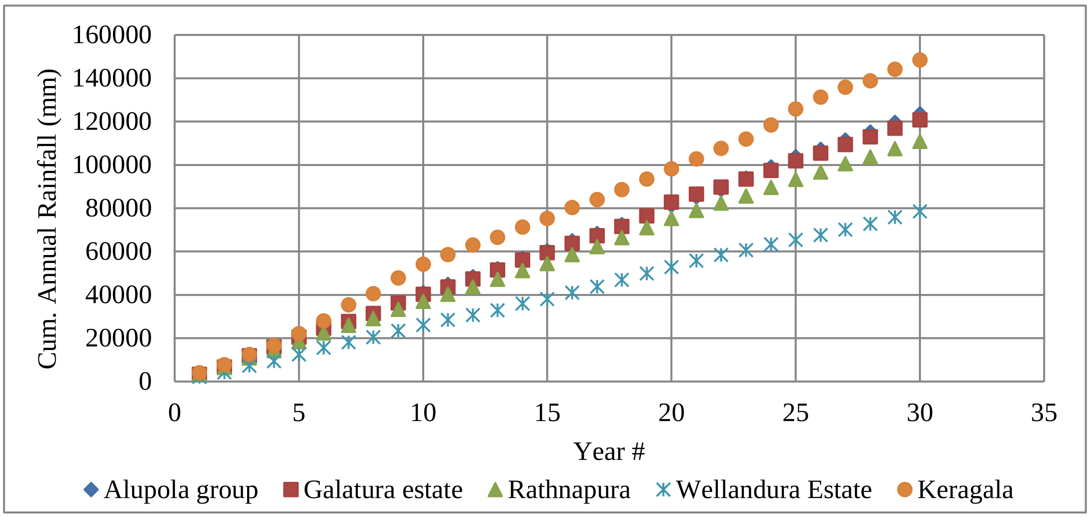

Figure 3-14: Single Mass Curves for rain gauging stations - Ellagawa Watershed

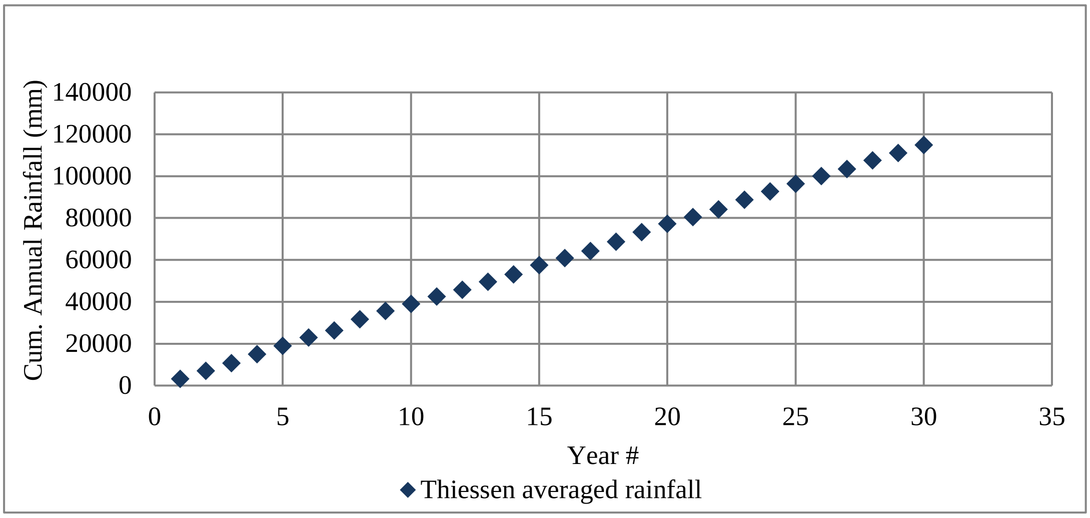

Figure 3-15: Single Mass Curve for Thiessen Averaged rainfall of Ellagawa Watershed

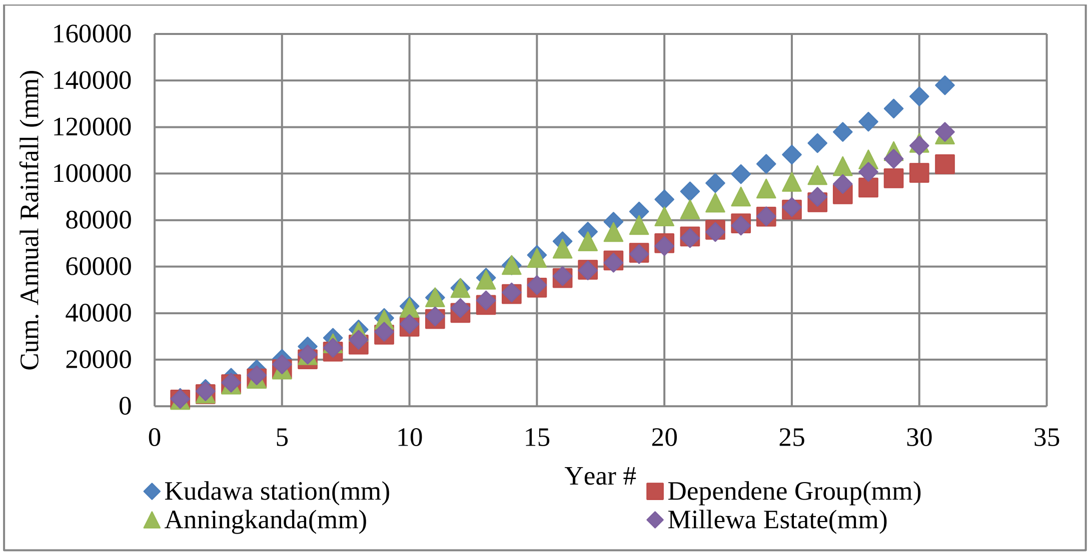

Figure 3-16: Single Mass Curves- Thawalama Watershed

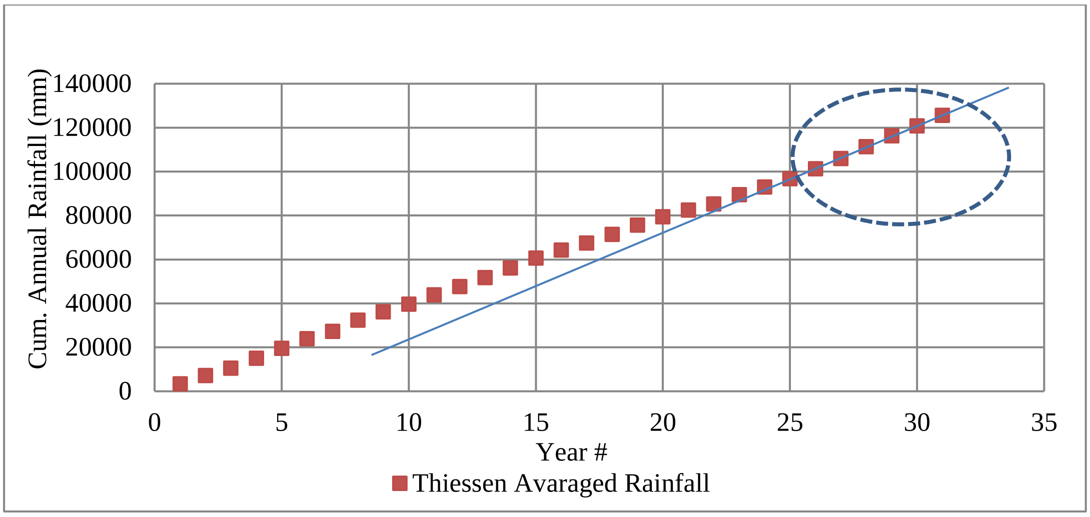

Figure 3-17: Single Mass Curve for Thiessen Averaged rainfall of Thawalama Watershed

A good consistency was observed in rainfall data of selected stations in Ellagawa watershed. The consistency was checked by the uniformity of the gradient of the single mass curves.

A poor consistency was observed in Millewa Estate after 2005, as shown in Figure 3-18. Since the Millewa Estate station is having the second highest Thiessen weight which is 0.373 as per Table 3-12, it has adversely affected on the overall consistency of Thiessen averaged rainfall of the Thawalama watershed as shown in Figure 3-17.

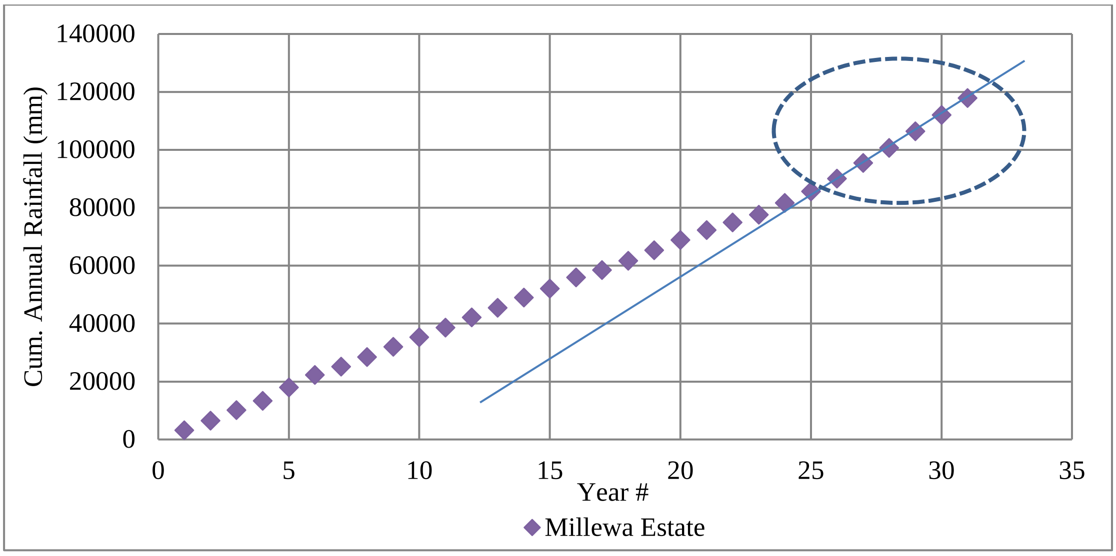

Figure 3-18: Single Mass Curve of Millewa Estate

3.6.4.2 Single mass curve analysis for stream flow data

Single mass curves were plotted as shown in Figure 3-19 and Figure 3-20 for stream flow data at Ellagawa and Thawalama stream gauging stations to check the consistency of the streamflow data. A good consistency was observed in Thawalama Stream flow data considering the uniformity of the gradient of corresponding single mass curve while observing a considerable inconsistency in Ellagawa stream flow data from year 2000 onwards according to Figure 3-19, verifying the observations done in annual visual data checking as shown in Figure 3-11.

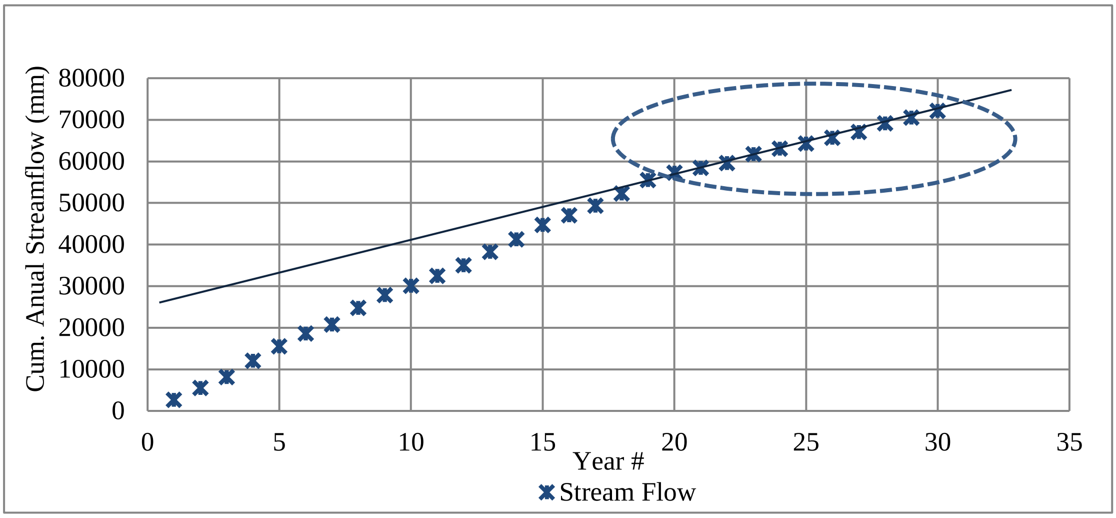

Figure 3-19: Single Mass Curve for Stream flow data at Ellagawa

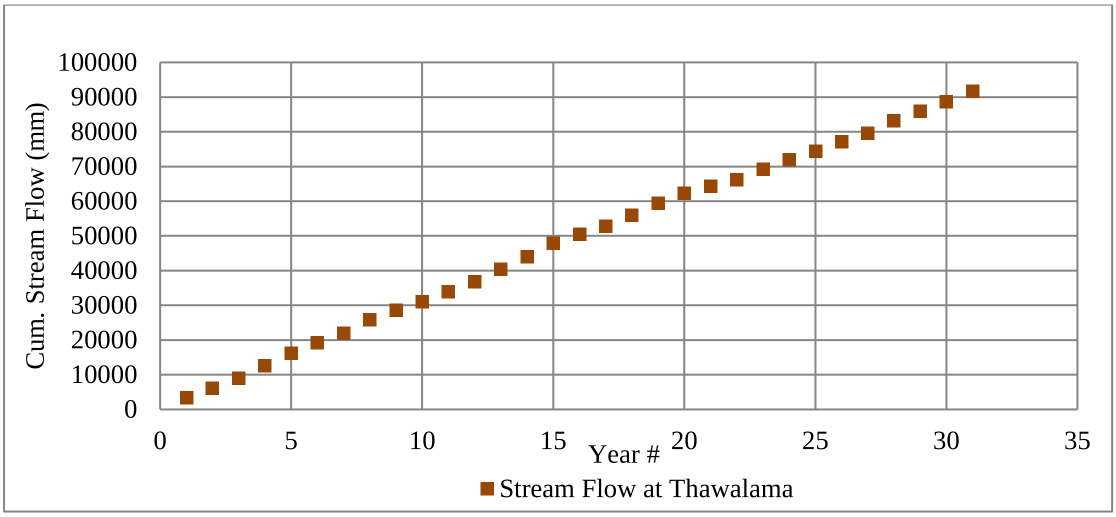

Figure 3-20: Single Mass Curve of stream flow data at Thawalama

3.6.4.3 Single mass curve analysis for pan evaporation data

Single mass curve was plotted as shown in Figure 3-21 for pan evaporation data at Rathnapura evaporation station to check the consistency of the evaporation data. A gradual deflection was observed in the last 6 years.

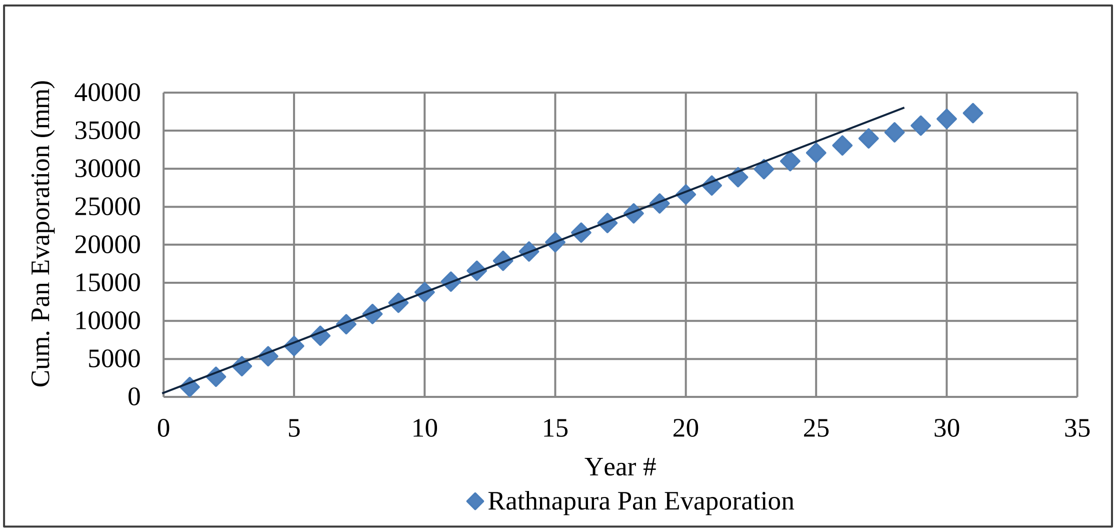

Figure 3-21: Single mass curve for Pan Evaporation

3.6.5 Double mass curve analysis

If the conditions relevant to the recording of a rain gauge station have undergone a considerable change during the recording period, inconsistency would arise in the rainfall data of that station. The main reasons for an inconsistency may be due to a shifting of a rain gauge to a new location, changes in the neighborhood of the station, changes in the ecosystem due to calamities and occurrence of an observational error from a certain date etc. The check which is done to identify this inconsistency is the Double mass curve technique which is based on the principle that when each recorded data comes from the same parent population, they are consistent (Subramanya, 2008).

The double mass curve analysis was done for all the stations of two watersheds as shown in Figure A-1.1 and Figure B-1.1 in Appendix A and Appendix B. In almost all the stations except Anningkanda and Millawa Estate, it was found an appropriate consistence gradient. At Anningkanda, it can be observed that a regaining of the initial gradient at the end of the curve but at Millewa Estate there is a slight increase in the gradient after 2005 which was observed even in respective single mass curve. But there is no evident information about any disturbance for the observed inconsistency to correct the data set to the initial gradient.

3.6.6 Annual water balance

For a watershed, in an interval of time Δt, continuity equation can be written as,

Mass Inflow – Mass Outflow = Change in Mass Storage

$$P - R - G - E - T = \Delta S \tag{18}$$

P- Precipitation, R- Surface Runoff, G- Net Ground Water Flow, E- Evaporation, T- Transpiration and ΔS- Change of Storage (Subramanya, 2008)

The above equation can be rearranged neglecting the change of storage (ΔS) in annual cycles as,

$$P - (R+G) - E - T = 0 \tag{19}$$

Rainfall - Stream flow = Evapotranspiration

Therefore, The Thiessen averaged rainfall minus streamflow was calculated and plotted against the annual pan evaporation to check the annual water balance for Ellagawa and Thawalama watersheds which have been shown in Figure 3-22 and Figure 3-23.

In Ellagawa watershed from 2000 onwards, the annual pan evaporation has been exceeded by the water balance between the rainfall and stream flow in an unusual manner. This has happened as a consequence of the sudden reduction observed in the stream flow after year 2000 and the gradual reduction of evaporation after year 2005. Since the above situation will adversely affect the model calibration and verification process, it was decided to select the input data range as year 1980-2000 (20 years). The adequacy of the data range was further verified with the support of literature.

In Thawalama watershed after 2005 onwards, the annual pan evaporation has been exceeded by the water balance between the rainfall and stream flow in an unusual manner. This is a reflection of the inconsistency of Thiessen averaged rainfall data and reduction of the pan evaporation after year 2005. There were two options to address this inconsistency. The first one was to remove the Millewa Estate as a rainfall data station in the calculation of Thiessen averaged rainfall and the second option was to remove the data from 2005 onwards in the calculation.

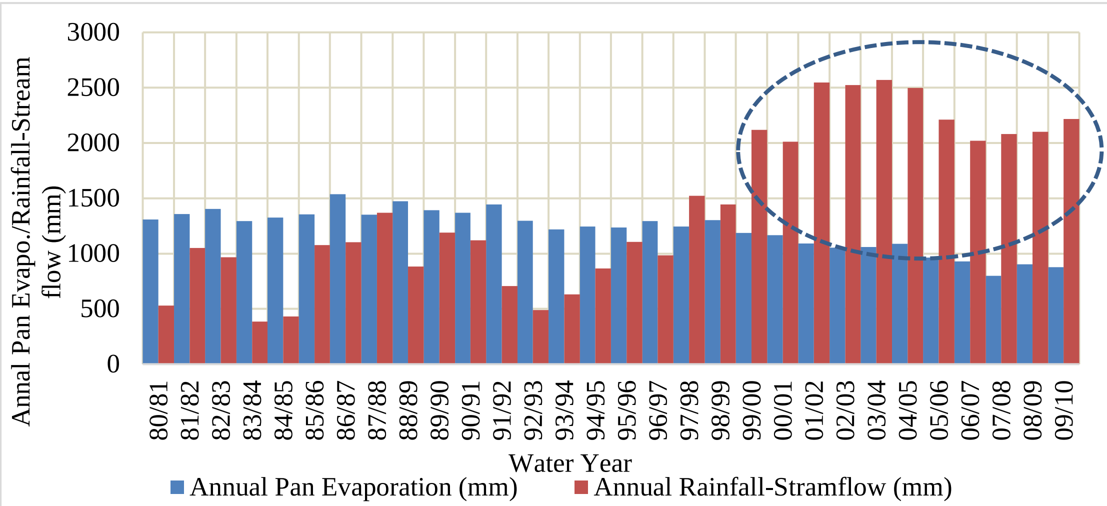

Figure 3-22: Annual Water Balance- Ellagawa Watershed

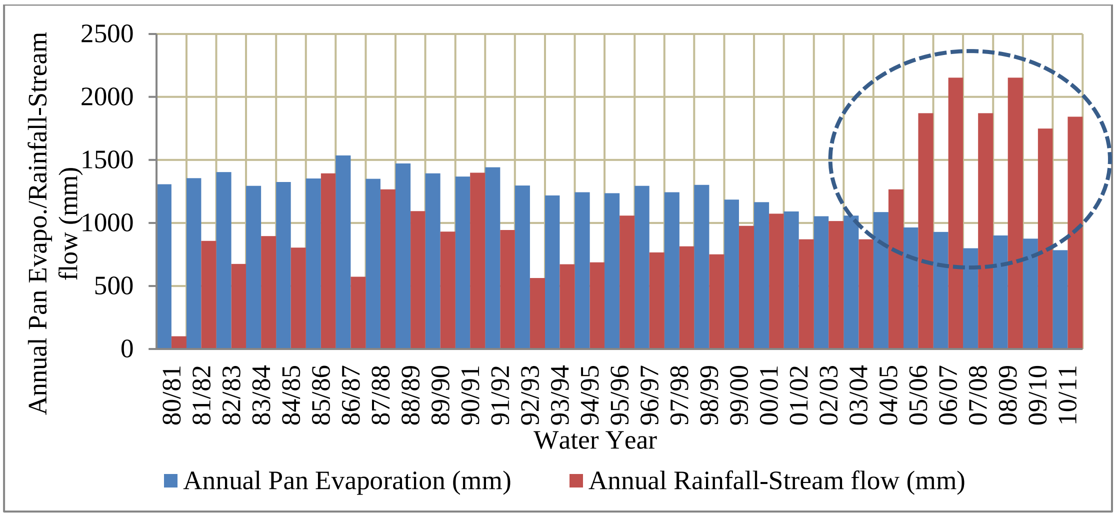

Figure 3-23: Annual Water Balance- Thawalama Watershed

The first option was not possible, due to the unavailability of rainfall data in a nearby station for the considered range. The other reason was the higher Thiessen weight of Millewa Estate. Therefore, it was decided to use the data range as 1980-2005 (25 years) for the model.

3.6.7 Monthly, annual and seasonal runoff coefficients

Monthly and annual runoff coefficients were calculated by dividing streamflow by Thiessen averaged rainfall and plotted against the corresponding Thiessen averaged rainfall. The identified periods with data errors were further verified with the annual plot of the runoff coefficients as shown in Figure 3-24 and Figure 3-25 in both watersheds.

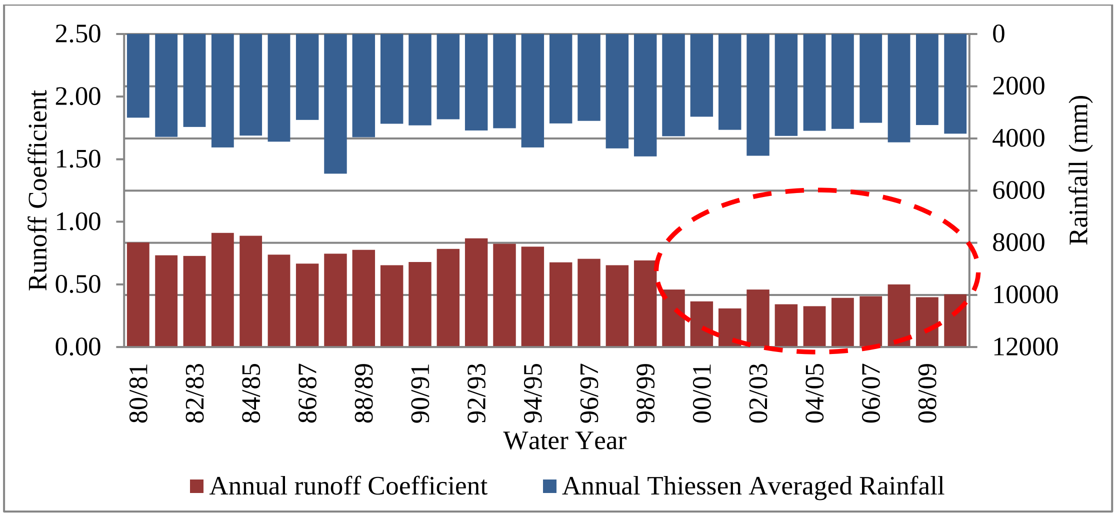

Figure 3-24: Annual runoff coefficient verses rainfall – Ellagawa Watershed

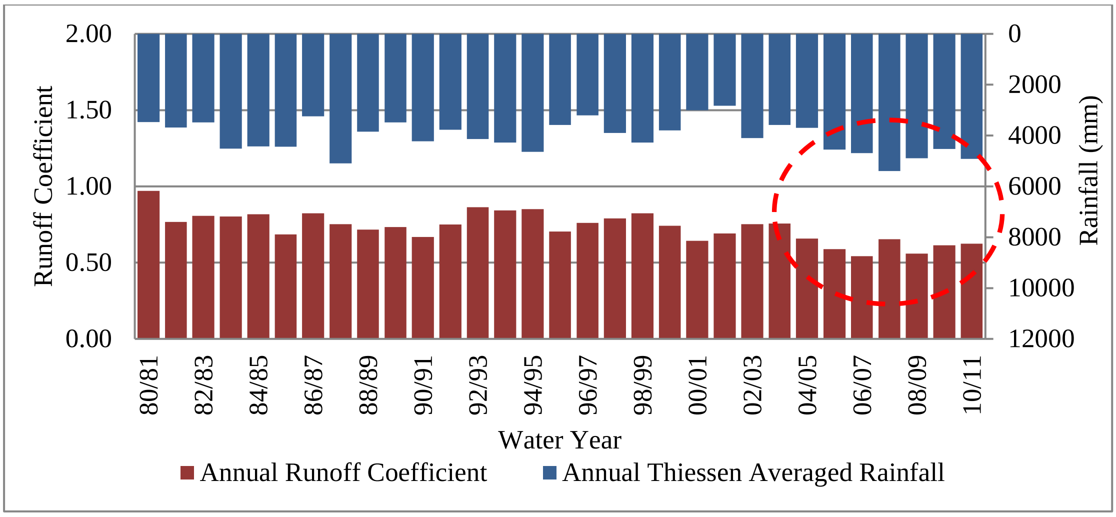

Figure 3-25: Annual runoff coefficient verses rainfall - Thawalama Watershed

In Ellagawa watershed, average annual runoff coefficient before and after 2000 is 0.74 and 0.39 while in Thawalama watershed, average annual runoff coefficient before and after 2005 is 0.77 and 0.60, respectively. This clearly shows that the data error existing after 2000 and 2005 in respective watersheds, which can directly affect the modelling exercise.

The plot of runoff coefficients verses rainfall for the selected data periods have further shown in Figure A-4.1 and Figure A-4.2 in Appendix A for Ellagawa watershed and Figure B-4.1 and Figure B-4.2 in Appendix B for Thawalama watershed. The relevant statistics are shown in Table 3-15.

In comparing both watersheds, relatively high values of runoff coefficients were observed in both watersheds may be due to the mountainous terrain existing. In Thawalama watershed, one unrealistic runoff coefficient value was observed in February 1991, which is 13.5. In this month, Thiessen averaged rainfall is 5.53 mm which is very low, and the stream flow is 74.37 mm. But in the visual check of rainfall verses streamflow, no unrealistic response was observed in this month.

Table 3-15: Monthly, Annual and Seasonal Runoff Coefficients

	Ellagawa Watershed				Thawalama Watershed			
	Monthly	Annual	Seasonal		Monthly	Annual	Seasonal	
			Yala	Maha			Yala	Maha
C_{avg}	0.72	0.74	0.75	0.73	0.9	0.77	0.75	0.79
C_{max}	2.22	0.91	1.16	0.99	13.5	0.97	0.94	1.00
C_{min}	0.08	0.46	0.39	0.53	0.3	0.64	0.46	0.60
C_{std}	0.34	0.10	0.17	0.12	0.85	0.07	0.10	0.10

3.6.8 Statistical parameters of data for the selected range

Statistical parameters were calculated and graphically presented for the selected data ranges for both watersheds. Under statistical parameters, monthly maximum, minimum, mean and standard deviation were taken in to consideration for rainfall, stream flow and evaporation data.

3.6.8.1 Precipitation

In Thawalama watershed, for the selected data period (1980-2005), the monthly mean of Thiessen averaged rainfall varies from 145 ~ 488 mm, while varying the minimum and maximum from 6 ~ 252 mm and 282 ~ 910 mm, respectively. The Thiessen averaged rainfall variation in 12 months for the considered data period for Thawalama watershed has been shown in Figure 3-26.

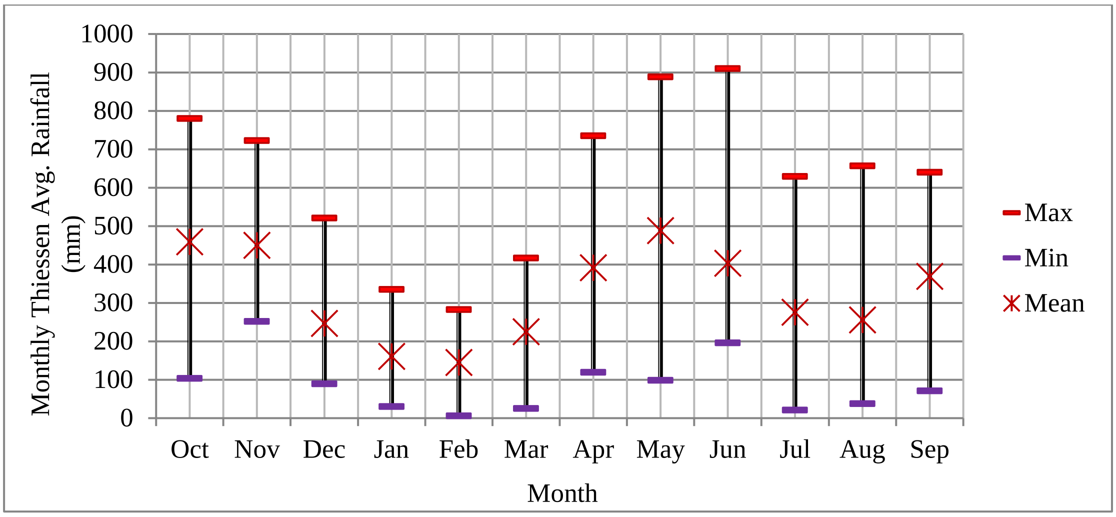

Figure 3-26: Monthly comparison of Thiessen Averaged Rainfall- Gin Ganga

In Ellagawa watershed, for the selected data period (1980-2000), the monthly mean of Thiessen averaged rainfall varies from 143 ~ 464 mm, while varying the minimum and maximum from 10 ~ 238 mm and 329 ~ 816 mm, respectively. The Thiessen averaged rainfall variation in 12 months for the considered data period for Ellagawa watershed has been shown in Figure 3-27.

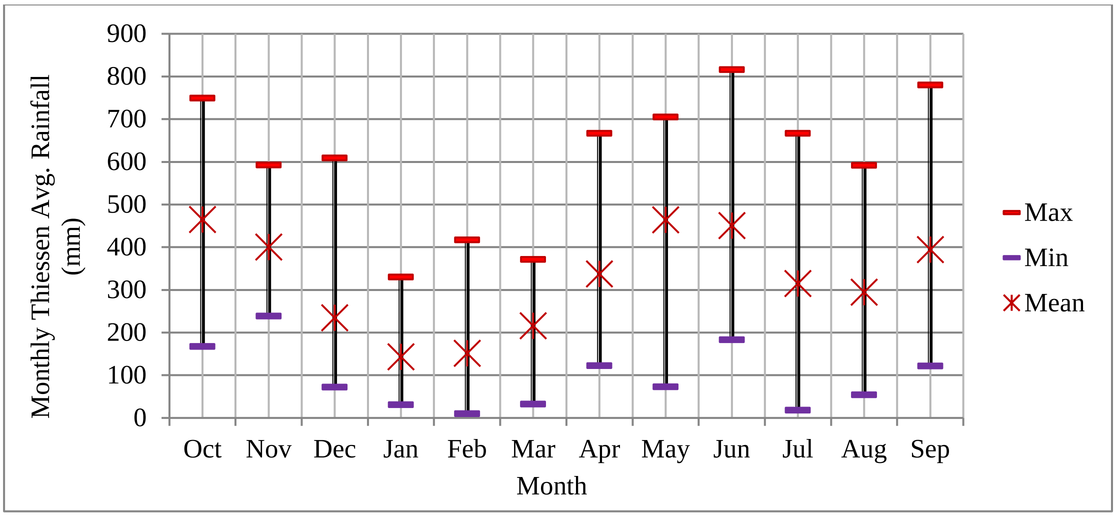

Figure 3-27:Monthly comparison of Thiessen Averaged Rainfall- Kalu Ganga

3.6.8.2 Stream flow

In Thawalama watershed, for the selected data period (1980-2005), the monthly mean of stream flow varies from 108-371 mm, while varying the minimum and maximum from 44-177 mm and 216-934 mm respectively. The stream flow variation in 12 months for the considered data period for Thawalama watershed has been shown in Figure 3-28.

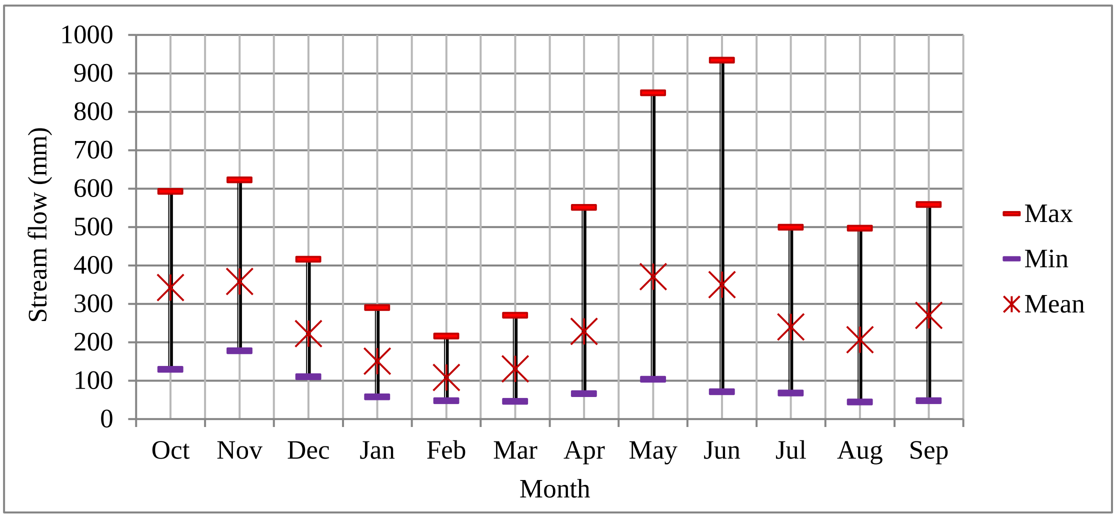

Figure 3-28: Monthly comparison of Stream flow- Gin Ganga

In Ellagawa watershed, for the selected data period (1980-2000), the monthly mean of stream flow varies from 62 ~ 443 mm, while varying the minimum and maximum from 20 ~ 129 mm and 162 ~ 1144 mm, respectively. The stream flow variation in 12 months for the considered data period for Ellagawa watershed has been shown in Figure 3-29.

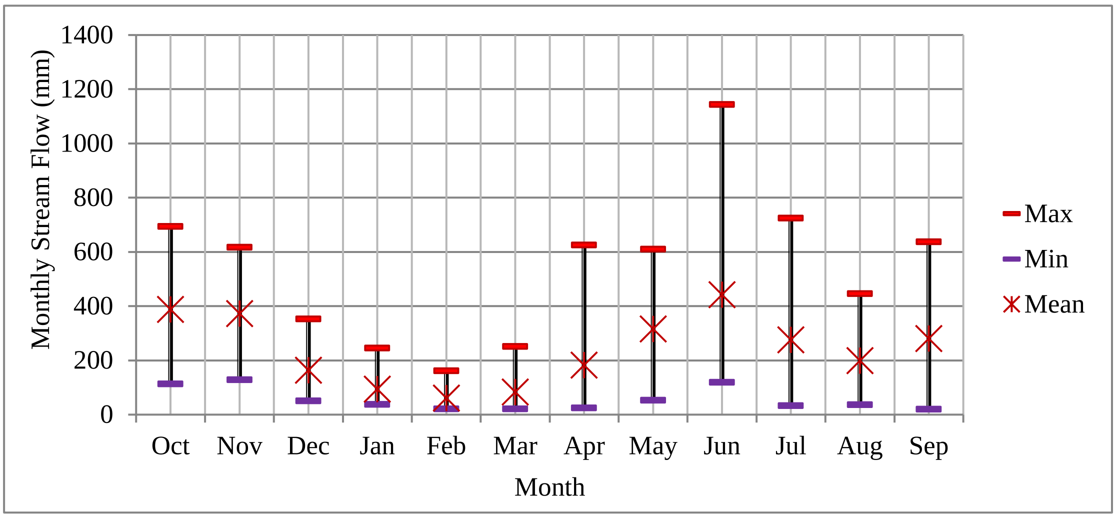

Figure 3-29:Monthly comparison of Stream flow- Kalu Ganga

3.6.8.3 Evaporation

For both Thawalama and Ellagawa watersheds, evaporation data of Rathnapura station was used. But the statistical parameters will vary due to different data periods in the two watersheds.

For Thawalama watershed, from 1980-2005 monthly mean of pan evaporation at Rathnapura station varies from 96 ~ 136 mm, while varying the minimum and maximum from 63 ~ 97 mm and 118 ~ 186 mm, respectively. The variation of pan evaporation in 12 months for the considered data period for Thawalama watershed of Gin Ganga has been shown in Figure 3-30.

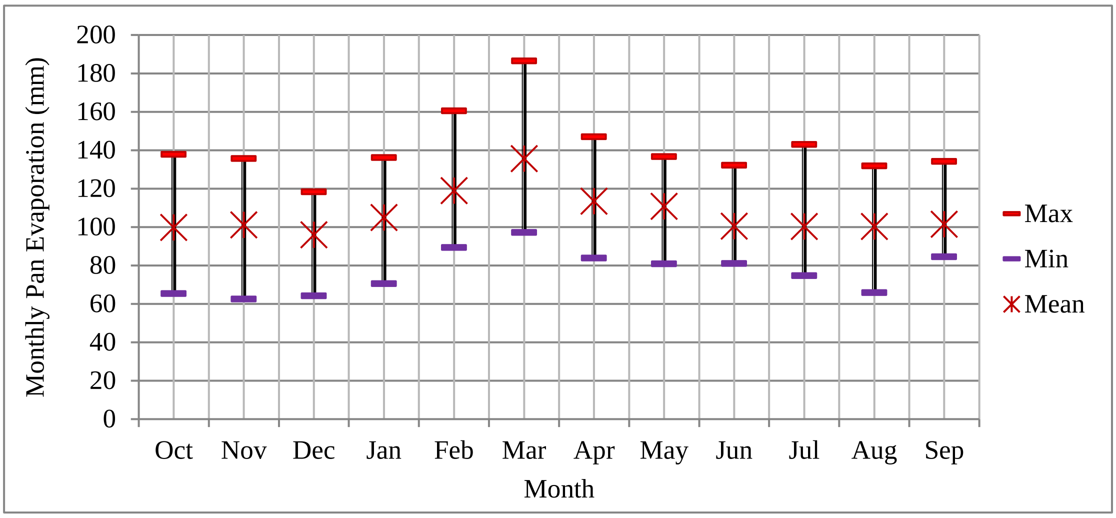

Figure 3-30: Monthly Comparison of Pan Evaporation-Gin Ganga

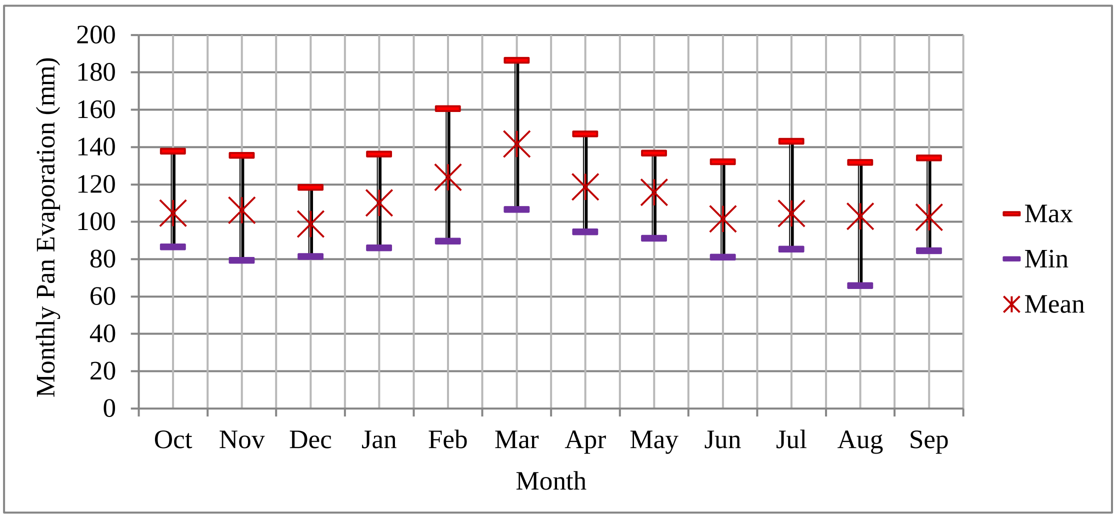

Figure 3-31:Monthly Comparison of Pan Evaporation-Kalu Ganga

In Ellagawa watershed, from 1980-2000, the monthly mean of pan evaporation at Rathnapura station varies from 99 ~ 142 mm, while varying the minimum and maximum from 66 ~ 107 mm and 118 ~ 186 mm, respectively. The variation of pan evaporation in 12 months for the considered data period for Ellagawa watershed of Kalu Ganga watershed has been shown in Figure 3-31.

4 ANALYSIS AND RESULTS

4.1 Calculation of potential evapotranspiration (PE)

Pan evaporation method was selected as the potential evapotranspiration calculation method after doing the literature survey and considering the data availability. In the calculation, pan coefficient (Kp) was taken as 0.8 and the weighted crop factor (Kc) was calculated by using the land use as shown in Table 4-1 and Table 4-2. The potential evapotranspiration was calculated as follows for both watersheds;

PE = Cp x Epan

Cp = Kp x Kc;

PE = Kp.Kc. Epan

The calculated Cp values for both watersheds have been summarized in Table 4-3.

Table 4-1: Weighted Kc - Thawalama Watershed

Land use	Area (A) (km^2)	Crop Factor (Kc)	A x Kc
Coconut/ Chena	31.276	1.00	31.276
Forest-Unclassified	122.799	1.00	122.799
Grass Land	0.501	1.00	0.501
Homesteads/Garden	31.396	1.00	31.396
Marsh	0.049	1.20	0.0588
Other Cultivation	1.881	1.05	1.975
Paddy	18.383	1.20	22.060
Rubber	18.575	1.00	18.575
Scrub land	39.830	1.20	47.796
Stream	3.978	1.05	4.177
Tea	89.736	1.00	89.736
	$\sum A = 358.4$	$\frac{\sum AKc}{\sum A} = 1.033$	$\sum A \times Kc = 370.3$

Table 4-2: Weighted Kc – Ellagawa Watershed

Land use	Area (A) (km^2)	Crop Factor (Kc)	A x Kc
Coconut/Chena	281.306	1.00	281.306
Forest-Unclassified	217.173	1.00	217.173
Grass Land	1.198	1.00	1.198
Homesteads/Garden	248.403	1.00	248.403
Marsh	0.222	1.20	0.266
Other Cultivation	26.657	1.00	26.657
Paddy	94.169	1.20	113.003
Rubber	350.14	1.00	350.140
Scrub land	21.707	1.20	26.048
Stream	19.153	1.05	20.111
Tea	116.98	1.00	116.980
	$\sum A = 1377.12$	$\frac{\sum AKc}{\sum A} = 1.018$	$\sum A \times Kc = 1401.29$

Table 4-3: Summary of Kc and Cp values for both watersheds

Watershed	Kp	Kc	Kp x Kc=Cp
Thawalama	0.8	1.033	0.827
Ellagawa	0.8	1.018	0.814

4.2 Warm up period, initial soil moisture content and groundwater content for the model

In the development of the two-parameter model by Xiong an Guo (1999) and the ‘abcd’ model by Thomas (1981), arbitrary values had been used as initial values stating that the experimental values are not mandatory.

In this study, using total data set (calibration and validation) of Kalu Ganga and Gin Ganga, models were run for 8 cycles and observed that the soil moisture storage

(S_{t-1}) and the ground water storage (G_{t-1})are reached to the quasi- steady state after one cycle for each watersheds as shown in Figure 4-1, Figure 4-2, Figure 4-3 and Figure 4-4.

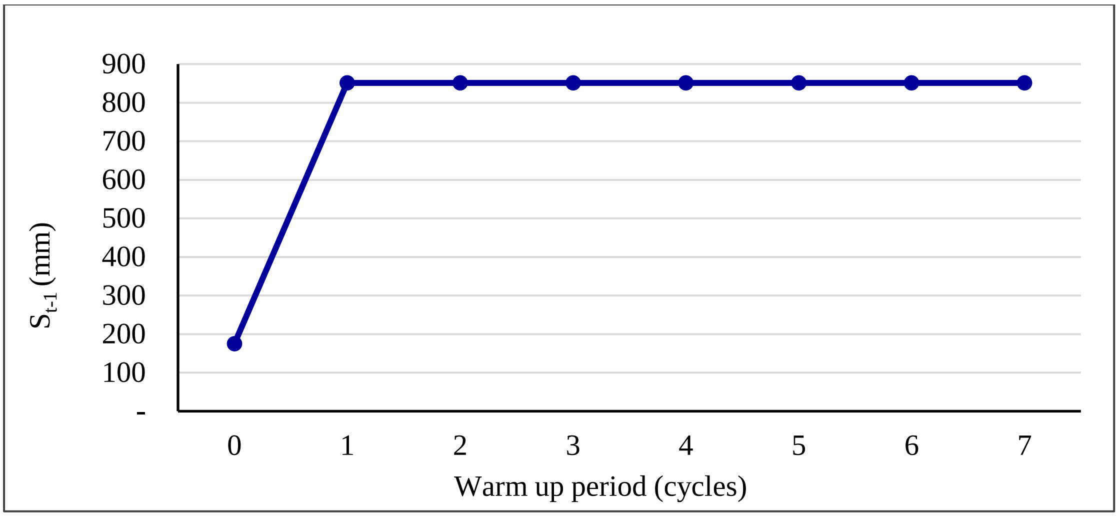

Figure 4-1: Warm up period and the corresponding initial soil moisture storage in Thawalama watershed

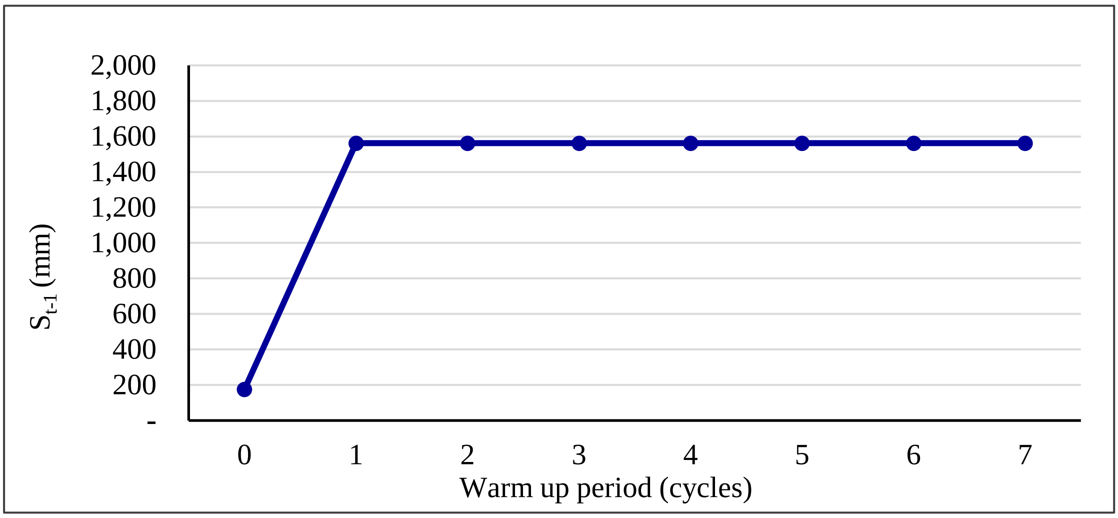

Figure 4-2: Warm up period and the corresponding initial soil moisture storage in Ellagawa watershed

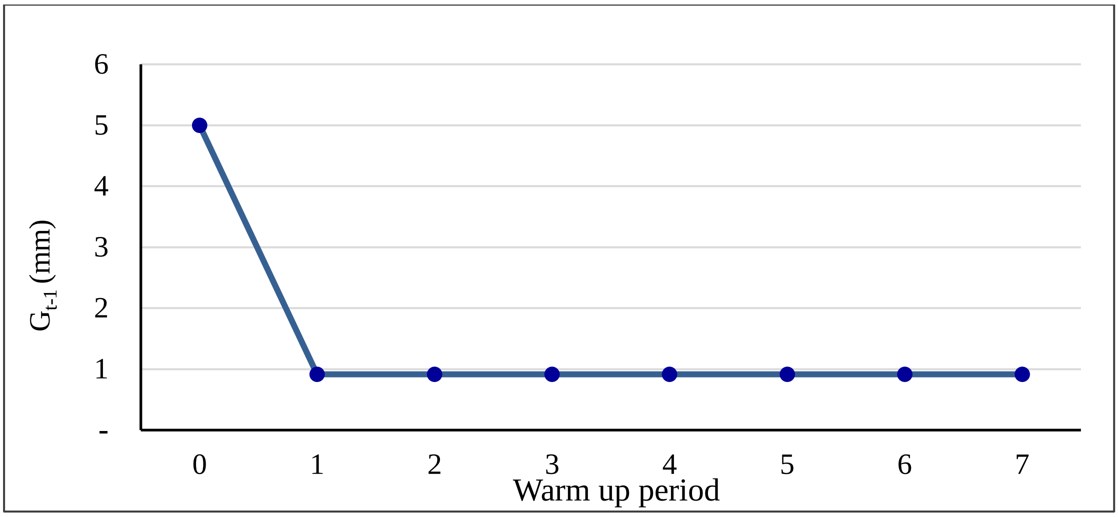

Figure 4-3: Warm up period and the corresponding initial groundwater storage in Thawalama watershed

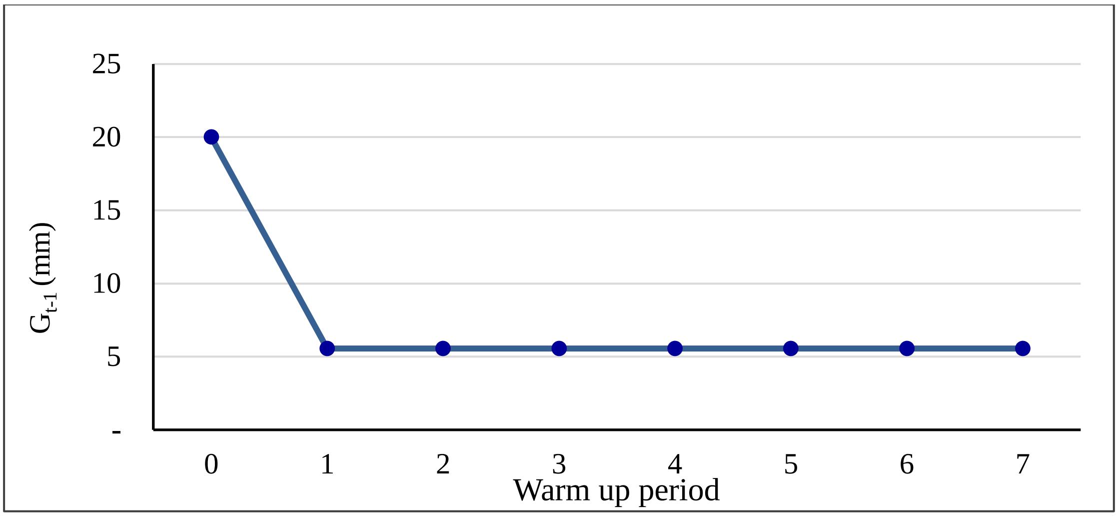

Figure 4-4: Warm up period and the corresponding initial groundwater storage in Ellagawa watershed

4.3 Calibration and validation of 'abcd' model by using objective functions and visual observation

4.3.1 First trial and parameter optimization in calibration and validation process

For the calibration, averages of a,b,c and d parameter values in the literature under different studies were used as initial values as shown in Table 4-4 and calibrated considering MRAE as the objective function. For the calibration and validation, data sets of the 8th cycle were used. Since by that time, the model has to be surely stabilized to its quasi steady state. The first calibration trial itself showed satisfactory results for Thawalama watershed but not for the Ellagawa watershed which has been shown in Table 4-5. For the comparison purpose, NSE value was used with MRAE. Then the models were calibrated for the global minimum of MRAE by using Solver along with Evolutionary method in Microsoft Excel which can be successfully used for the parameter optimization. When setting the ranges of each parameters, even the outside values of the literature were also considered since the global minimum can be fallen out of the ranges of literature. At the optimization it was clearly observed that MRAE and NSE had reached to a very low and high values respectively. After the optimization, the parameter values were used for the validation period and observed the objective function. Even in the validation period, it was observed good values for both MRAE and NSE.

Table 4-4: Initial values for model parameters for both watersheds

Model parameter	Range from literature	Average as the initial value for the model
a	0.873-0.999	0.936
b	14-1900	957
c	0-1	0.5
d	0-1	0.5

The visual compatibility of the simulated outflow hydrograph with the observed hydrograph was checked in both calibration and validation process. A poor visual compatibility was observed in the first trial at calibration as shown in Figure 4-5 to

Figure 4-8 and a good visual compatibility was observed when the parameters were optimized in calibration and validation as shown in Figure 4-9 to Figure 4-16.

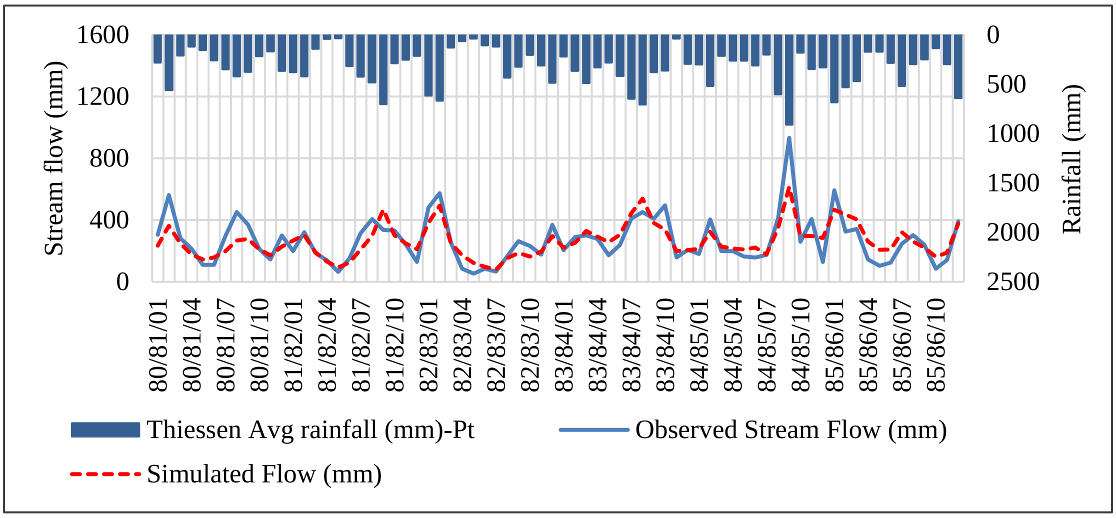

Figure 4-5: Simulated flow from first trial (1980-1985) in calibration- Gin Ganga

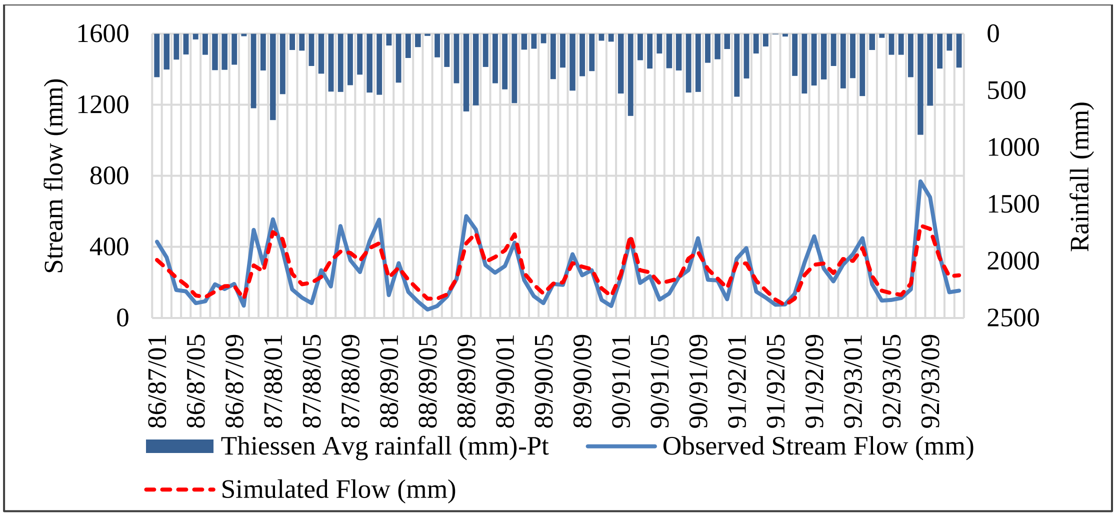

Figure 4-6: Simulated Flow from first trial (1986-1993) in calibration- Gin Ganga

Table 4-5: Objective function values from first calibration trial

Watershed	MRAE	Nash Sutcliff Efficiency
Thawalama	0.30	0.73
Ellagawa	0.76	0.63

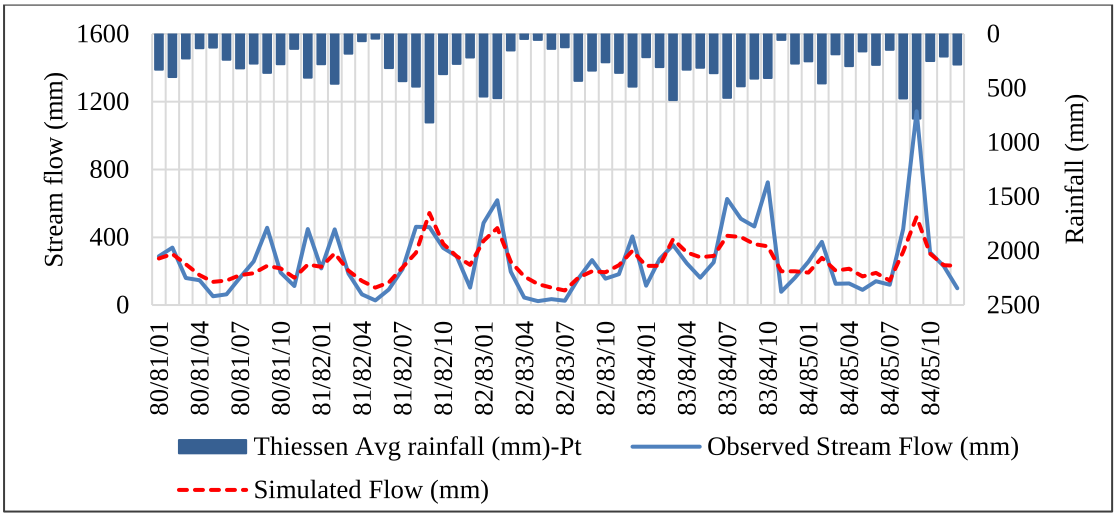

Figure 4-7: Simulated flow from first trial (1980-1985) in calibration - Kalu Ganga

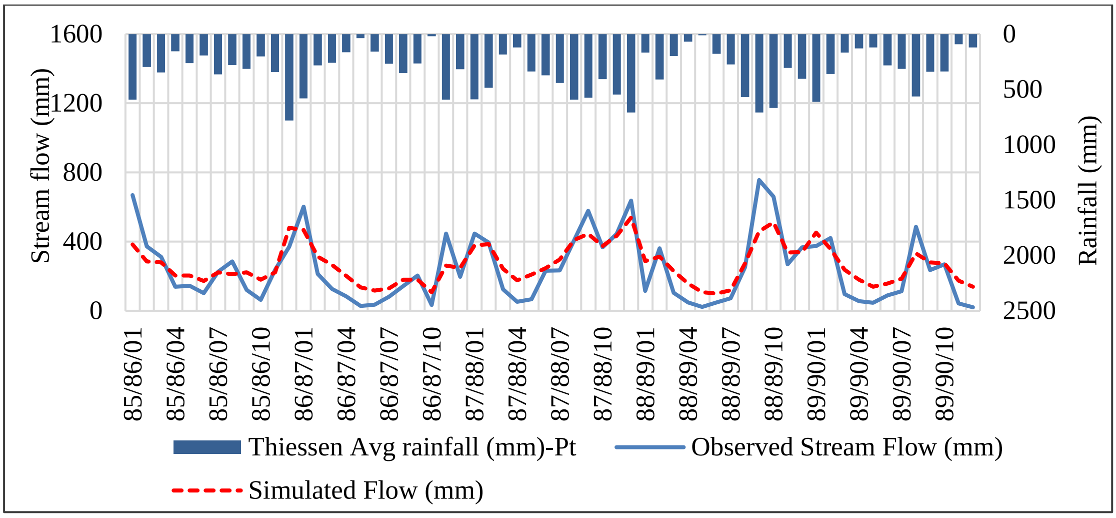

Figure 4-8: Simulated flow from first trial (1980-1990) in calibration- Kalu Ganga

The optimized a, b, c and d parameters has been summarized in Table 4-6 as shown below and the corresponding simulated hydrographs have been shown in Figure 4-9 to Figure 4-16.

Table 4-6: Optimized "abcd" parameters and objective functions

Watershed	Parameter	Parameter value	Objective function			
			Calibration		Validation	
			MRAE	Nash	MRAE	Nash
Thawalama	a	0.961	0.21	0.81	0.23	0.80
	b	1066				
	c	0.003				
	d	0.813				
Ellagawa	a	0.998	0.26	0.77	0.43	0.73
	b	1644				
	c	0.013				
	d	0.741				

4.3.2 Outflow hydrographs related to optimized parameters

Simulated flow was plotted on the top of the observed flow, to see the visual compatibility of the outflow hydrograph after optimizing parameters by using MRAE.

4.3.2.1 Observed and simulated outflow hydrographs from Calibration of 'abcd' model for Gin Ganga

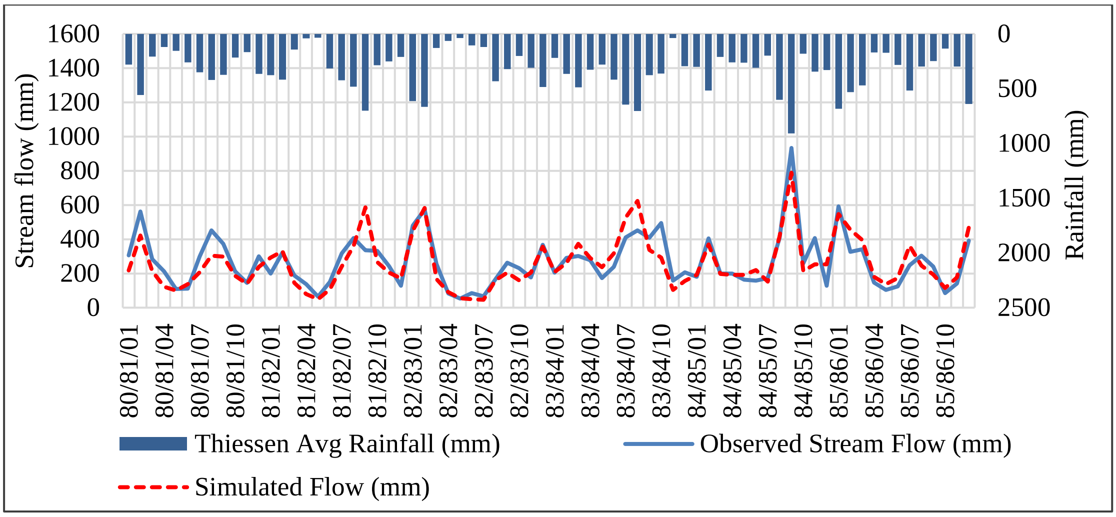

Figure 4-9: Calibration Results I - Outflow hydrograph of Gin Ganga for 1980~1985

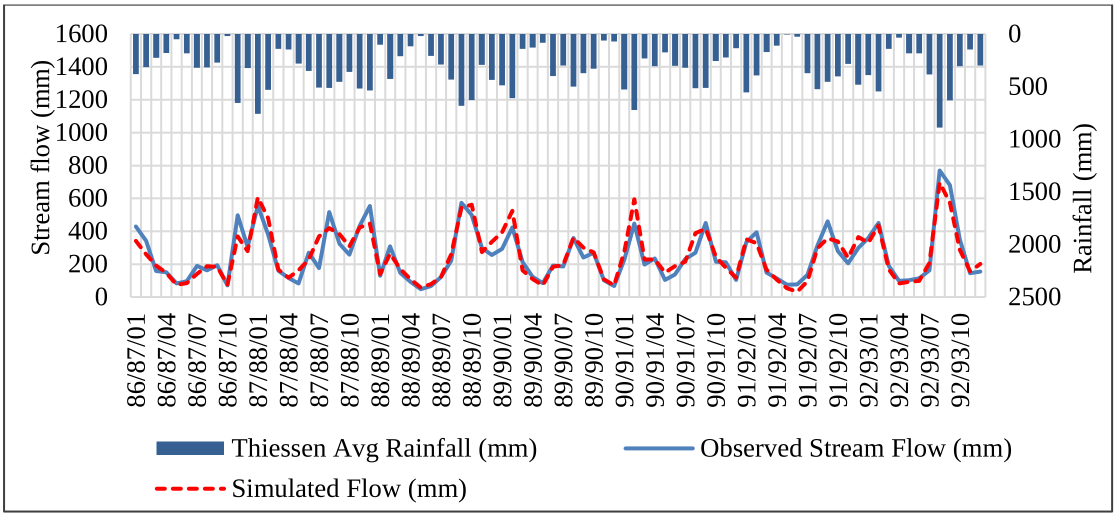

Figure 4-10: Calibration Results II - Outflow hydrograph of Gin Ganga for 1986~1992

4.3.2.2 Observed and simulated outflow hydrographs from Validation of 'abcd' model for Gin Ganga

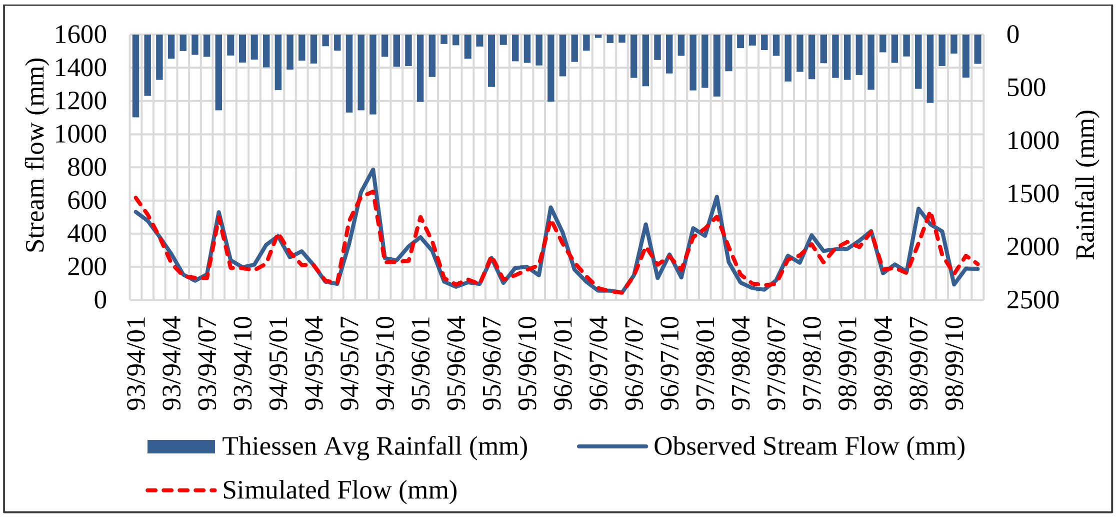

Figure 4-11: Validation Results I - Outflow hydrograph of Gin Ganga for 1993-1998

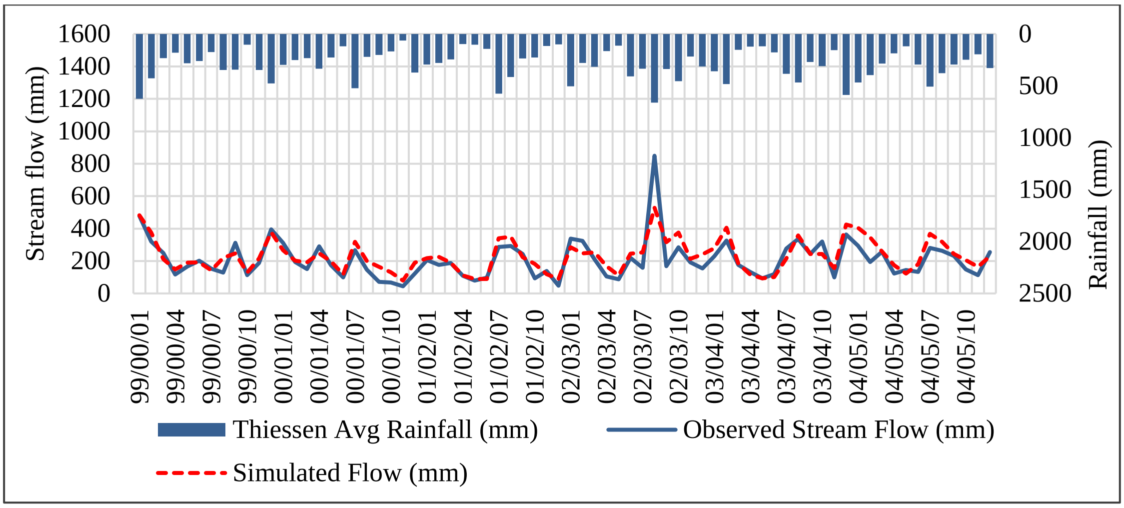

Figure 4-12: Validation Results II -Outflow hydrograph of Gin Ganga for 1999-2004

4.3.2.3 Observed and simulated outflow hydrographs from Calibration of ‘abcd’ model for Kalu Ganga

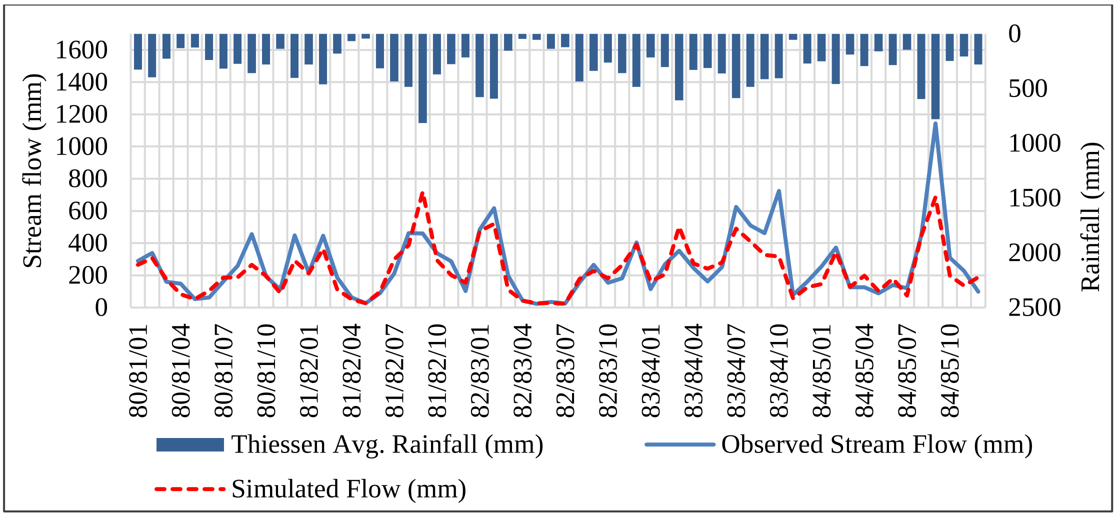

Figure 4-13: Calibration Results I - Outflow hydrograph of Kalu Ganga for 1980-1984

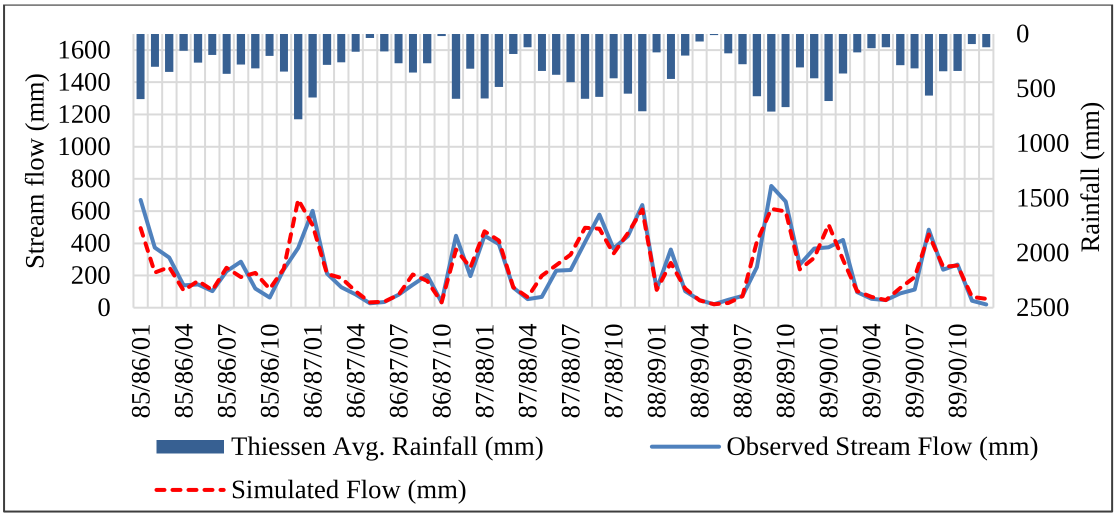

Figure 4-14: Calibration Results II - Outflow hydrograph of Kalu Ganga for 1985-1989

4.3.2.4 Observed and simulated outflow hydrographs from Validation of abcd model for Kalu Ganga

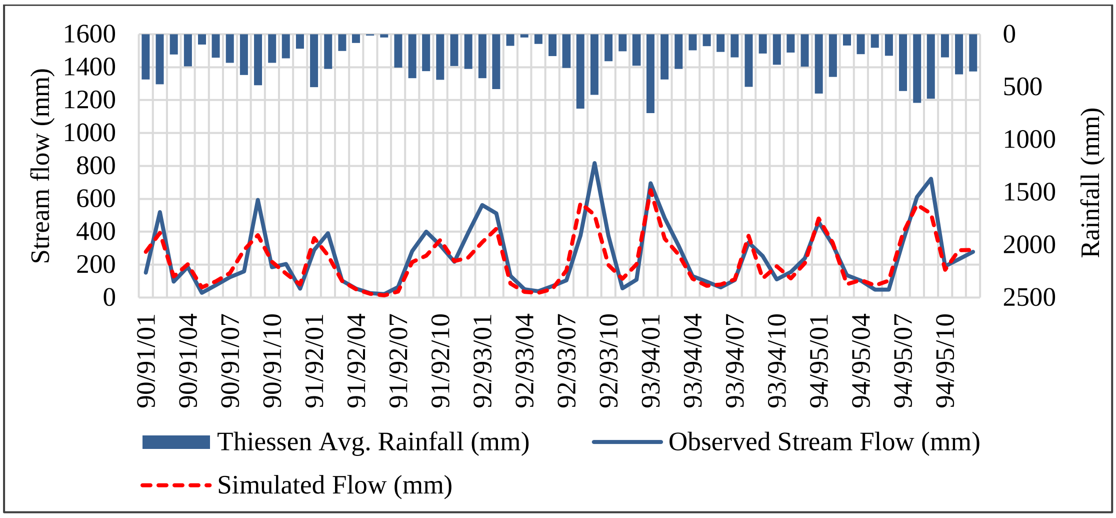

Figure 4-15: Validation Results I - Outflow hydrograph of Kalu Ganga for 1990-1994

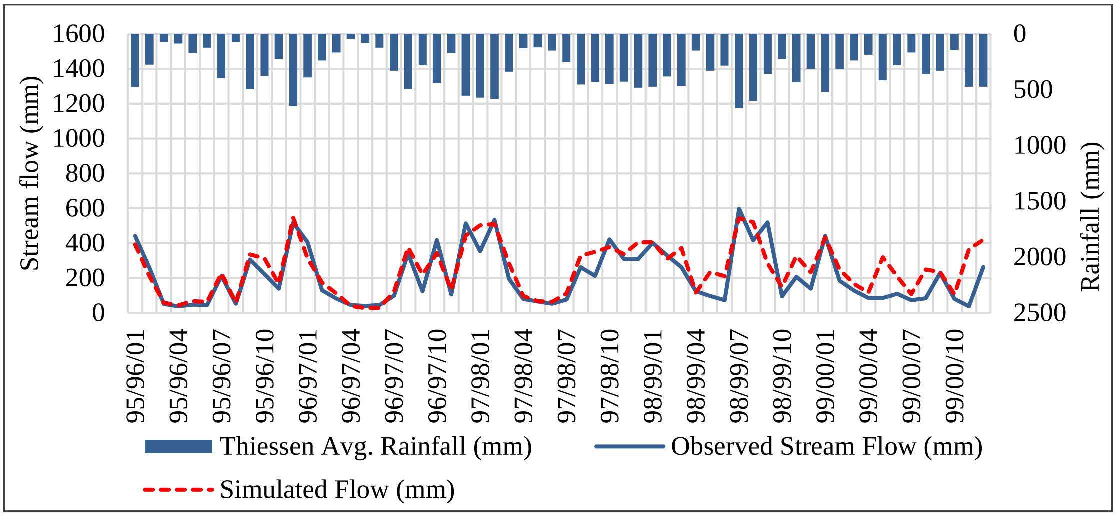

Figure 4-16: Validation Results II - Outflow hydrograph of Kalu Ganga for 1995-2000

4.4 Annual water balance check after calibration and validation

An annual water balance check was performed by using Thiessen averaged rainfall, pan evaporation, observed stream flow and simulated stream flow as shown in Figure 4-17 to Figure 4-20. The difference between the observed water balance and the water balance from the simulation (Annual water balance difference) was demarcated in a separate column to check the water balance in flow simulation. In the calibration, it is required to maintain the previous water balance which was existed between the observed flow and rainfall in simulated condition.

4.4.1 Annual water balance of Gin Ganga- for calibration period

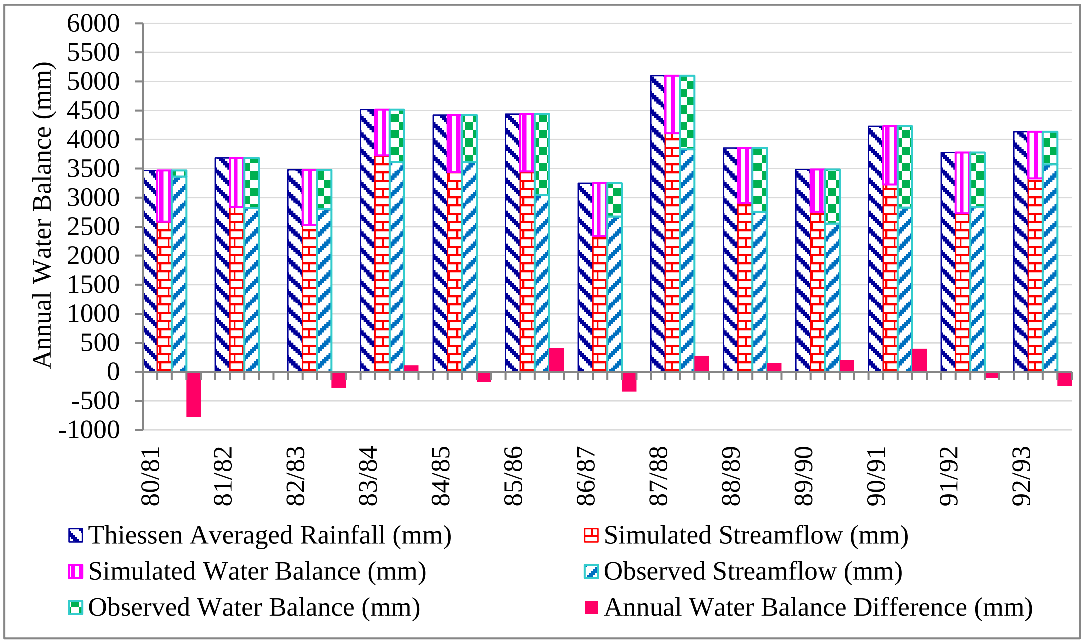

Figure 4-17: Annual water balance of Gin Ganga – Calibration

4.4.2 Annual water balance of Gin Ganga- for validation period

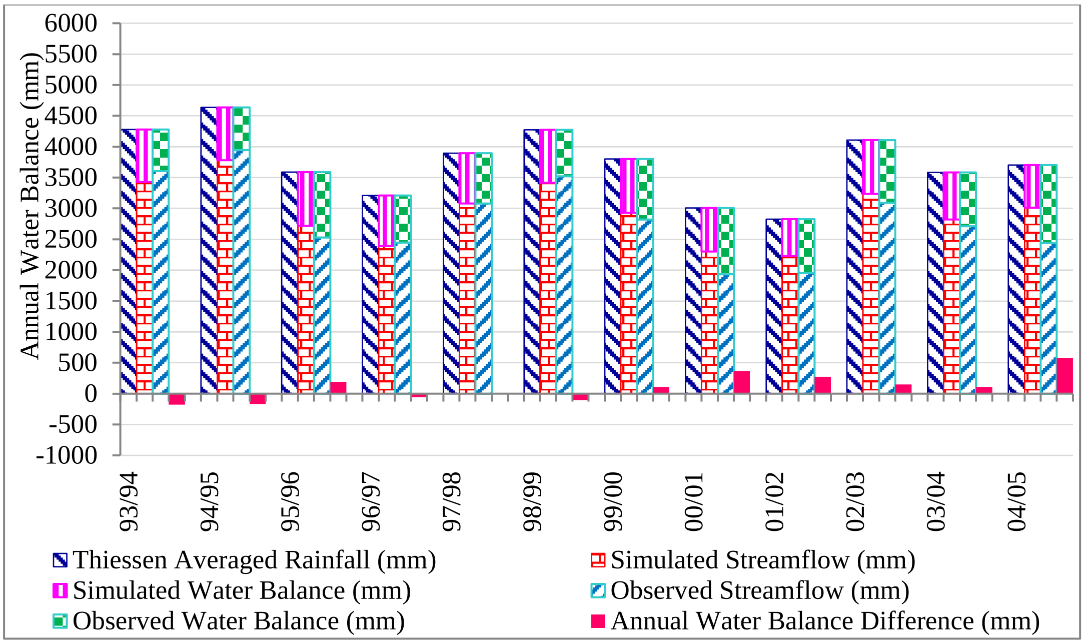

Figure 4-18: Annual water balance of Gin Ganga – Validation

4.4.3 Annual water balance of Kalu Ganga- for calibration period

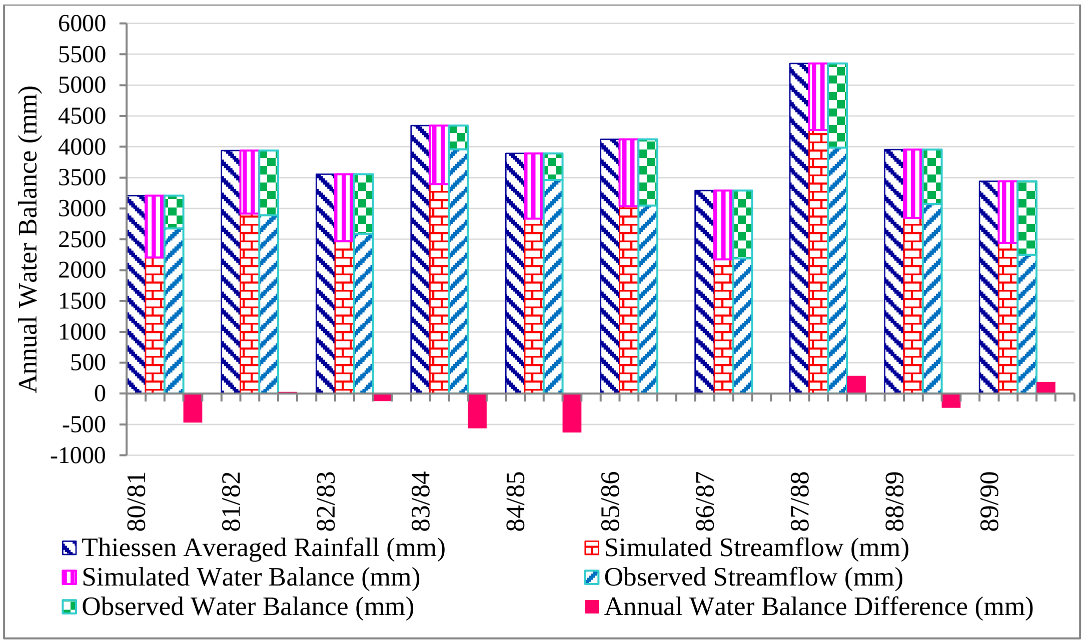

Figure 4-19: Annual water balance of Kalu Ganga – Calibration

4.4.4 Annual water balance of Kalu Ganga- for validation period

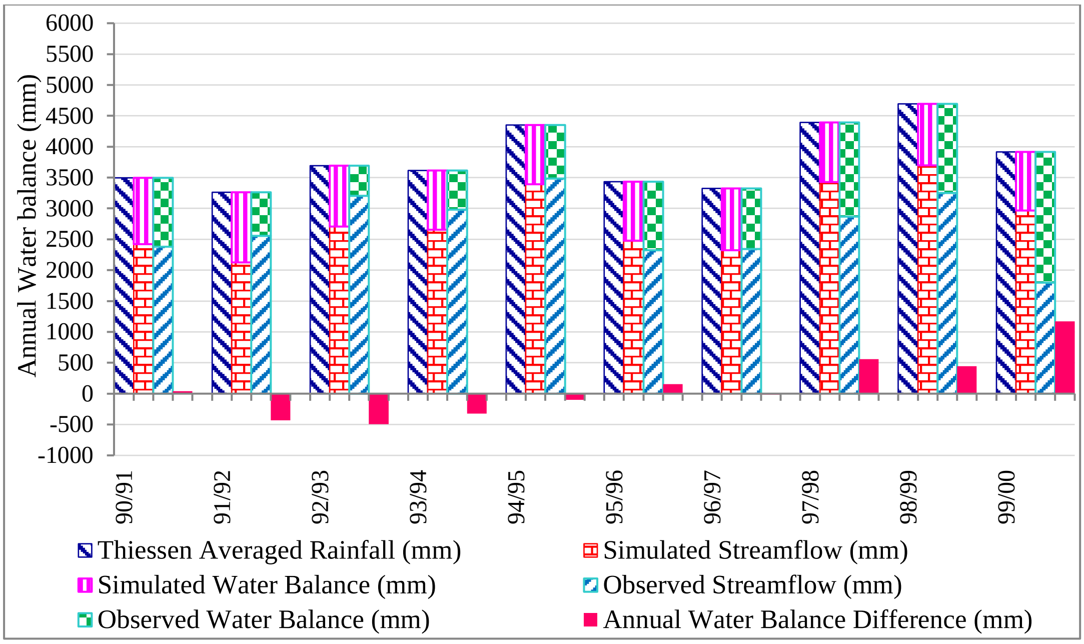

Figure 4-20: Annual water balance of Kalu Ganga – Validation

4.5 Determination of high, medium and low flows by using flow duration curves

A flow duration curve characterizes the ability of the watershed to provide flows of various magnitudes. The shape of a flow duration curve in its upper and lower regions is particularly significant in evaluating the watershed and stream characteristics. The shape of the curve in the high flow region indicates the type of flood regime the watershed is likely to have, and the shape of the low flow region characterizes the ability of the basin to sustain low flows during dry periods. A very steep curve, which shows high flows for short periods would be expected for rain caused floods on small watersheds.

In developing the flow duration curve, the monthly discharge values were rearranged according to the descending order and ranked starting from one. The exceedance probability was calculated as follows.

P = 100 * [M / (n + 1)] Where, P = the probability that a given flow will be equaled or exceeded (% of time)

M = the ranked position on the listing (dimensionless)

n = the number of events for period of record (dimensionless)

The probability of exceedance indicates how much percentage a discharge value has been exceeded.

Graphs were plotted as shown in Figure 4-21, Figure 4-23, Figure 4-25 and Figure 4-27, exceedance probability verses observed stream flow for both Thawalama (Gin Ganga) and Ellagawa (Kalu Ganga) watersheds for calibration and validation period separately to identify the three flow regimes of high, medium and low. It was difficult to identify the deflection point of slope by simple observation which led to plot the logarithmic observed stream flow against the exceedance probability as shown in Figure 4-22, Figure 4-24, Figure 4-26 and Figure 4-28.

4.5.1 Flow duration curves for Gin Ganga

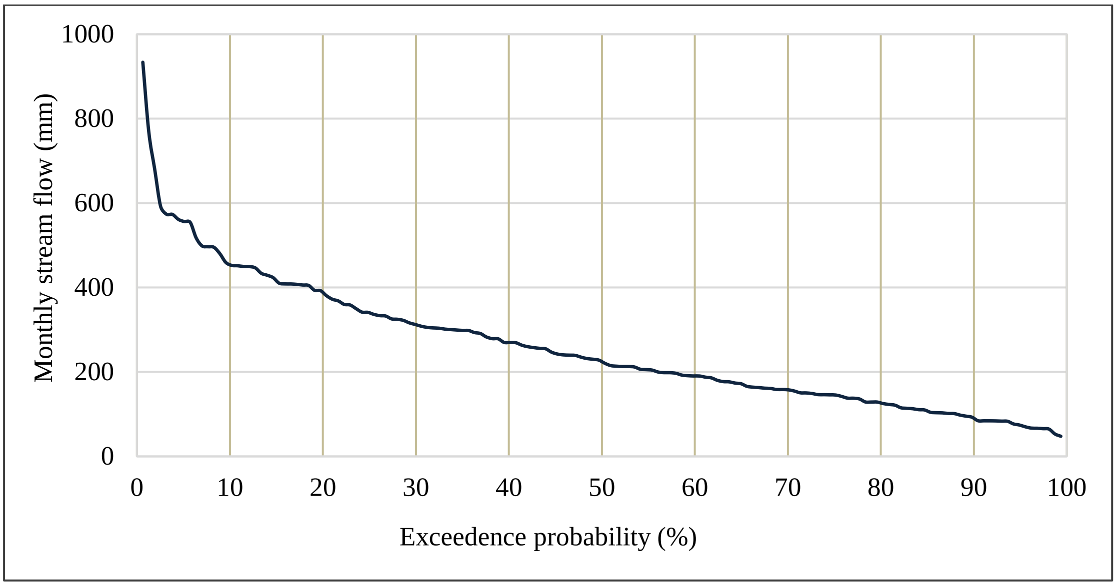

Figure 4-21: Flow Duration Curve for Gin Ganga for the calibration period

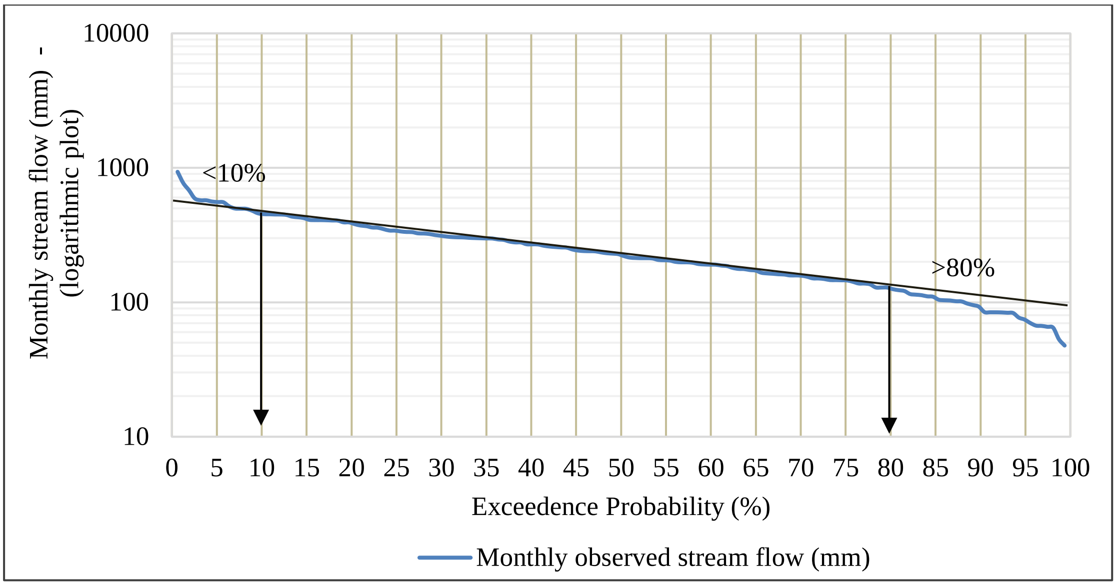

Figure 4-22: Logarithmic plot of flow Duration Curve for Gin Ganga for the calibration period

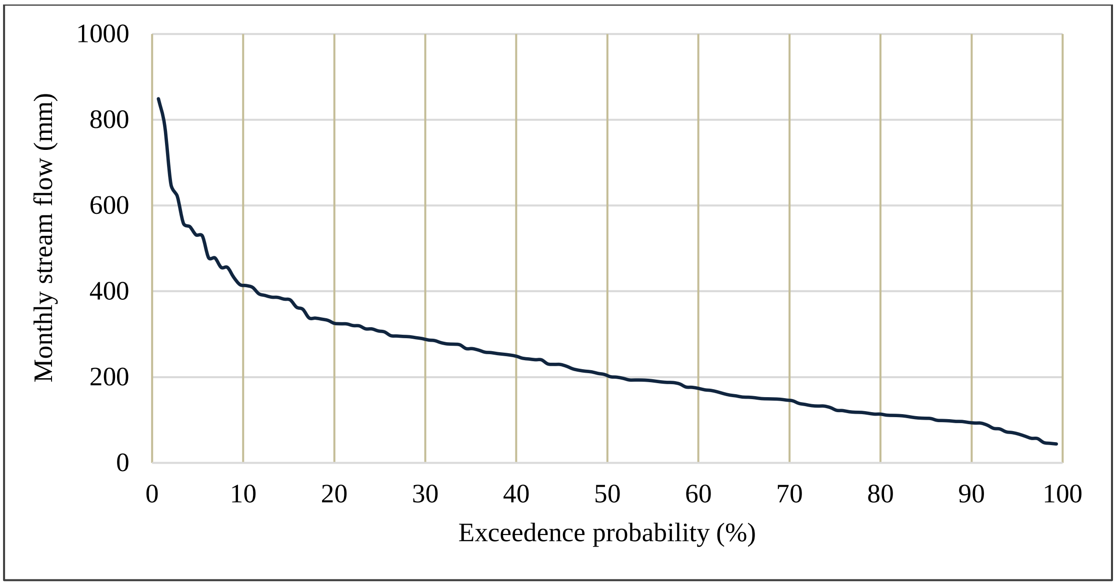

Figure 4-23: Flow Duration Curve for Gin Ganga for the verification period

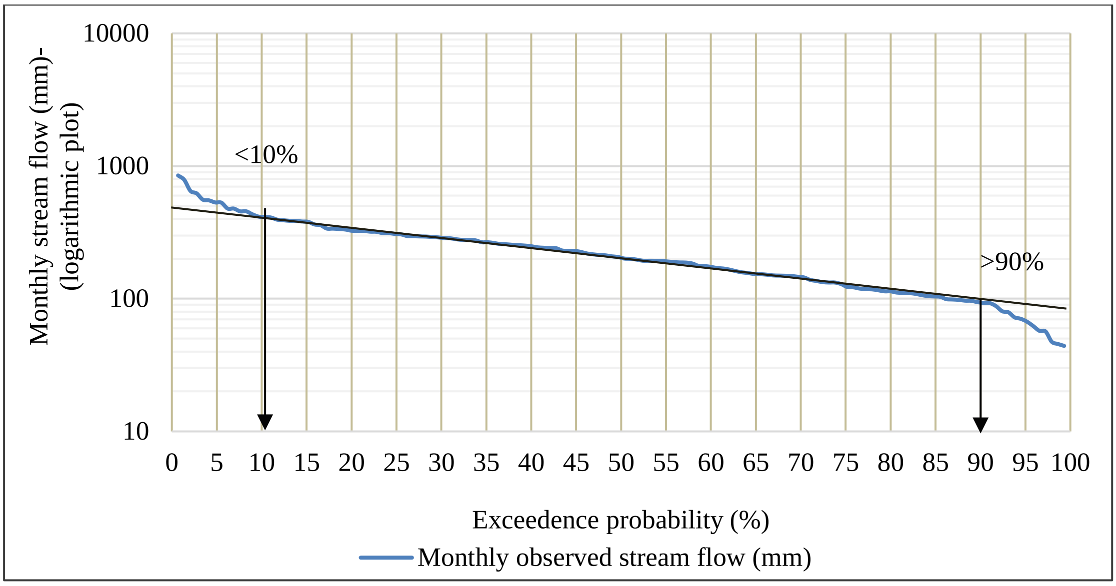

Figure 4-24: Logarithmic plot of flow Duration Curve for Gin Ganga for the verification period

4.5.2 Flow duration curves for Kalu Ganga

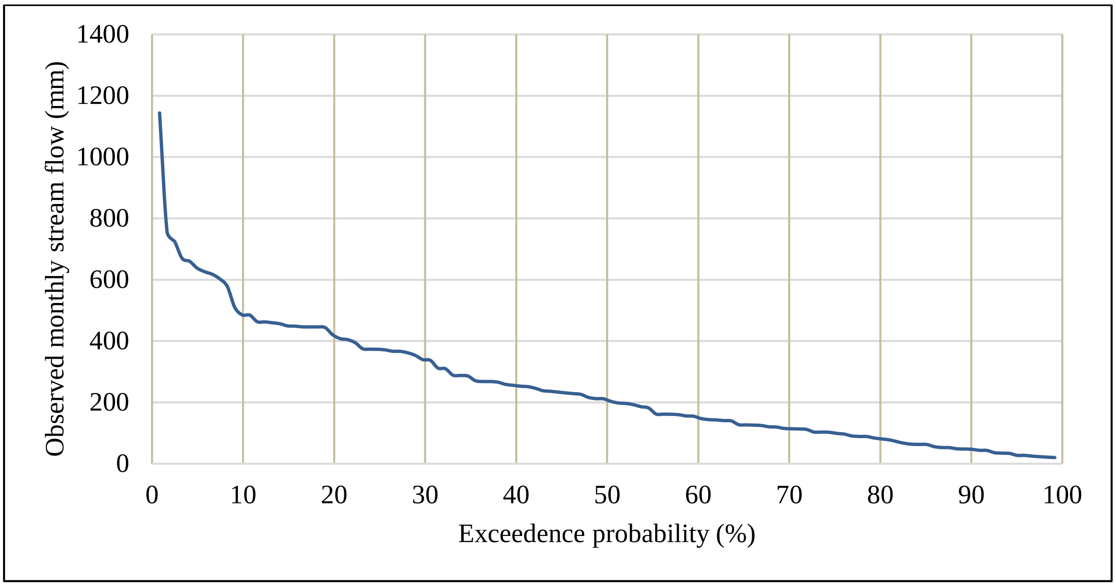

Figure 4-25: Flow Duration Curve for Kalu Ganga for the calibration period

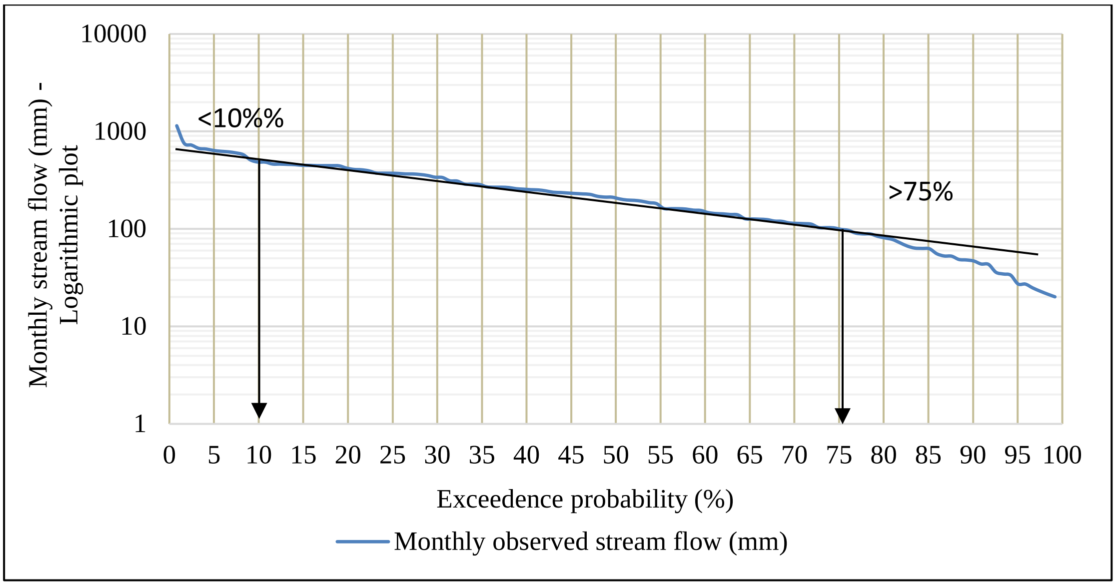

Figure 4-26: Logarithmic plot of flow Duration Curve for Kalu Ganga for the calibration period

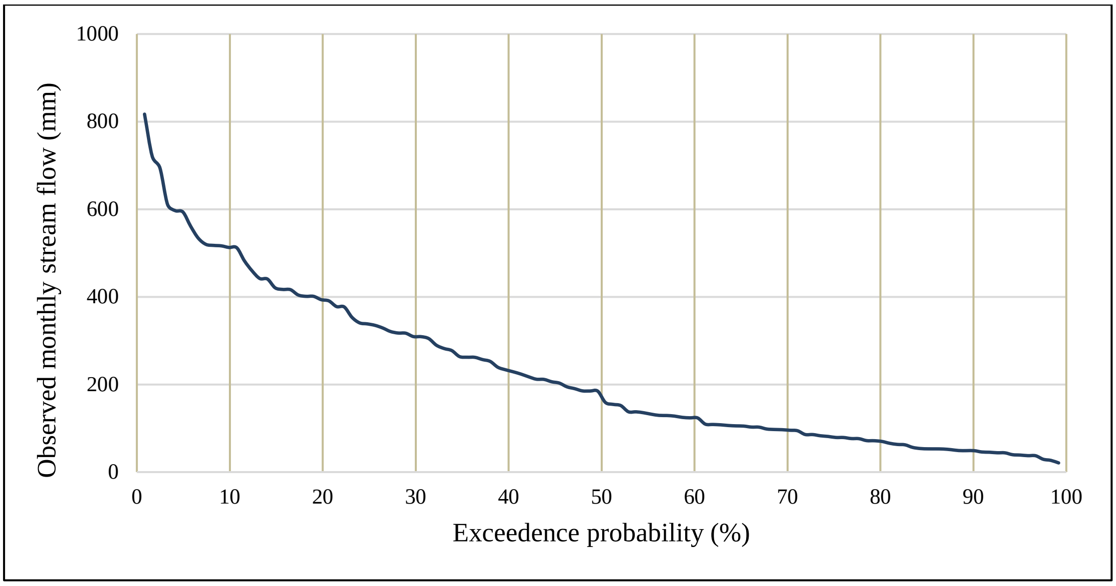

Figure 4-27: Flow Duration Curve for Kalu Ganga for the verification period

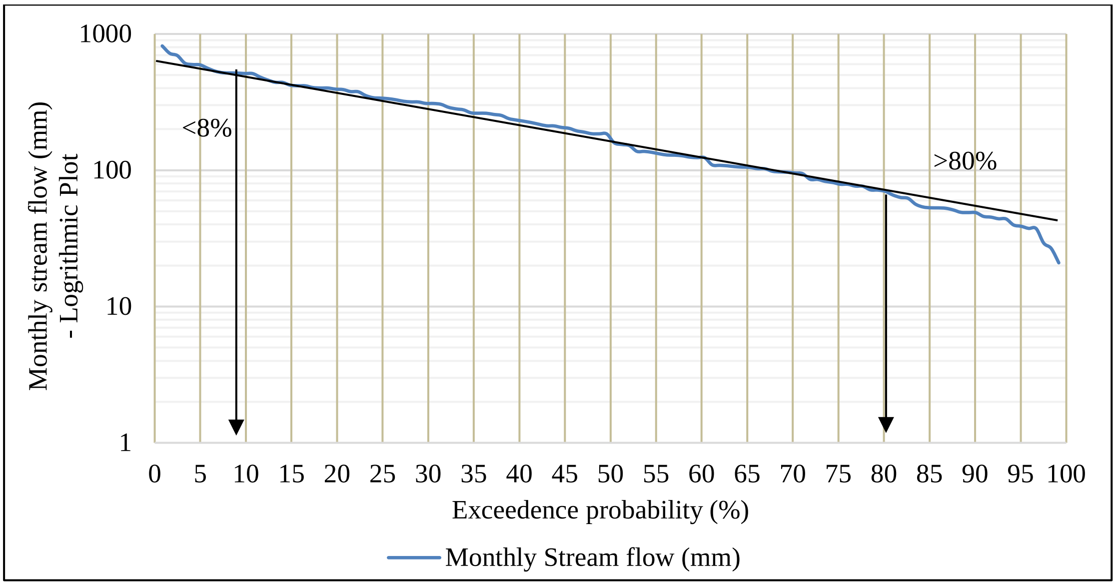

Figure 4-28: Logarithmic plot of flow Duration Curve for Kalu Ganga for the verification period

By logarithmic plots of flow duration curves, flow regimes were identified easily by using the deflection points and summarized in Table 4-7.

Table 4-7: Identified flow regimes for Gin and Kalu Ganga watersheds at Thawalama and Ellagawa

Watershed		**Flow Regime**	**Exceedance Probability**	**Relevant Discharge (mm)**
Gin Ganga at Thawalama	Calibration	High	< 10	>450
		Medium	10-80	450-140
		Low	>80	<140
	Validation	High	< 10	>420
		Medium	10-90	420-90
		Low	>90	<90
Kalu Ganga at Ellagawa	Calibration	High	< 10	>480
		Medium	10-75	480-100
		Low	>75	<100
	Validation	High	<8	>520
		Medium	8-80	520-70
		Low	>80	<70

4.6 Flow duration curve analysis for the simulated flow in Kalu Ganga and Gin Ganga

The flow duration curves for the simulated flow in both calibration and validation were plotted on top of the observed flow duration curve to check the matching of simulation visually for the three flow regimes.

4.6.1 Flow duration curve for the simulated flow in Gin Ganga for calibration period

For Gin Ganga, simulated flow was plotted for the corresponding observed flow in the flow duration curves in normal and logarithmic plots considering calibration period as shown in Figure 4-29 and Figure 4-30.

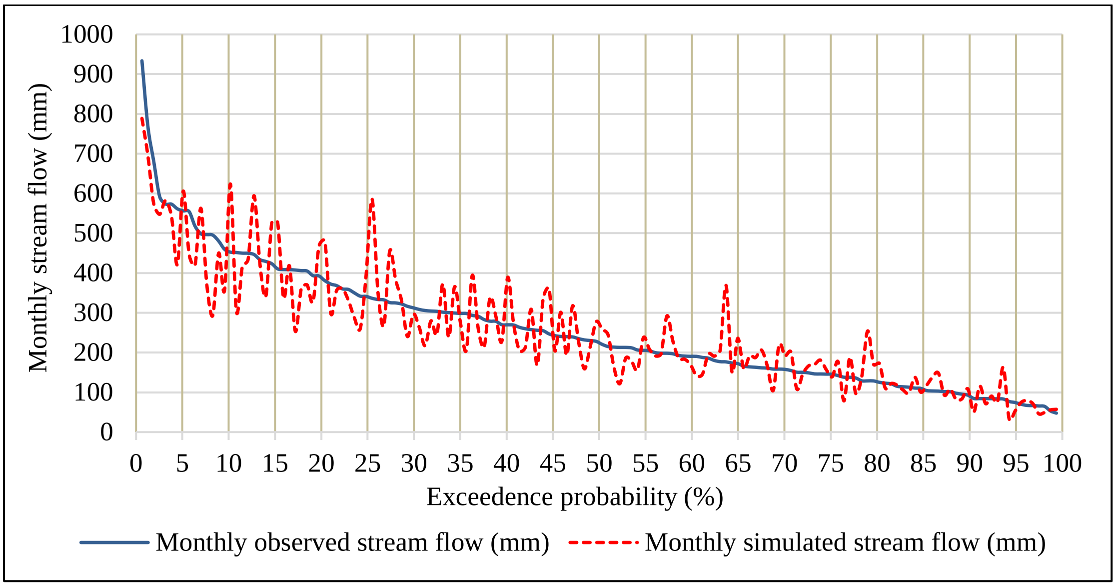

Figure 4-29: Flow Duration Curve for observed and simulated flow in Gin Ganga for Calibration

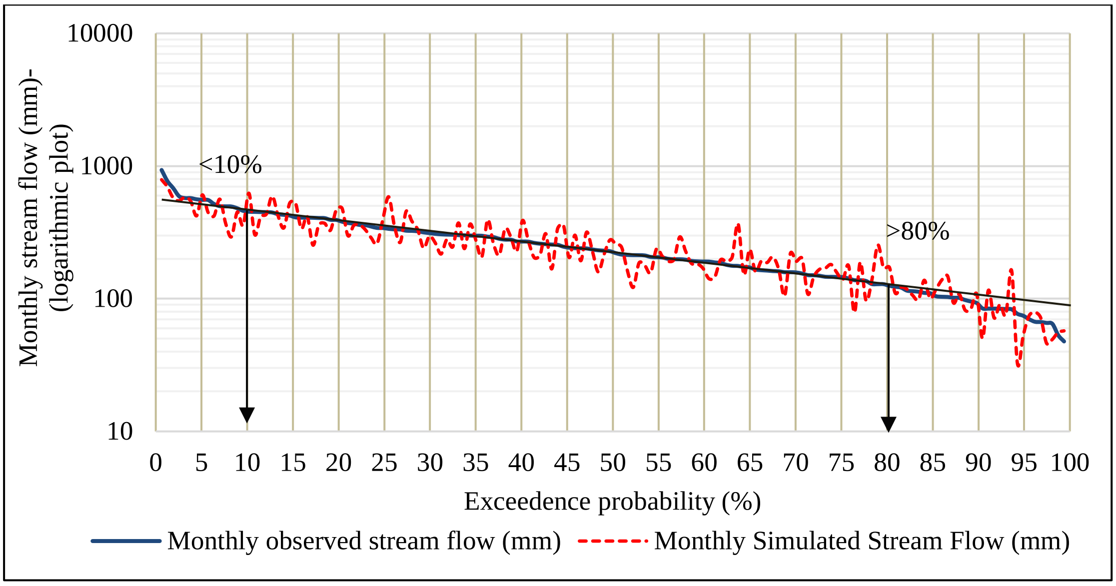

Figure 4-30: Logarithmic plot of flow Duration Curve for observed and simulated flow in Gin Ganga for Calibration

4.6.2 Flow duration curve for the simulated flow in Gin Ganga for validation period

For Gin Ganga, simulated flow was plotted for the corresponding observed flow in the flow duration curves in normal and logarithmic plots considering validation period as shown in Figure 4-31 and Figure 4-32.

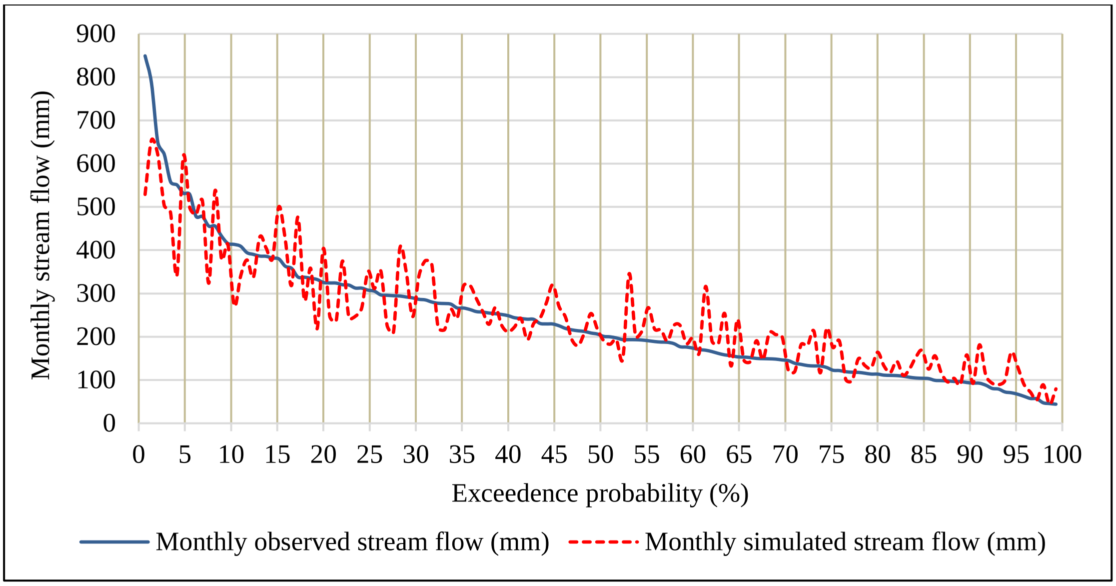

Figure 4-31: Flow Duration Curve for observed and simulated flow in Gin Ganga for Validation

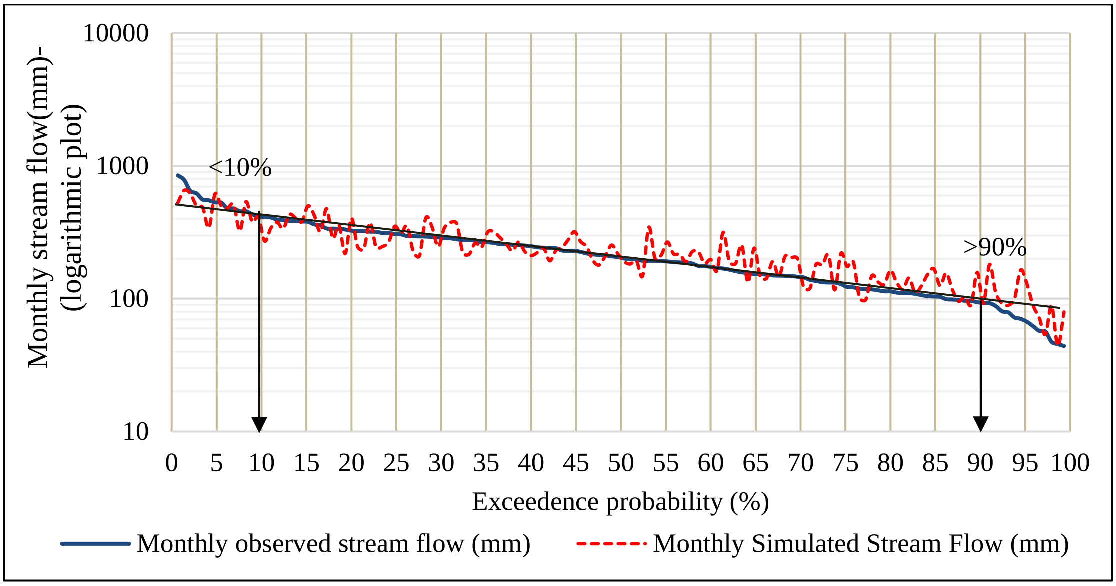

Figure 4-32: Logarithmic plot of flow Duration Curve for observed and simulated flow in Gin Ganga for Validation

4.6.3 Flow duration curve for the simulated flow in Kalu Ganga for calibration period

For Kalu Ganga, simulated flow was plotted for the corresponding observed flow in the flow duration curves in normal and logarithmic plots considering calibration period as shown in Figure 4-33 and Figure 4-34.

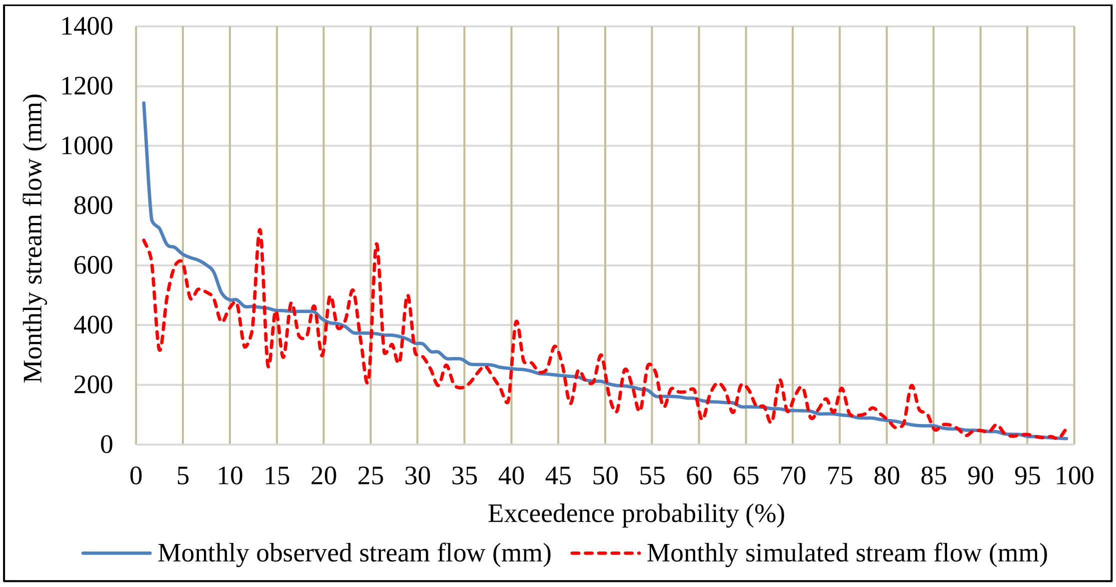

Figure 4-33: Flow Duration Curve for observed and simulated flow in Kalu Ganga for Calibration

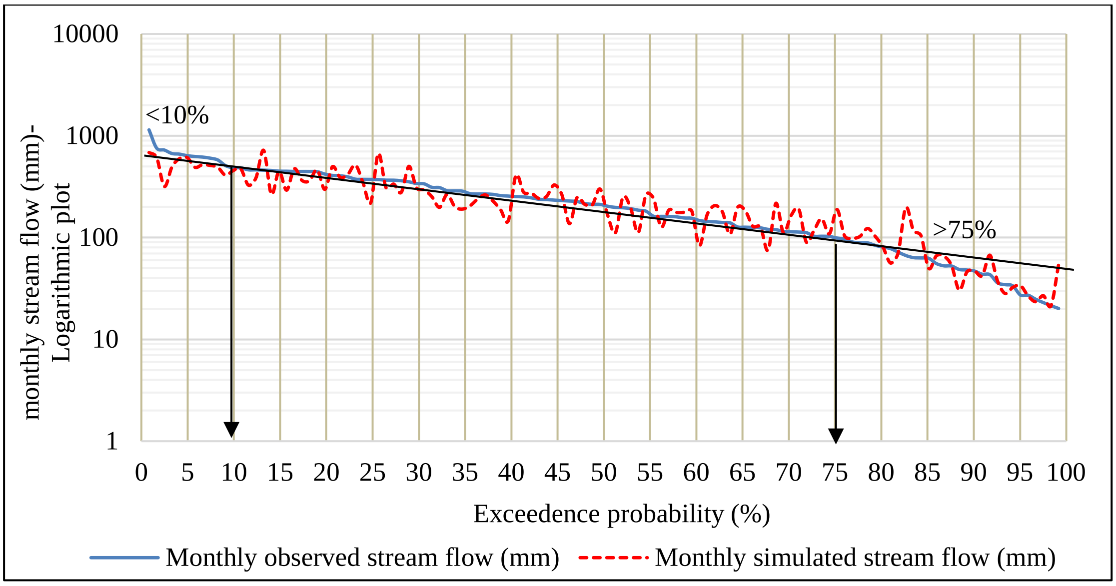

Figure 4-34: Logarithmic plot of flow Duration Curve for observed and simulated flow in Kalu Ganga for calibration

4.6.4 Flow duration curve for the simulated flow in Kalu Ganga for validation period

For Kalu Ganga, simulated flow was plotted for the corresponding observed flow in the flow duration curves in normal and logarithmic plots considering validation period as shown in Figure 4-35 and Figure 4-36.

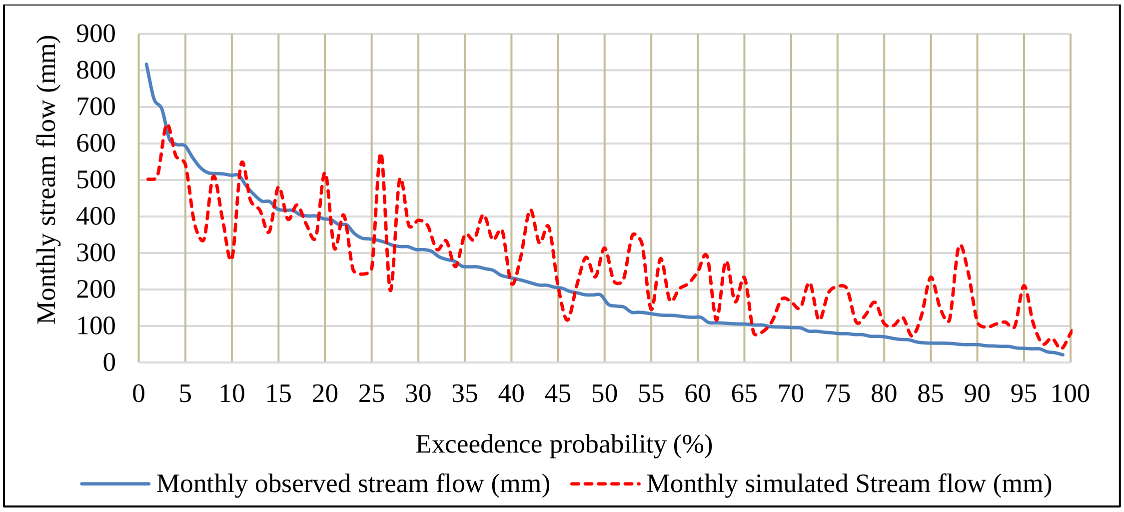

Figure 4-35: Flow Duration Curve for observed and simulated flow in Kalu Ganga for Validation

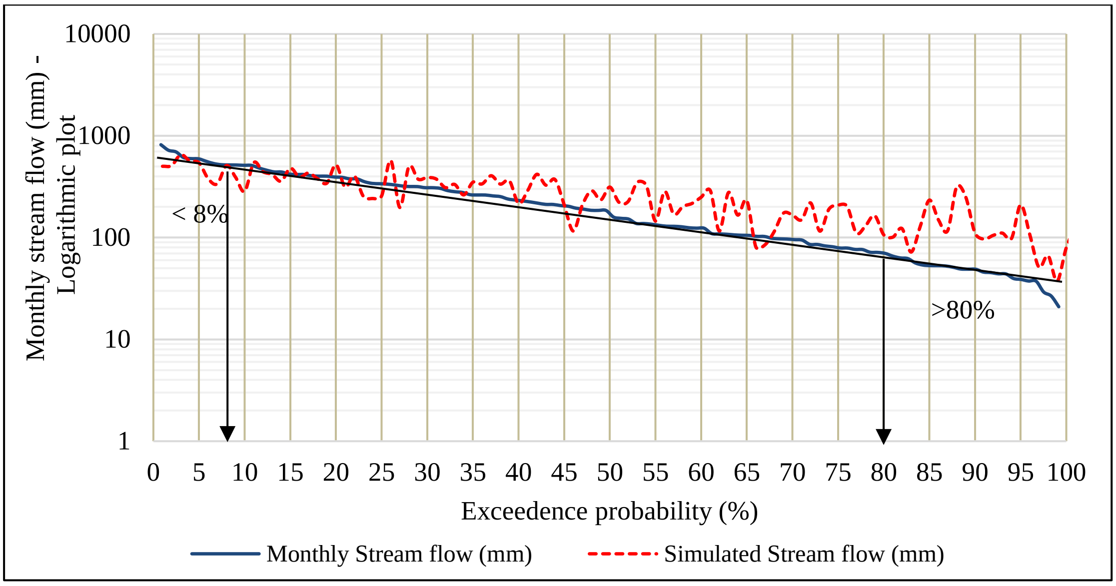

Figure 4-36: Logarithmic plot of flow Duration Curve for observed and simulated flow in Kalu Ganga for validation

4.7 Model suitability analysis for different flow regimes

After the overall calibration and validation of ‘abcd’ model, it is important to check the performance of the model for different flow regimes which had been identified and summarized under Table 4-8. By using this high, medium and low regime criterion, the observed flow was divided, and the objective functions were checked. Since the quantity of data specially for high and low flow regimes is low, Nash Sutcliffe efficiency criteria was highly deviated and did not consider for checking. But MRAE criteria gave appropriate results except in low flow regime for both watersheds. The results of flow regime analysis are presented in Table 4-8.

Table 4-8: MRAE for high medium and low flows

Watershed	Flow Regime	MRAE	
		Calibration	Validation
Thawalama	High	0.18	0.17
	Medium	0.20	0.22
	Low	0.24	0.47
Ellagawa	High	0.19	0.25
	Medium	0.25	0.38
	Low	0.32	0.43

4.8 Parameter sensitivity analysis

It is expected that in future, the catchment conditions will change, affecting the model parameters. These timely changes in the parameters can affect the validity of the model making it not suitable anymore.

Model parameter sensitivity analysis was performed in this research to identify which input parameter contribute most to output variability and once the model is in production use, what consequence results from changing a given input parameter.

The overall parameter sensitivity analysis was carried out calculating the sensitivity index (SI) by varying a parameter in its full range while keeping the other parameters fixed considering the dependent variables as MRAE, NSE, average annual water balance difference and the standard deviation of average annual water balance difference as shown from Figure 4-37 to Figure 4-44.

The local sensitivity analysis was carried out to identify the parameter which is having the highest variability at different percentage changes from respective optimized values. The percentages which have been varied from optimized parameter value were selected considering a common range for all the parameters. The respective plots have been shown from Figure 4-45 to Figure 4-48.

4.8.1 Overall model sensitivity analysis for Thawalama watershed in Gin Ganga by varying the parameters in their full range

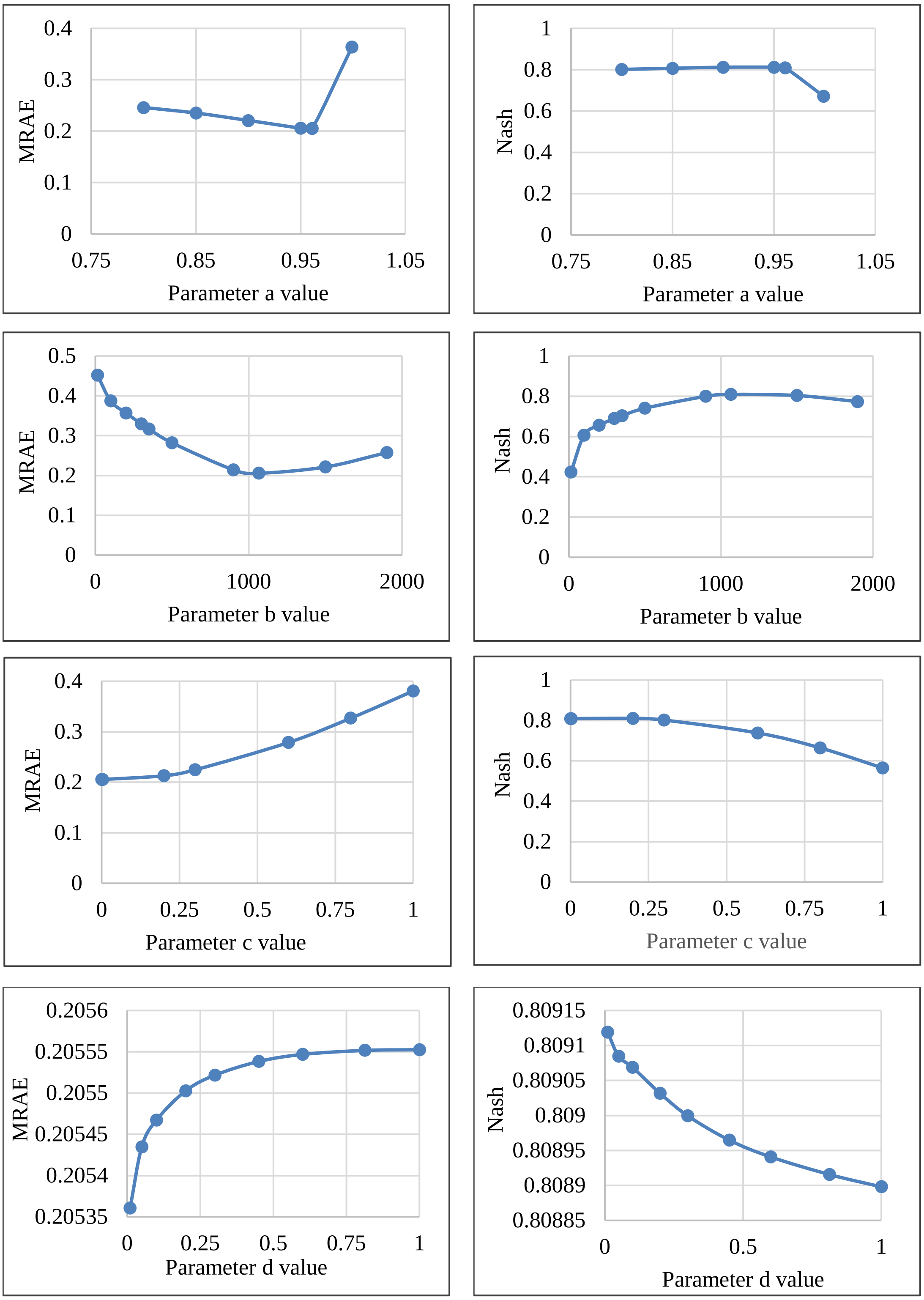

Figure 4-37: Variation of objective functions verses parameters for calibration period - Gin Ganga

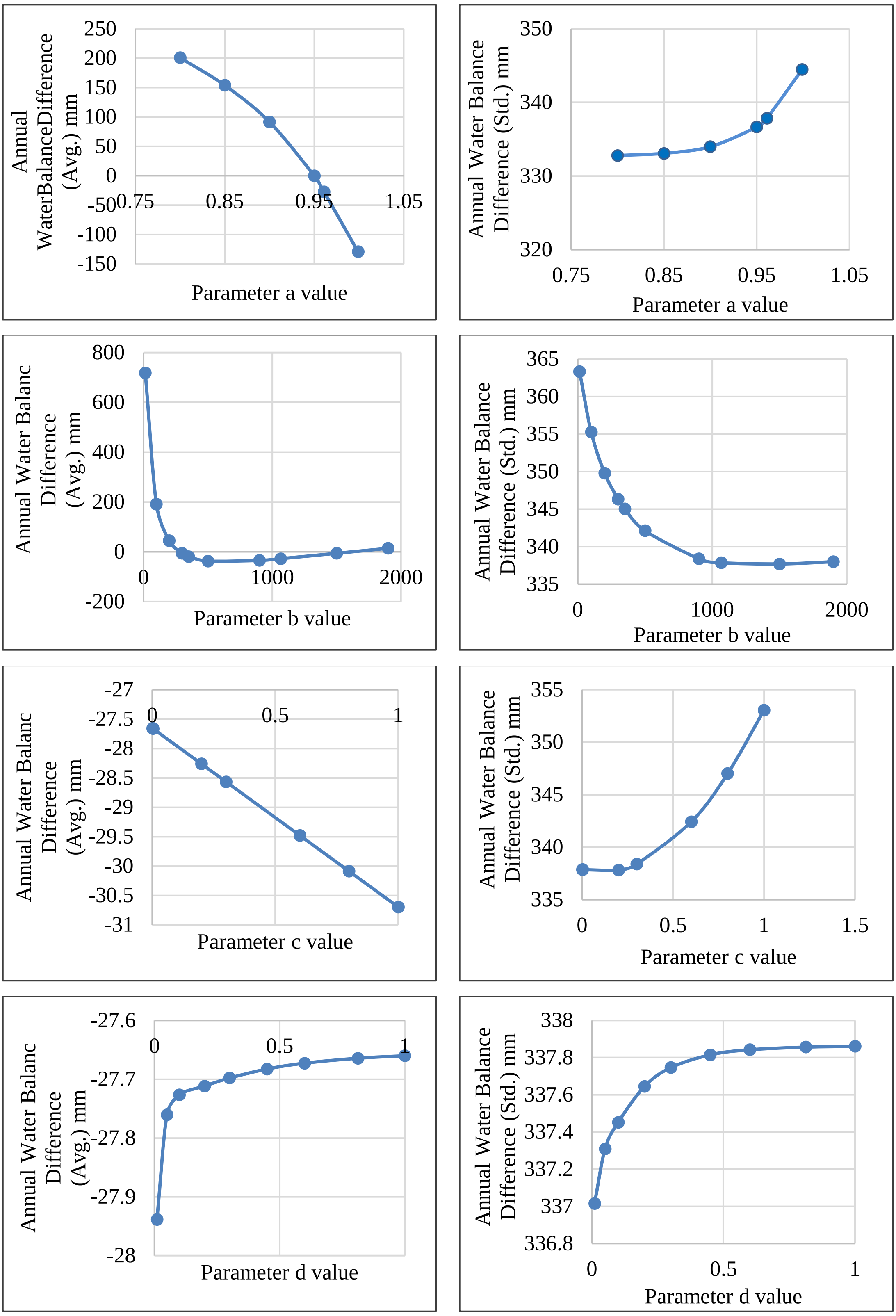

Figure 4-38 :Variation of average and standard deviation of annual water balance difference verses parameters for calibration period - Gin ganga

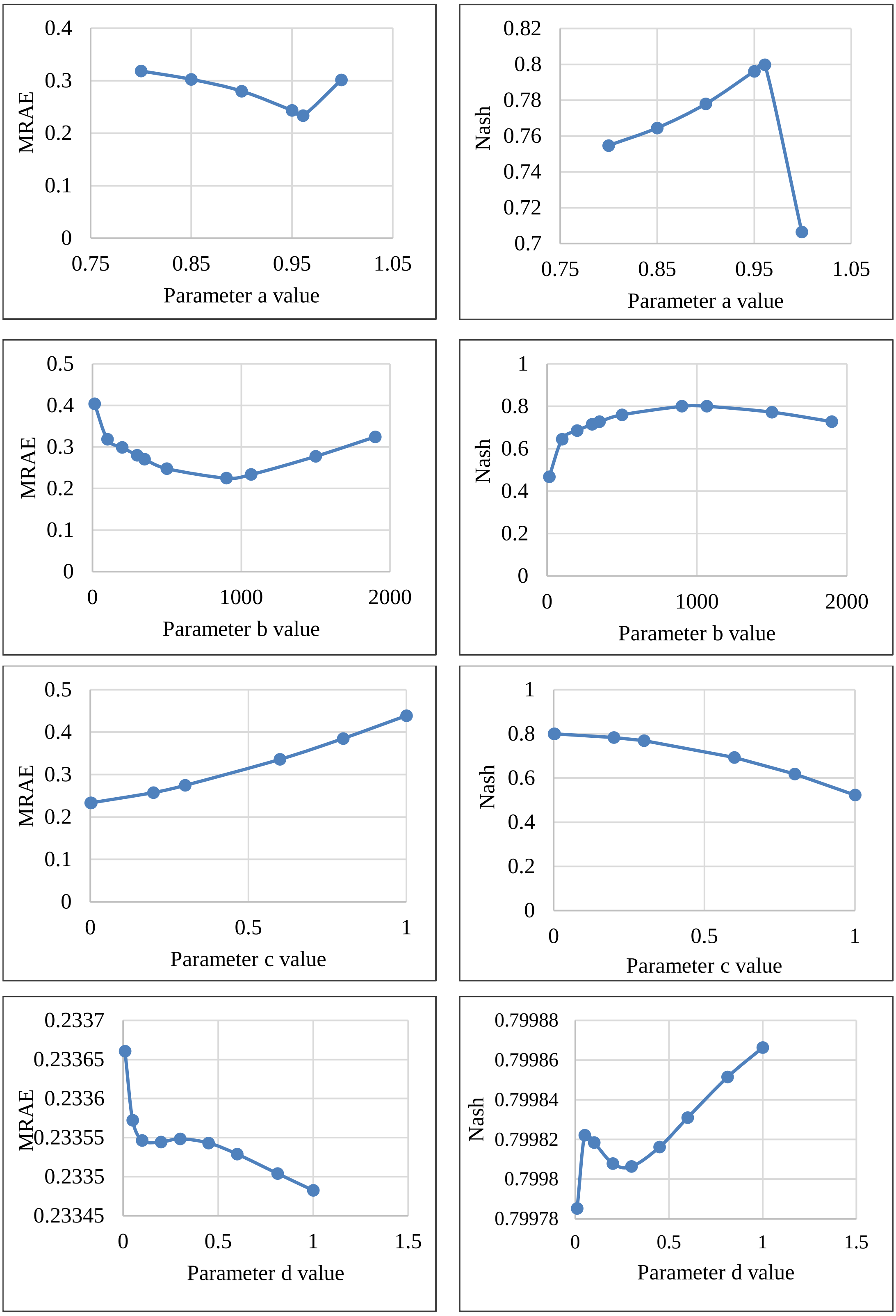

Figure 4-39 : Variation of objective functions verses parameters for validation period – Gin Ganga

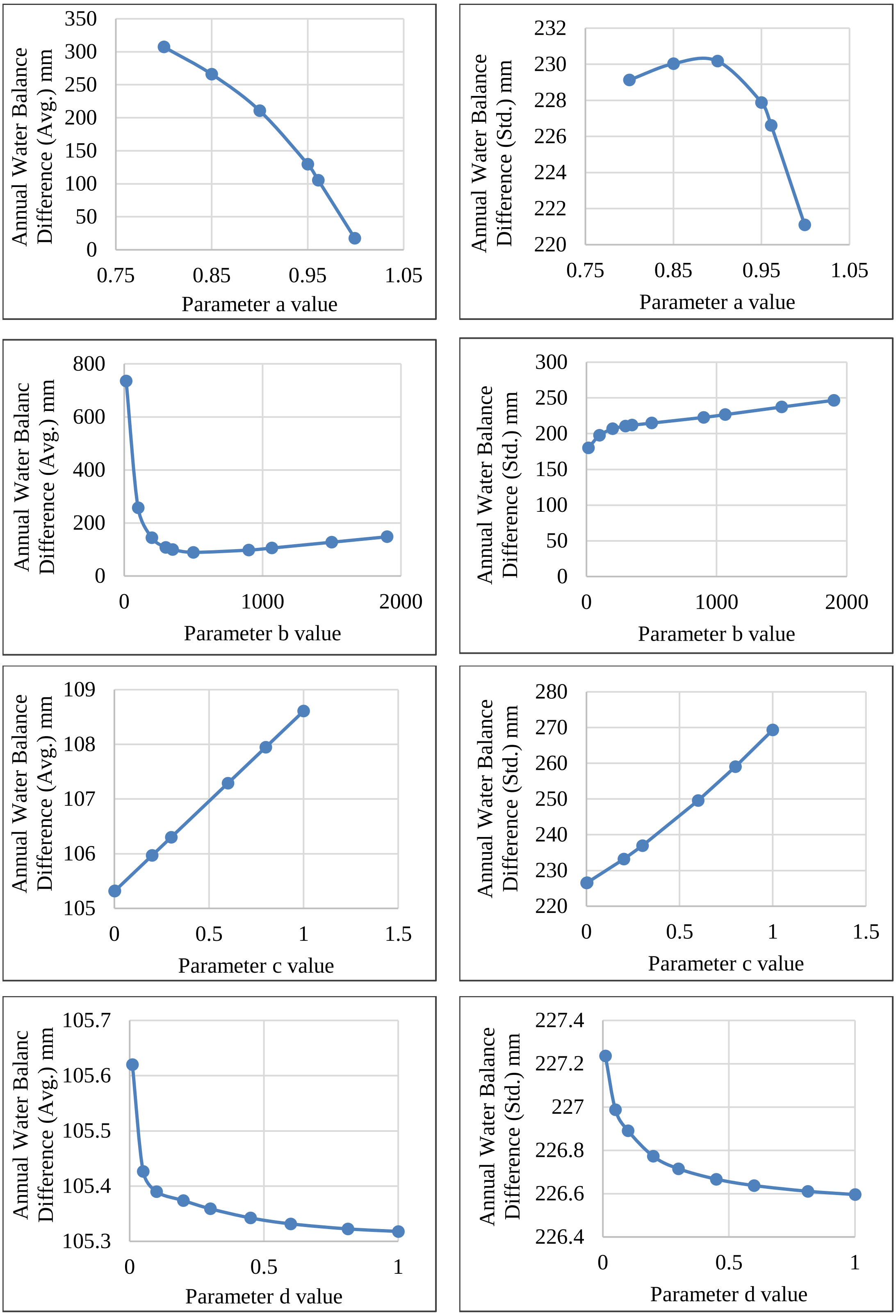

Figure 4-40 :Variation of average and standard deviation of annual water balance difference verses parameters for validation period - Gin ganga

4.8.2 Overall model sensitivity analysis for Ellagawa watershed in Kalu Ganga by varying the parameters in their full range

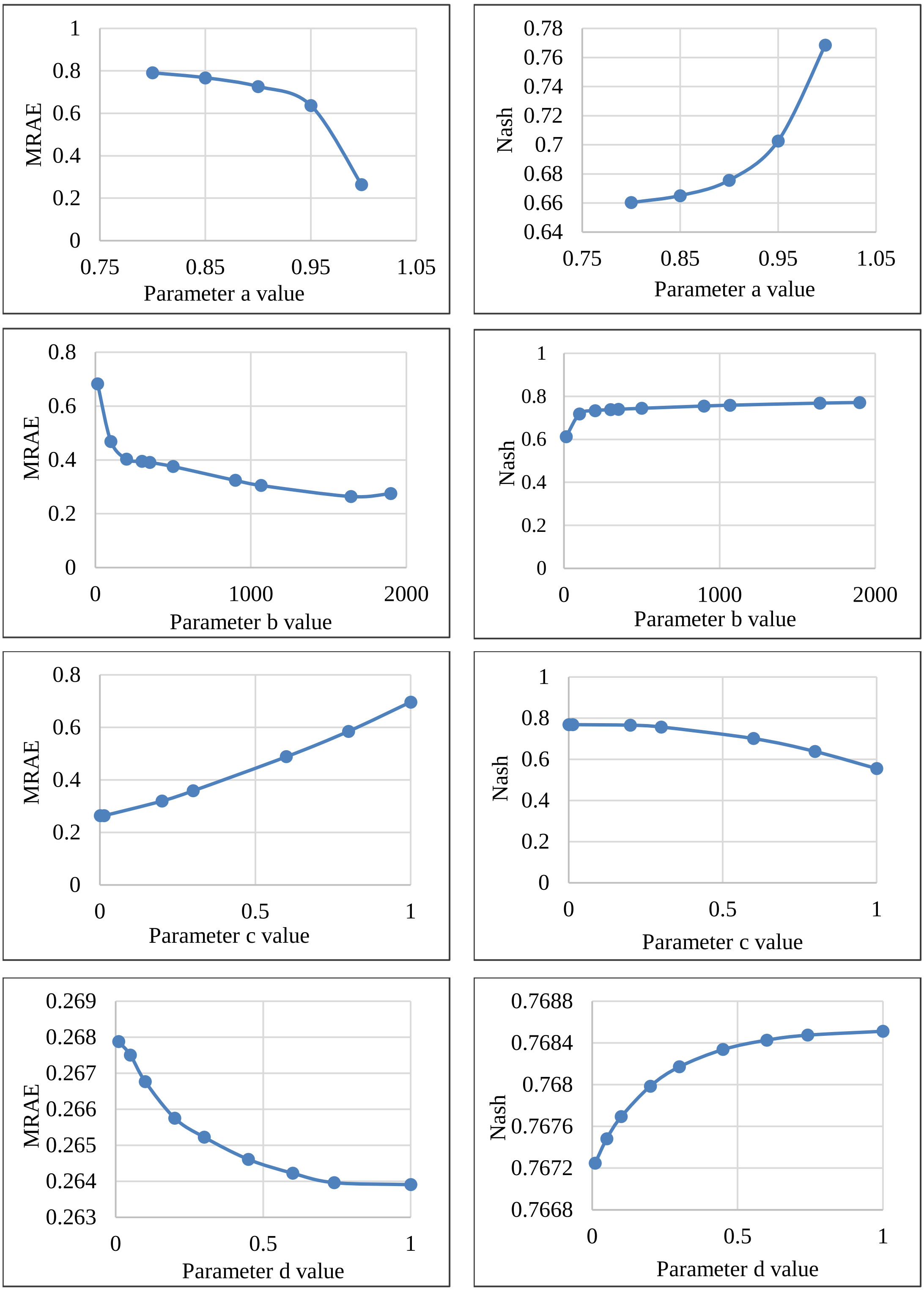

Figure 4-41: Variation of objective functions verses parameters for calibration period - Kalu Ganga

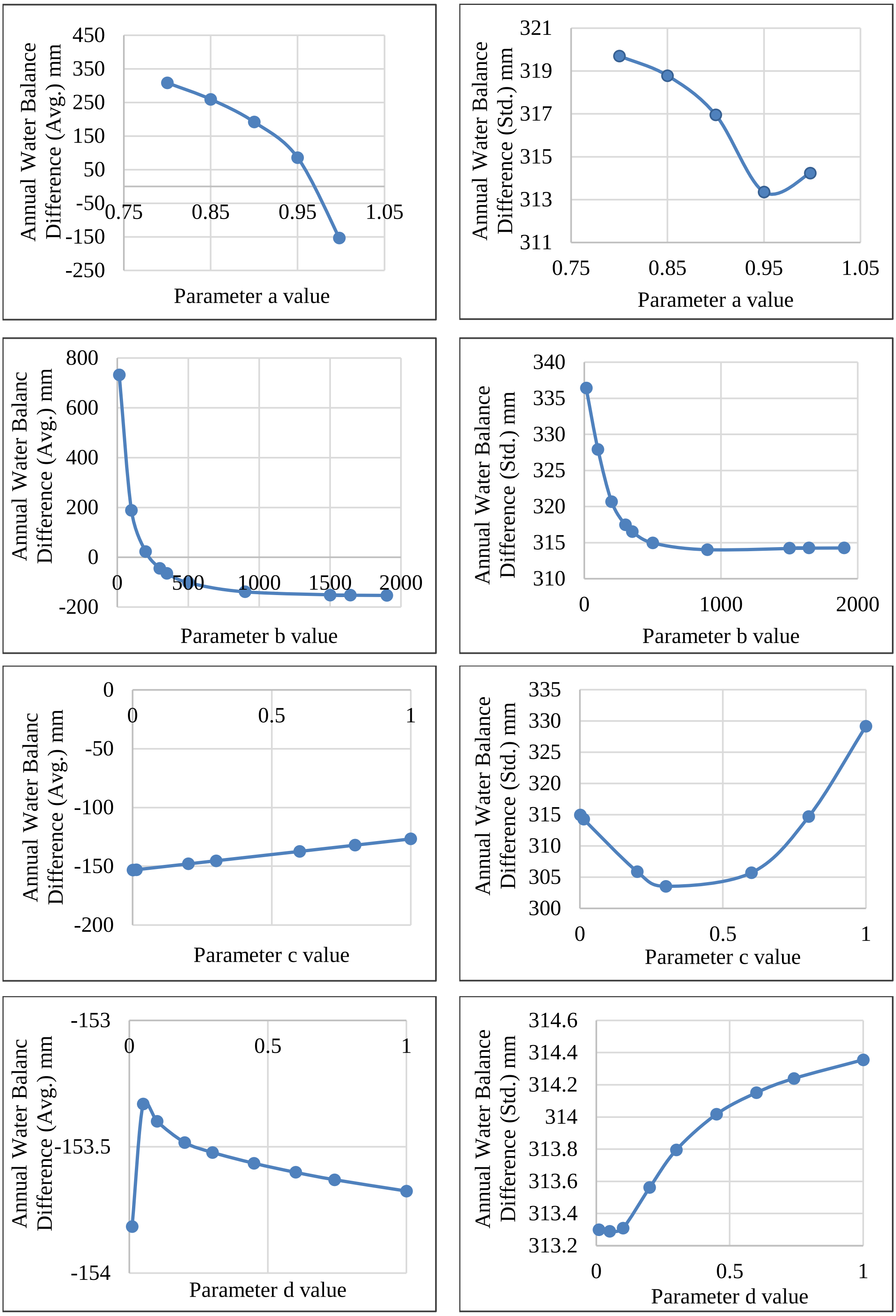

Figure 4-42 :Variation of average and standard deviation of annual water balance difference verses parameters for calibration period - Kalu ganga

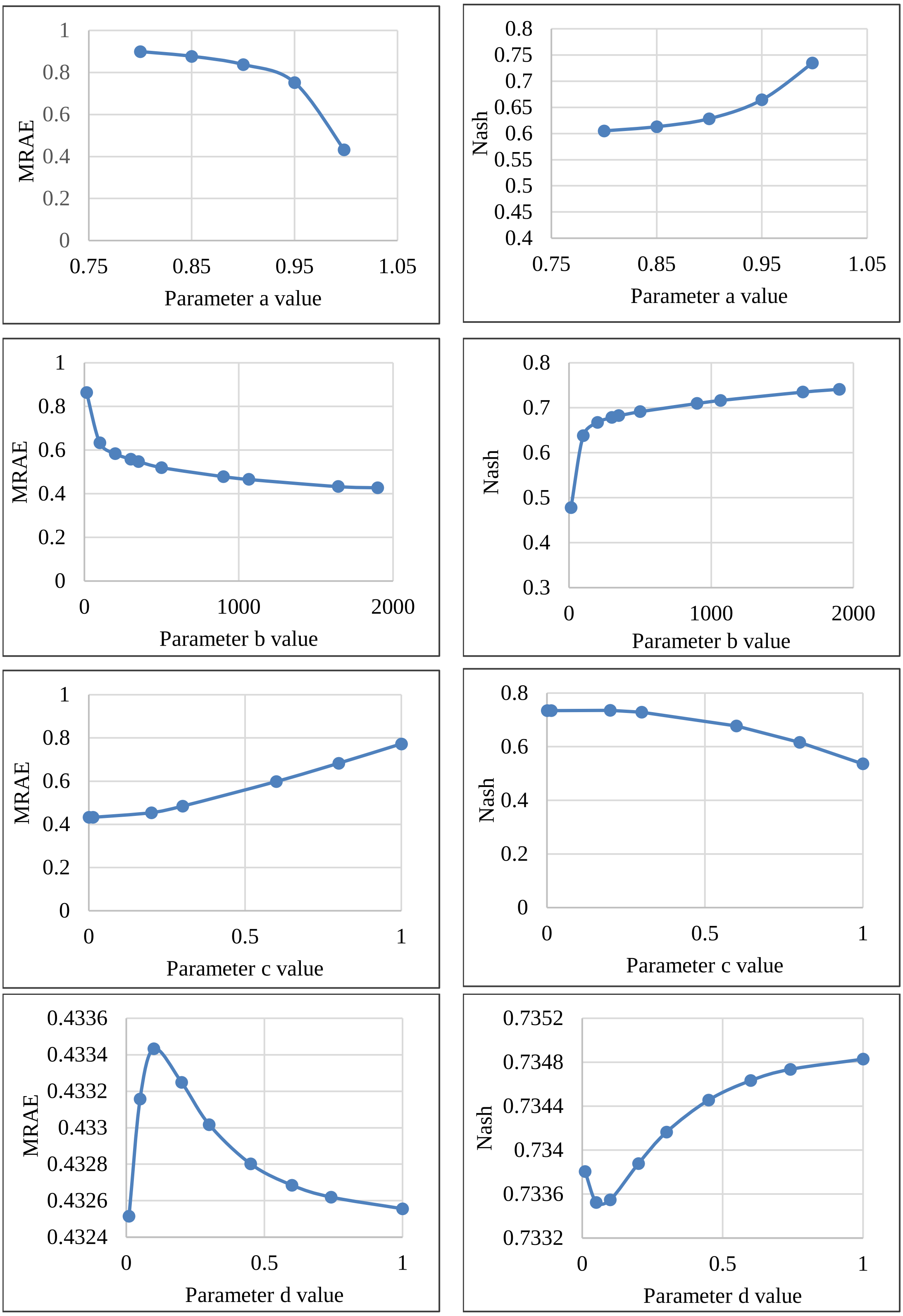

Figure 4-43: Variation of objective functions verses parameters for validation period - Kalu Ganga

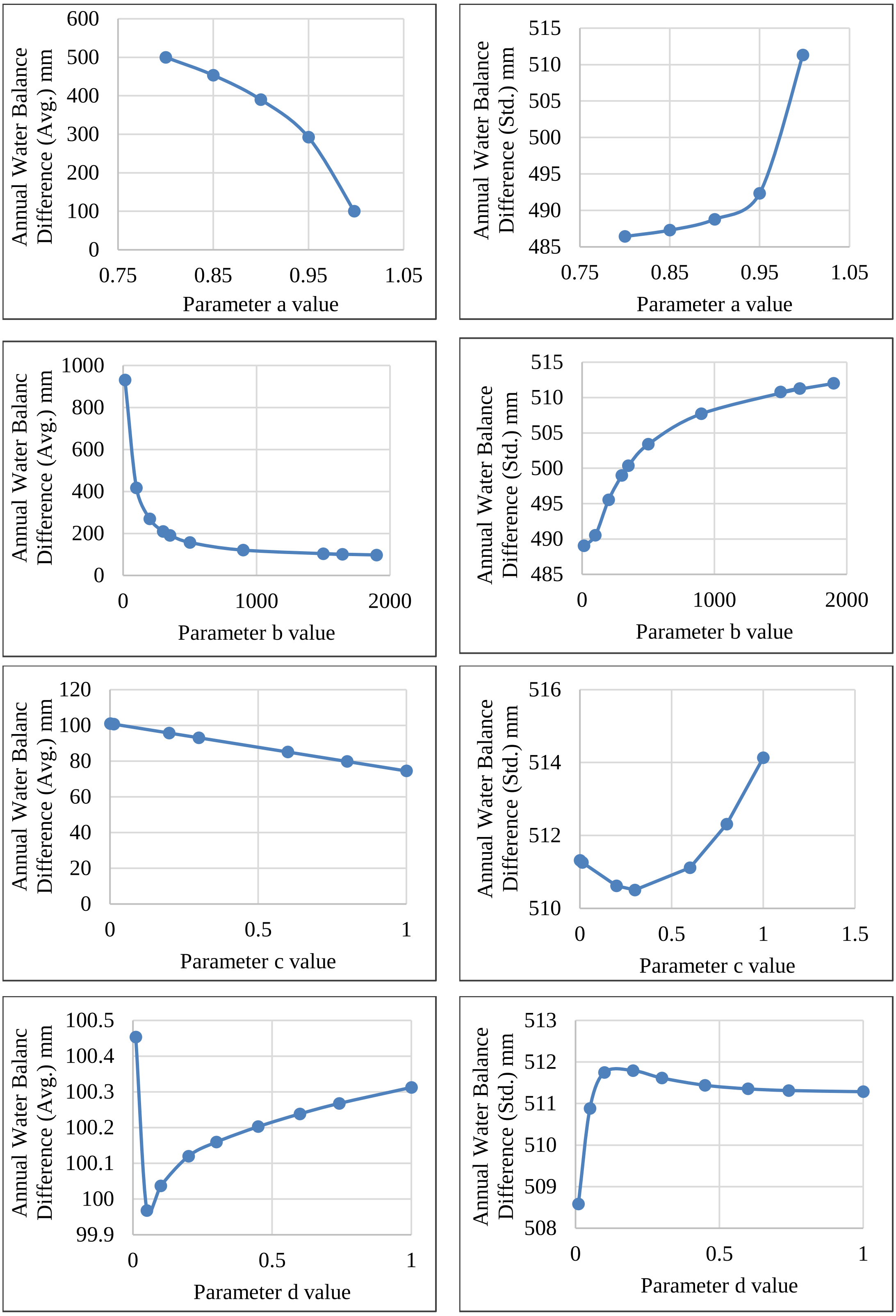

Figure 4-44 :Variation of average and standard deviation of annual water balance difference verses parameters for validation period - Kalu Ganga

4.8.3 Local sensitivity analysis for Thawalama watershed in Gin Ganga

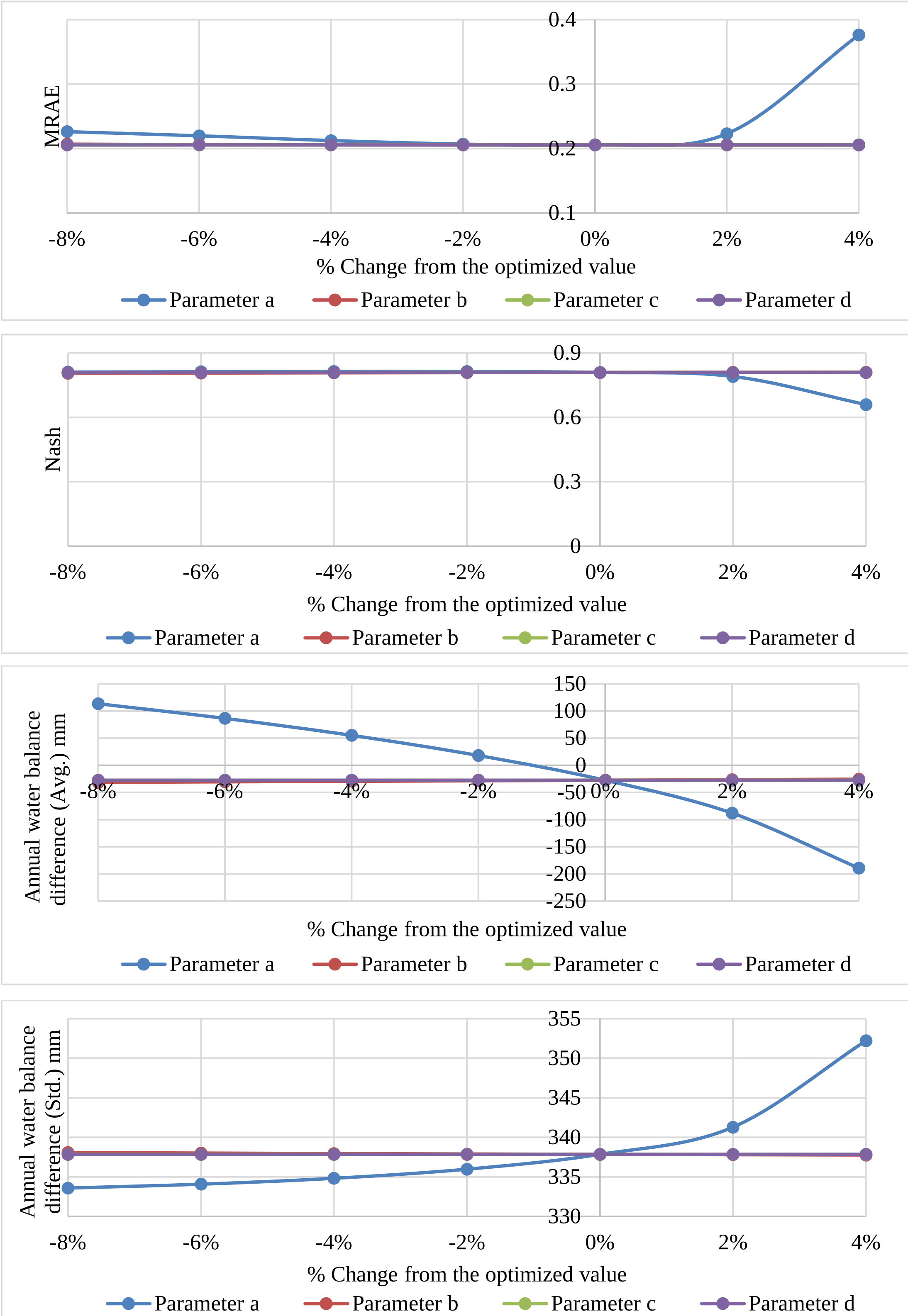

Figure 4-45 : Local sensitivity analysis for calibration period – Gin Ganga

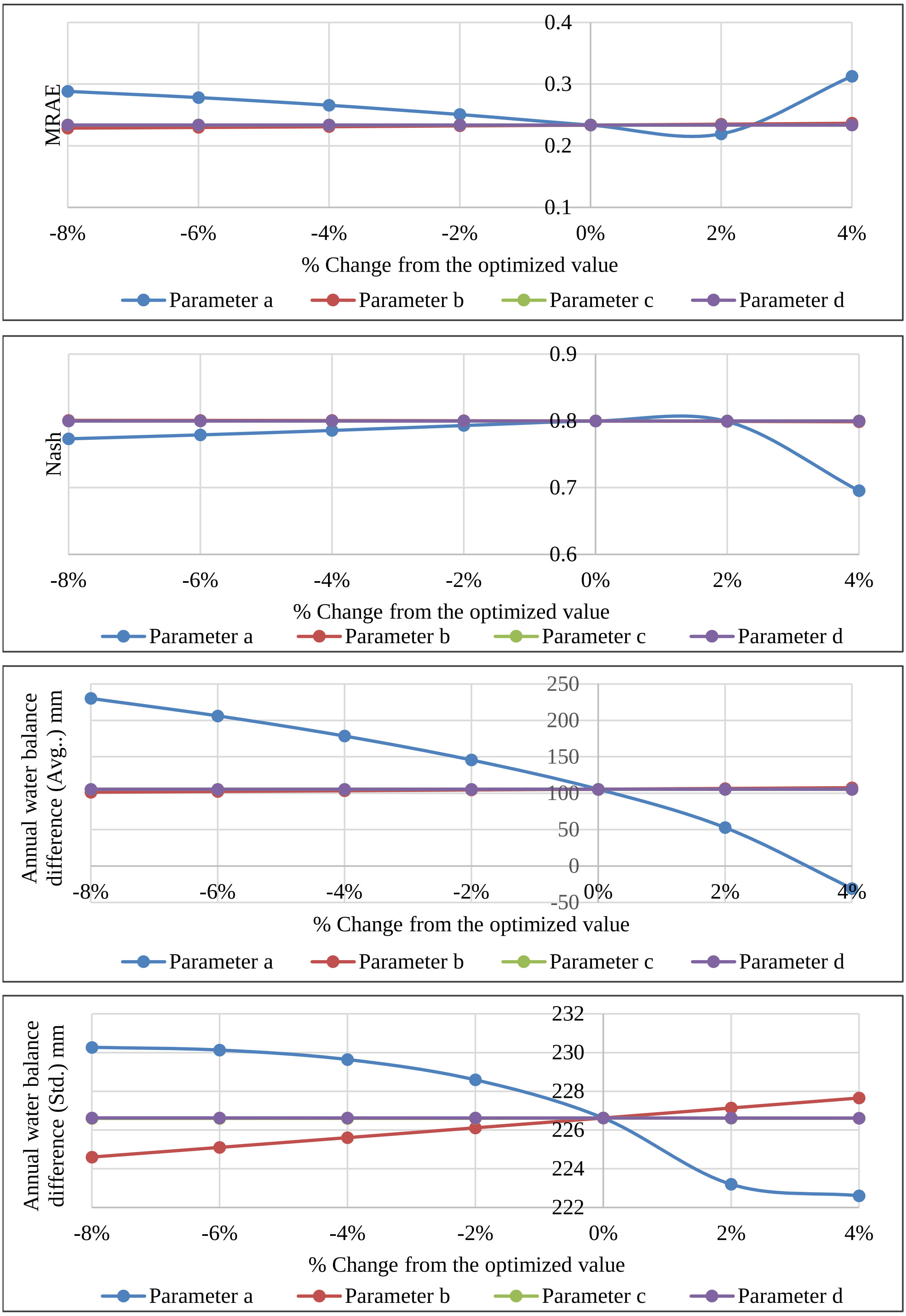

Figure 4-46 : Local sensitivity analysis for validation period – Gin Ganga

4.8.4 Local sensitivity analysis for Ellagawa watershed in Kalu Ganga

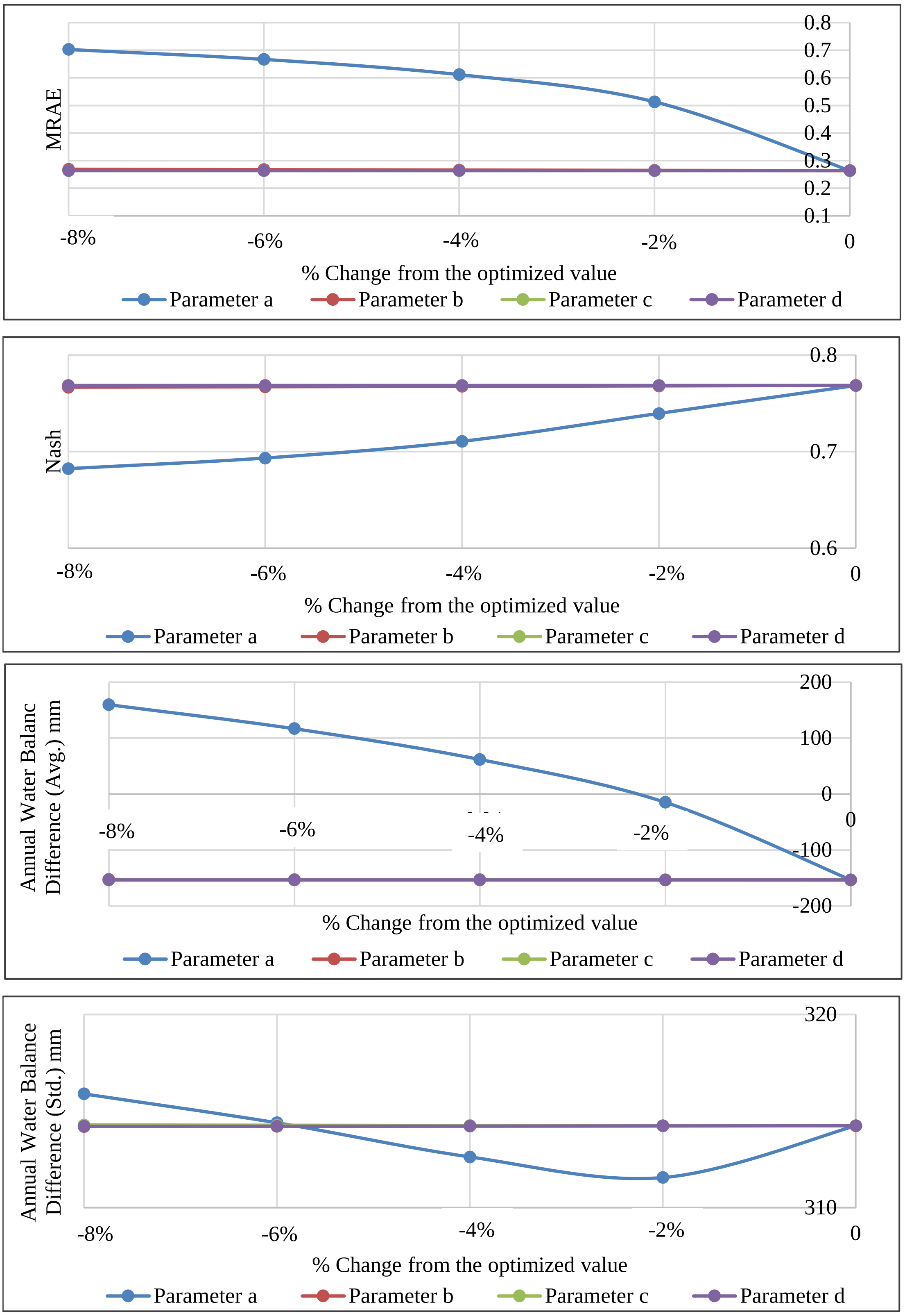

Figure 4-47 :Local sensitivity analysis for calibration period - Kalu Ganga

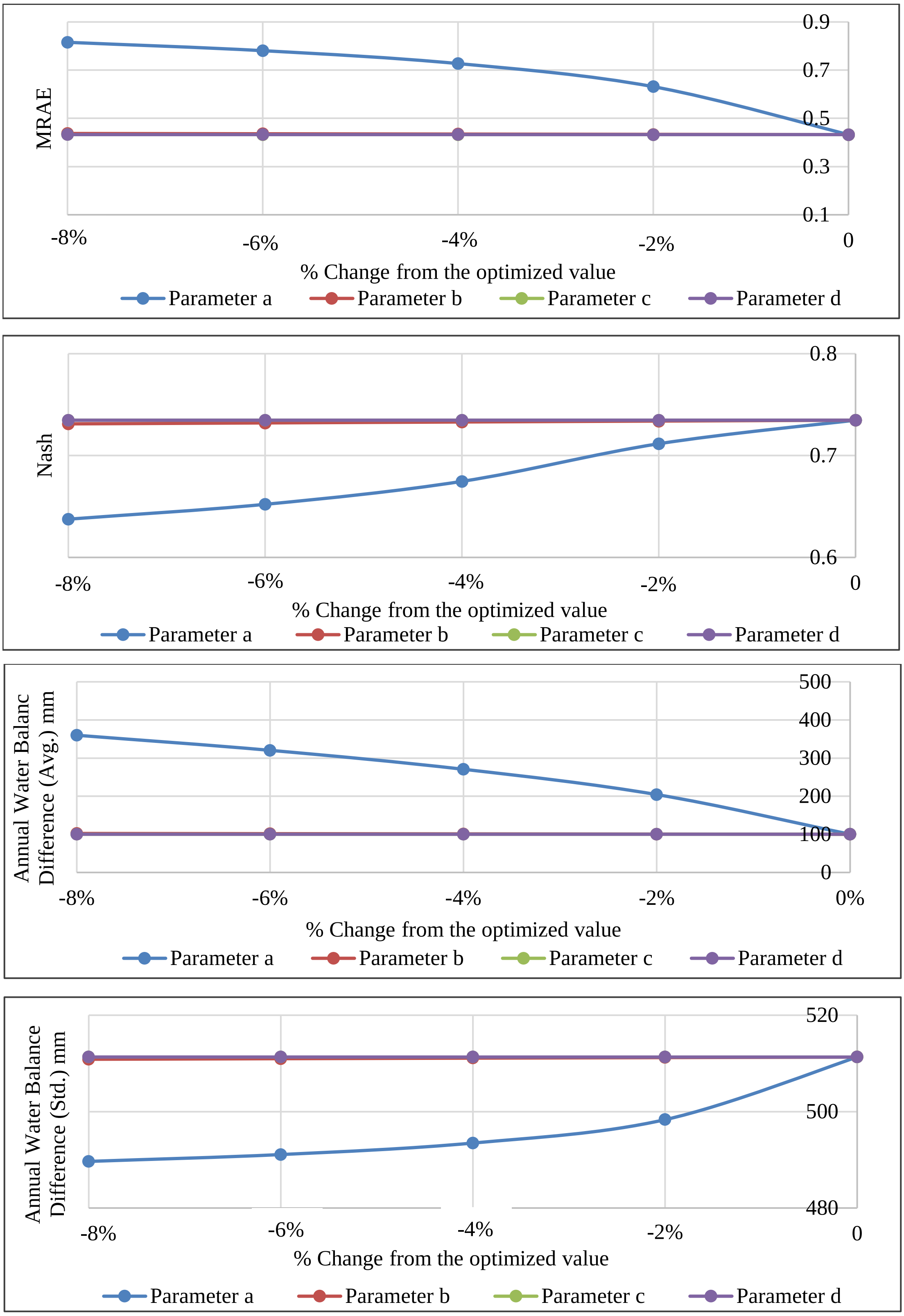

Figure 4-48 :Local sensitivity analysis for validation period - Kalu Ganga

Table 4-9: Calculated Sensitivity Index (SI) for a,b,c,d parameters in Gin Gaga for calibration period considering different outputs

Parameter	MRAE	NSE	Annual Water Balance Difference (Avg.)	Annual Water Balance Difference (Std.)
a	0.44	0.17	1.64	0.03
b	0.55	0.48	1.05	0.07
c	0.46	0.30	-0.11	0.04
d	0.0009	0.0003	-0.0101	0.0025

Table 4-10: Calculated Sensitivity Index (SI) for a,b,c,d parameters in Gin Gaga for validation period considering different outputs

Parameter	MRAE	NSE	Annual Water Balance Difference (Avg.)	Annual Water Balance Difference (Std.)
a	0.27	0.12	0.94	0.04
b	0.44	0.42	0.88	0.27
c	0.47	0.35	0.03	0.16
d	0.0008	0.0001	0.0029	0.0028

Table 4-11: Calculated Sensitivity Index (SI) for a,b,c,d parameters in Kalu Gaga for calibration period considering different outputs

Parameter	MRAE	NSE	Annual Water Balance Difference (Avg.)	Annual Water Balance Difference (Std.)
a	0.67	0.14	1.50	0.02
b	0.61	0.21	1.21	0.07
c	0.62	0.28	-0.21	0.08
d	0.015	0.002	-0.003	0.003

Table 4-12: Calculated Sensitivity Index (SI) for a,b,c,d parameters in Kalu Gaga for validation period considering different outputs

Parameter	MRAE	NSE	Annual Water Balance Difference (Avg.)	Annual Water Balance Difference (Std.)
a	0.52	0.18	0.80	0.05
b	0.51	0.35	0.90	0.04
c	0.44	0.27	0.26	0.01
d	0.002	0.002	0.005	0.006

By using the calculated SI values for calibration and validation periods as shown in Table 4-9, Table 4-10, Table 4-11 and Table 4-12, a compound SI was calculated by multiplying the respective SI values in calibration and validation periods to rank the a,b,c and d parameters which have been shown in Table 4-13 and Table 4-14.

Table 4-13: Ranking of a,b,c,d parameters in Gin Ganga according to compound SI

Parameter	**MRAE**	**Rank**	**NSE**	**Rank**	**Annual Water Balance Difference (Avg.)**	**Rank**	**Annual Water Balance Difference (Std.)**	**Rank**
a	0.116	3	0.020	3	1.550	1	0.001	3
b	0.241	1	0.198	1	0.924	2	0.019	1
c	0.215	2	0.105	2	-0.003	3	0.007	2
d	7.11647 E-07	4	2.76776 E-08	4	-2.88061 E-05	4	7.04398 E-06	4

Table 4-14: Ranking of a,b,c,d parameters in Kalu Ganga according to compound SI

Parameter	**MRAE**	**Rank**	**NSE**	**Rank**	**Annual Water Balance Difference (Avg.)**	**Rank**	**Annual Water Balance Difference (Std.)**	**Rank**
a	0.3459	1	0.0249	3	1.1977	1	0.0010	2
b	0.3098	2	0.0730	2	1.0827	2	0.0030	1
c	0.2733	3	0.0754	1	-0.0549	3	0.0005	3
d	3.13966 E-05	4	2.91985 E-06	4	-1.53261 E-05	4	2.1276 E-05	4

4.9 Application of the ‘abcd’ model for water resources investigation

Generally, under the water resources investigation, the soil moisture content, groundwater storage, surface runoff and groundwater flow is considered as the main components and can be readily get those as an output from the “abcd” model. Annual groundwater flow and surface water flow have been identified for both the watersheds, for calibration and validation periods separately as shown in Figure 4-49 to Figure 4-52 while the seasonal variation of groundwater flow and surface water flow is shown in Figure 4-53 to Figure 4-60. The monthly groundwater storage variation and soil moisture storage variation of both watershed has been shown in Figure 4-61 to Figure 4-66.

4.9.1 Annual groundwater flow and surface runoff

4.9.1.1 Annual groundwater flow and surface runoff – Thawalama watershed

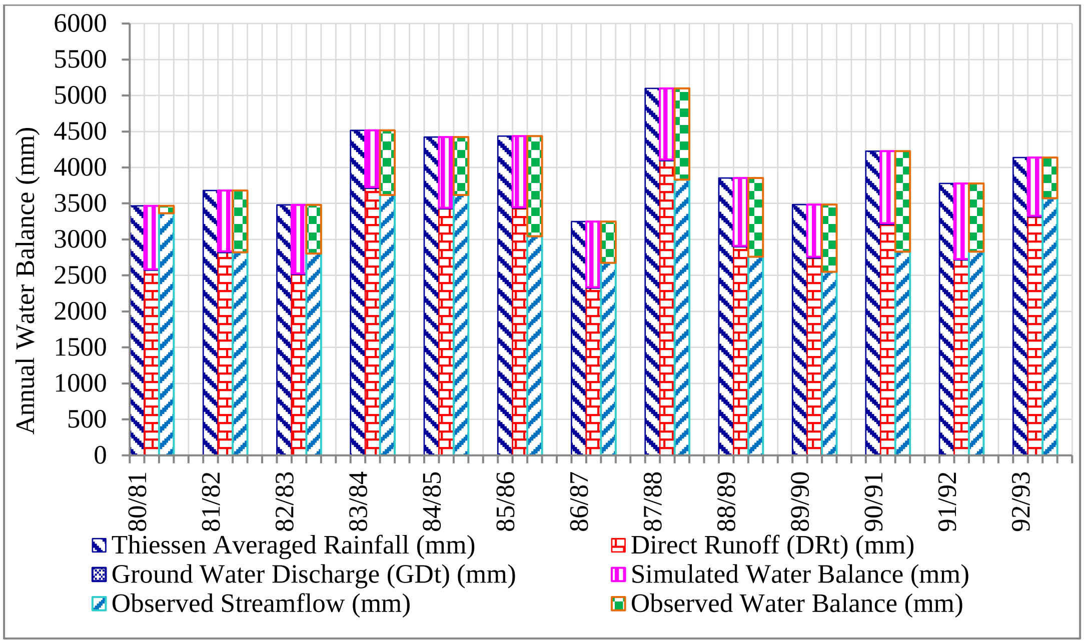

Figure 4-49: Annual surface water flow and groundwater flow of Thawalama watershed for calibration period

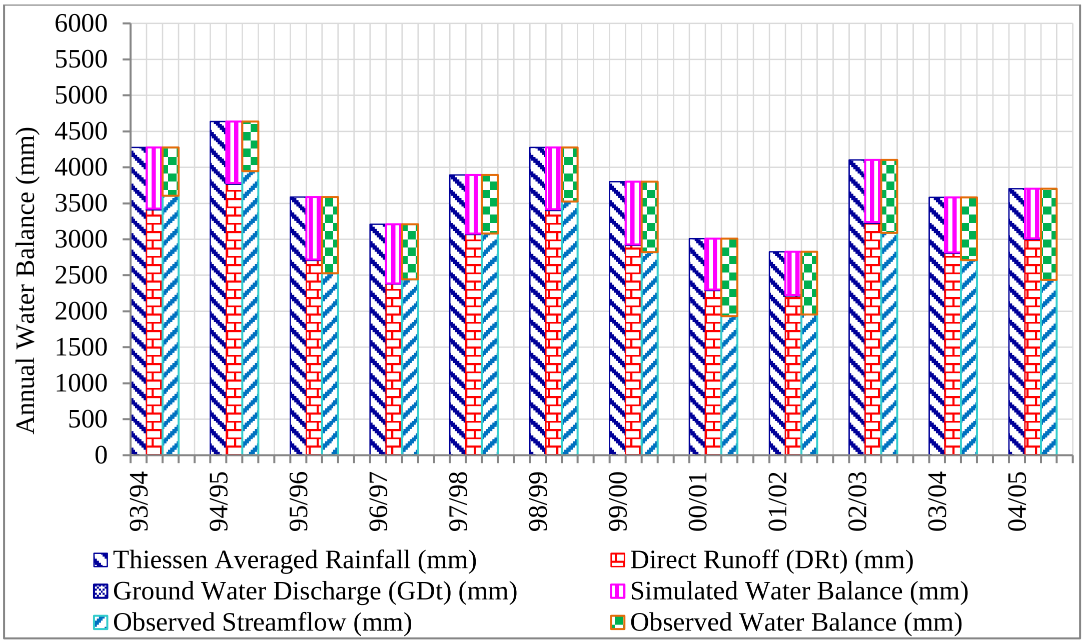

Figure 4-50: Annual surface water flow and groundwater flow of Thawalama watershed for validation period

4.9.1.2 Annual groundwater flow and surface runoff – Ellagawa watershed

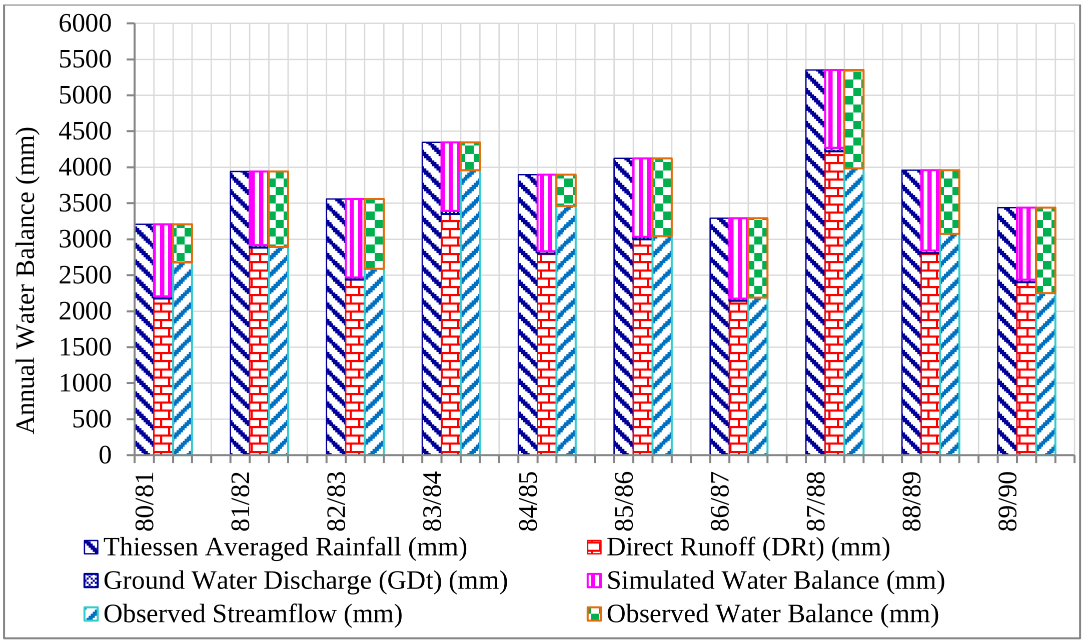

Figure 4-51: Annual surface water flow and groundwater flow of Ellagawa watershed for calibration period

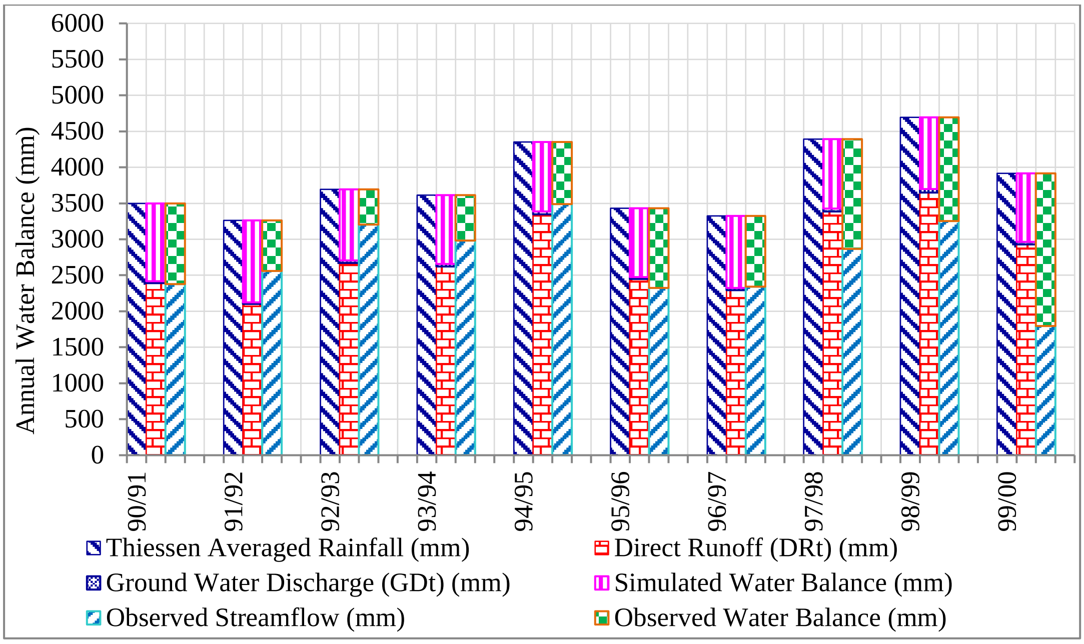

Figure 4-52: Annual surface water flow and groundwater flow of Ellagawa watershed for validation period

4.9.2 Seasonal groundwater flow and surface runoff

4.9.2.1 Seasonal groundwater flow and surface runoff –Thawalama watershed

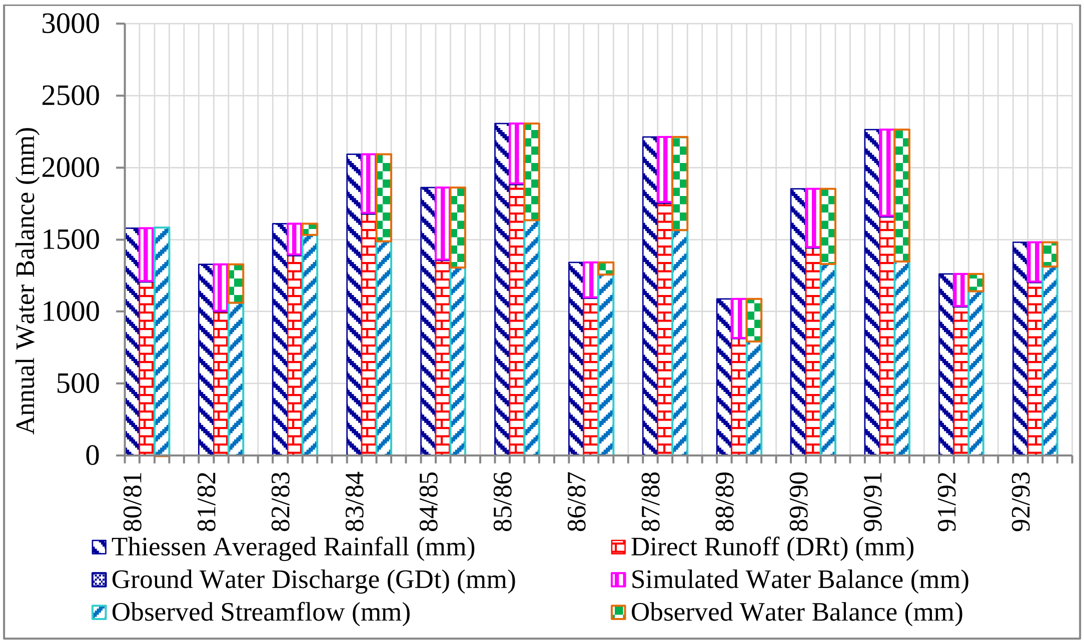

Figure 4-53: Surface water flow and groundwater flow of Thawalama watershed for calibration period -Maha season

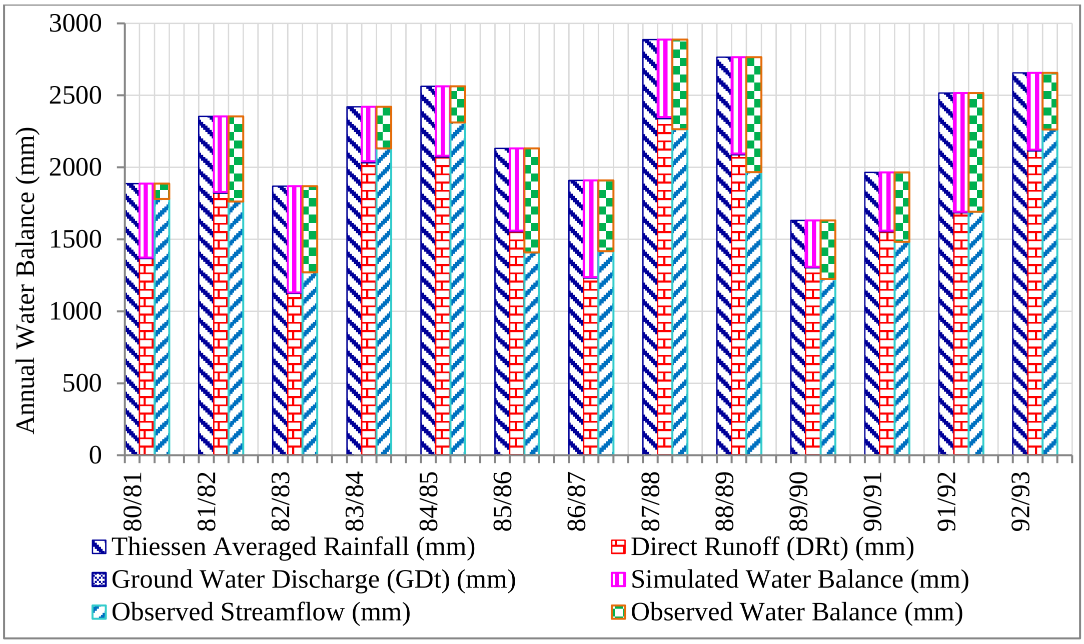

Figure 4-54: Surface water flow and groundwater flow of Thawalama watershed for calibration period -Yala season

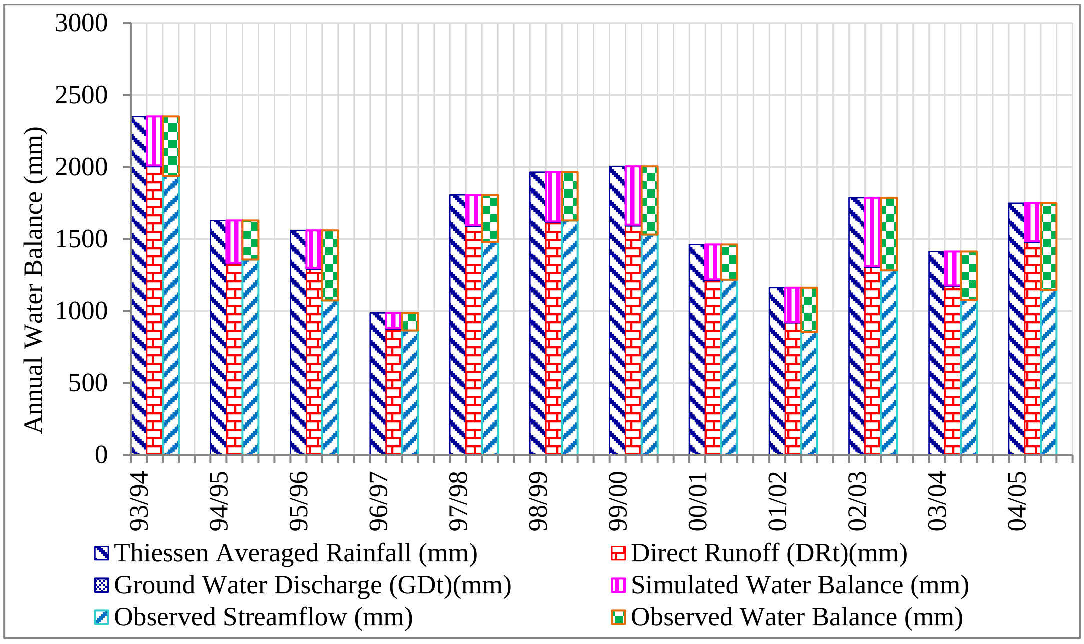

Figure 4-55: Surface water flow and groundwater flow of Thawalama watershed for validation period -Maha season

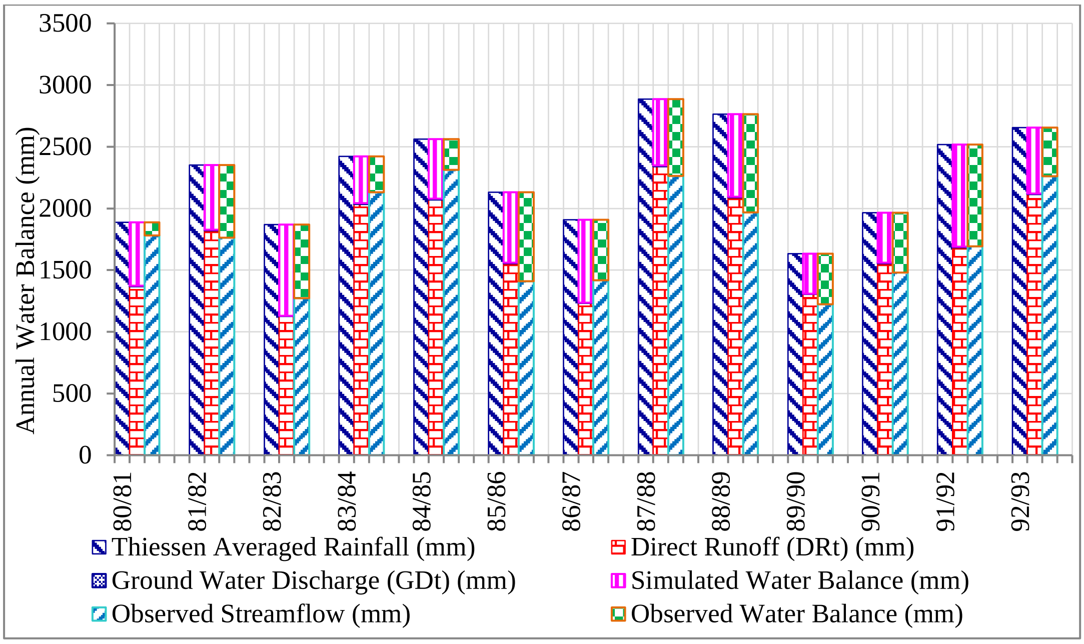

Figure 4-56: Surface water flow and groundwater flow of Thawalama watershed for validation period -Yala season

4.9.2.2 Seasonal ground water flow and surface runoff – Ellagawa watershed

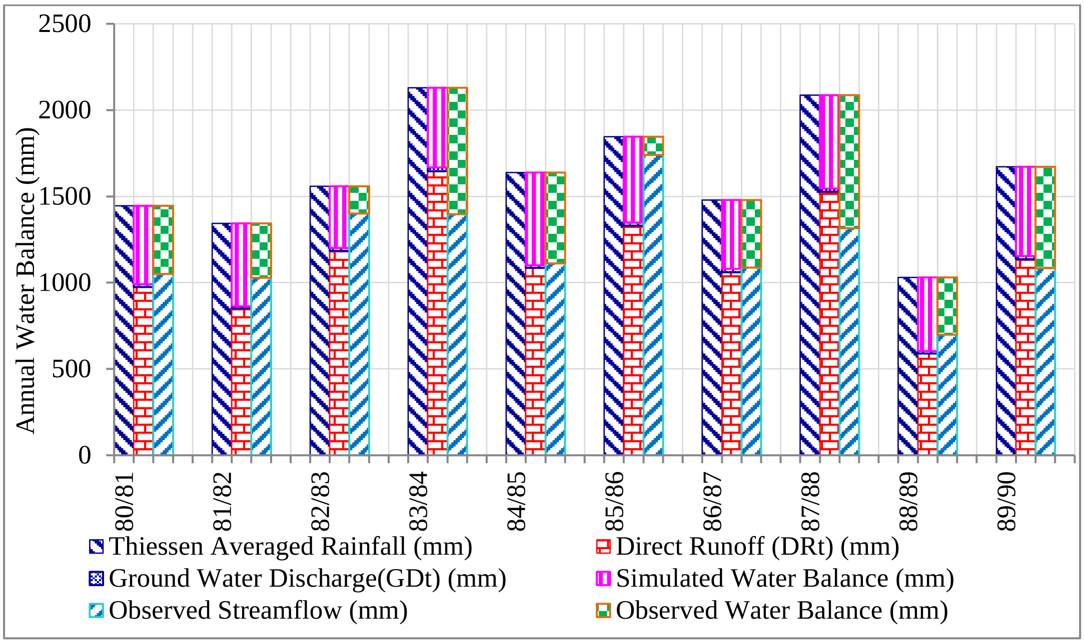

Figure 4-57: Surface water flow and Groundwater flow of Ellagawa watershed for calibration period -Maha season

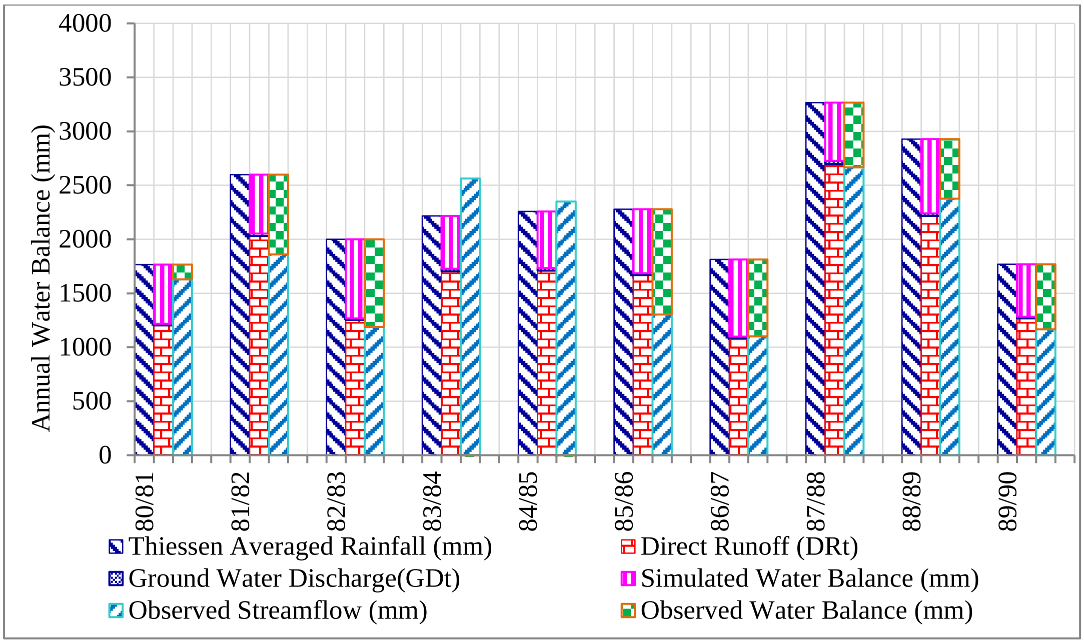

Figure 4-58: Surface water flow and Groundwater flow of Ellagawa watershed for calibration period -Yala season

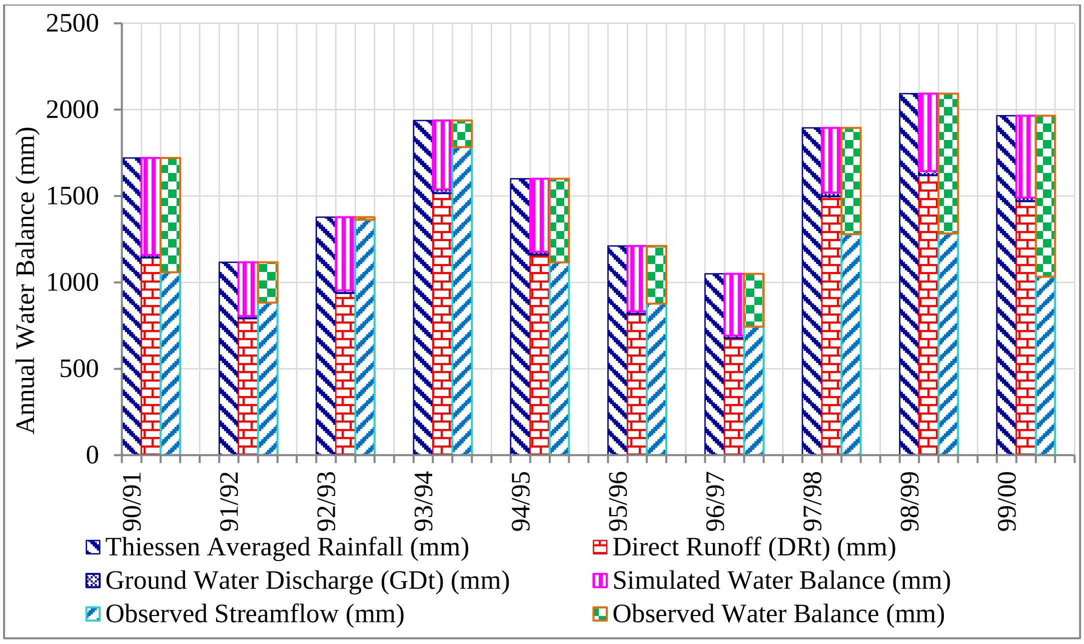

Figure 4-59: Surface water flow and Groundwater flow of Ellagawa watershed for validation period -Maha season

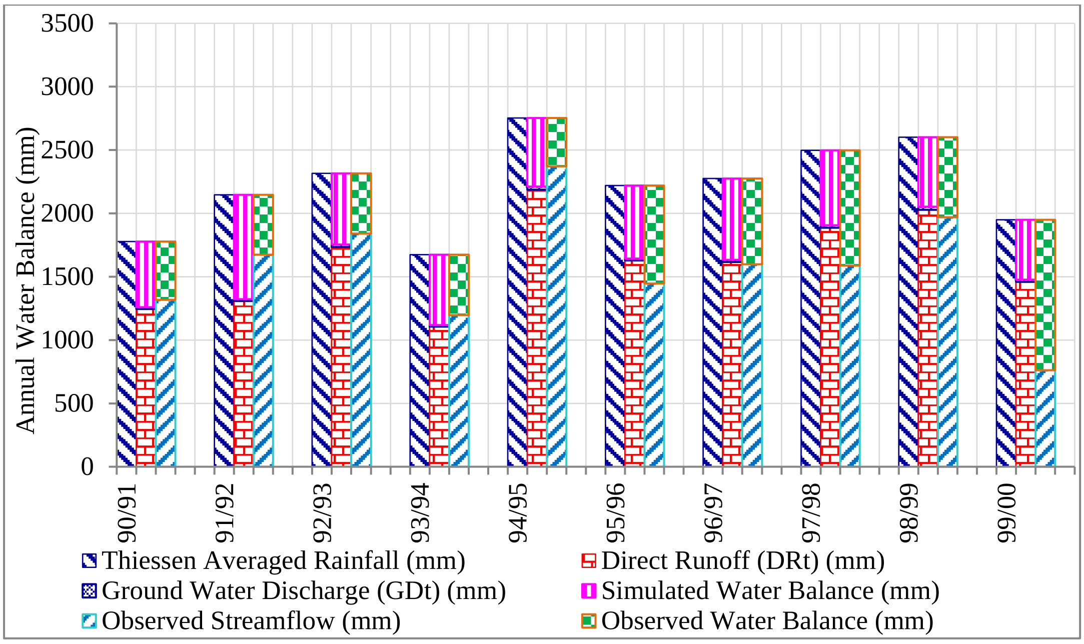

Figure 4-60: Surface water flow and Groundwater flow of Ellagawa watershed for validation period -Yala season

4.9.3 Monthly soil moisture and groundwater storage variation

4.9.3.1 Monthly soil moisture and groundwater storage variation of Thawalama watershed

The monthly groundwater storage variation and soil moisture storage variation for Thawalama watershed has been shown from Figure 4-61 and Figure 4-64.

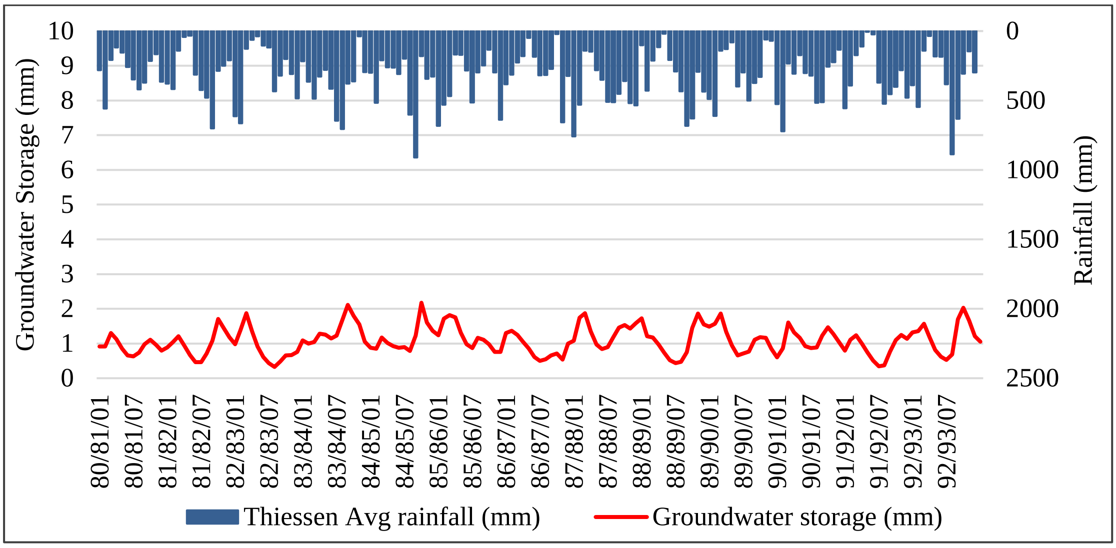

Figure 4-61: Groundwater storage variation in Thawlama watershed for calibration period

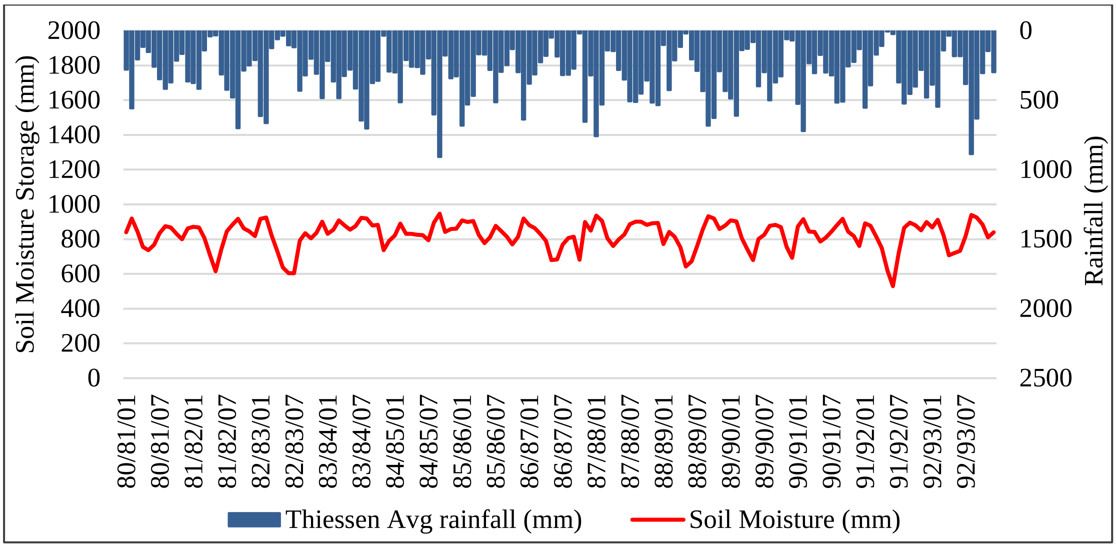

Figure 4-62: Soil moisture variation in Thawlama watershed for calibration period

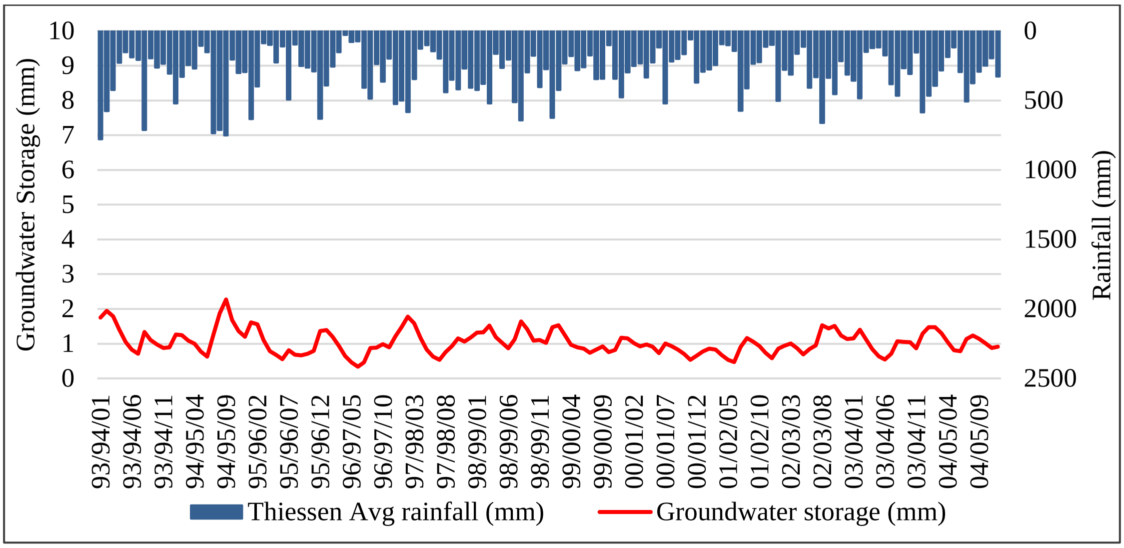

Figure 4-63: Ground water storage variation in Thawalama watershed for validation period

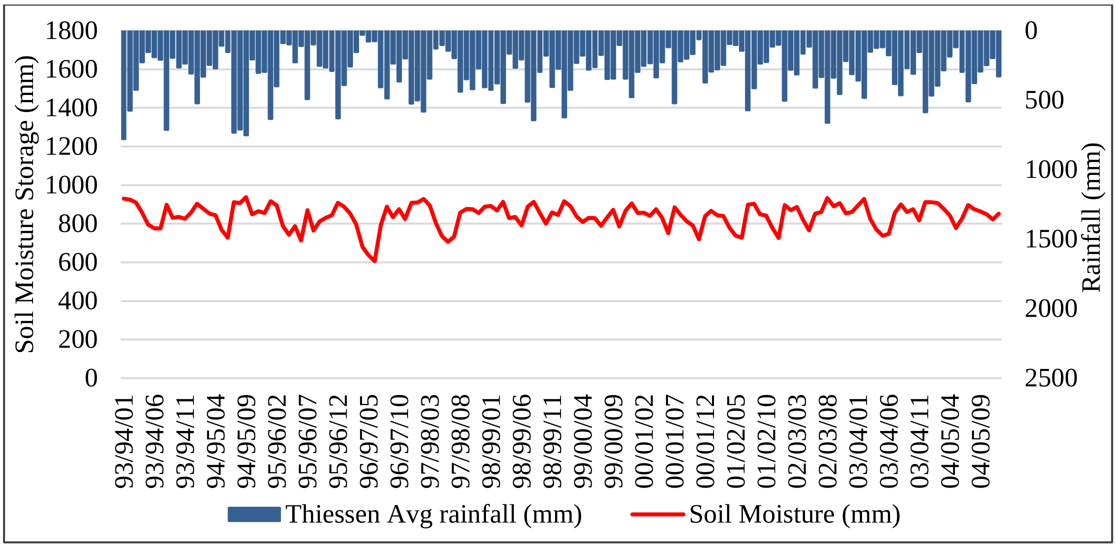

Figure 4-64: Soil moisture and variation in Thawalama watershed for validation period

4.9.3.2 Monthly soil moisture and ground water storage variation of Ellagawa watershed

The monthly groundwater storage variation and soil moisture storage variation for Ellagawa watershed has been shown from Figure 4-65 to Figure 4-68.

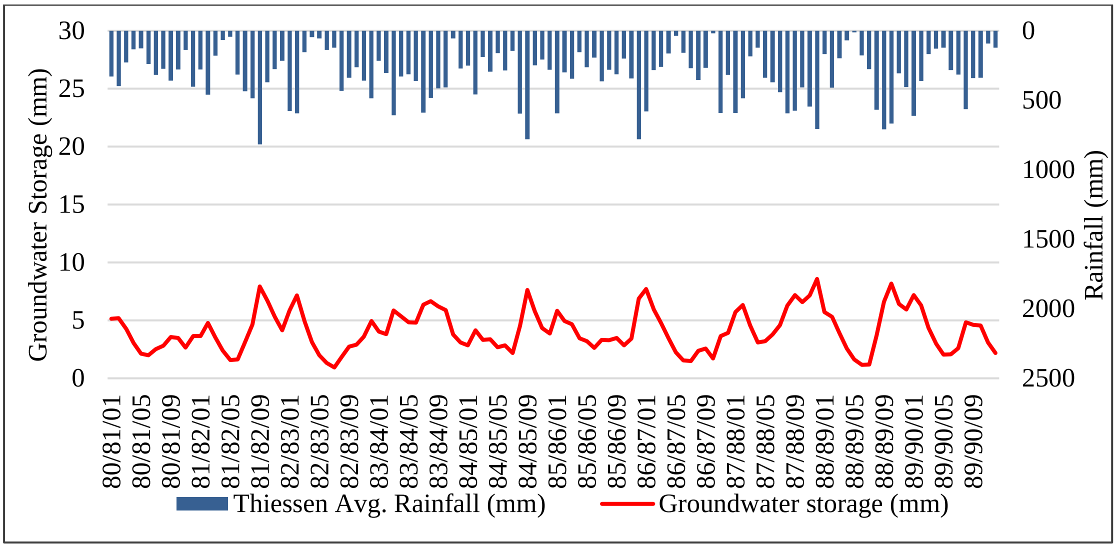

Figure 4-65: Groundwater storage variation in Ellagawa watershed for calibration period

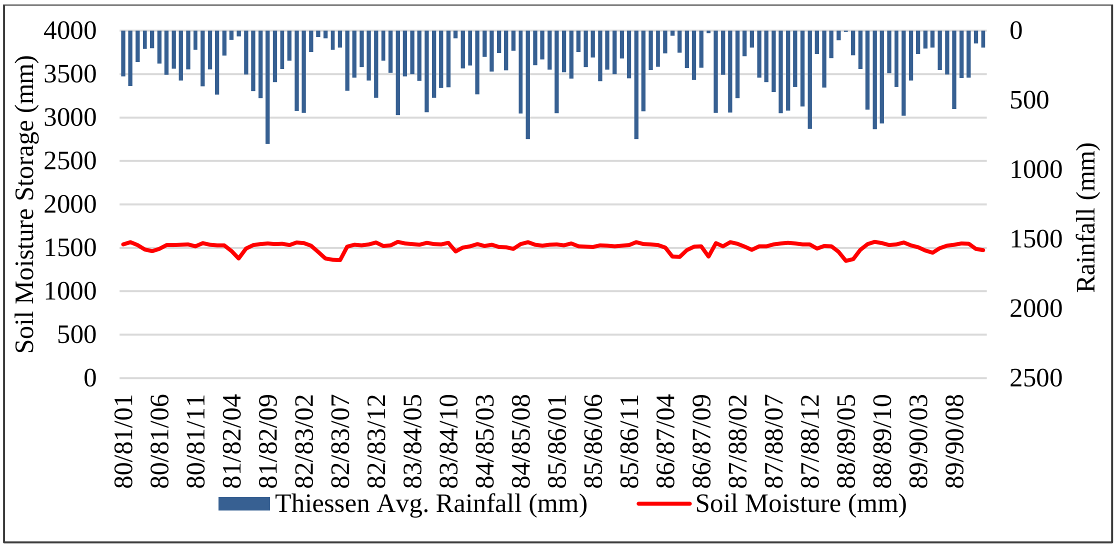

Figure 4-66: Soil moisture variation in Ellagawa watershed for calibration period

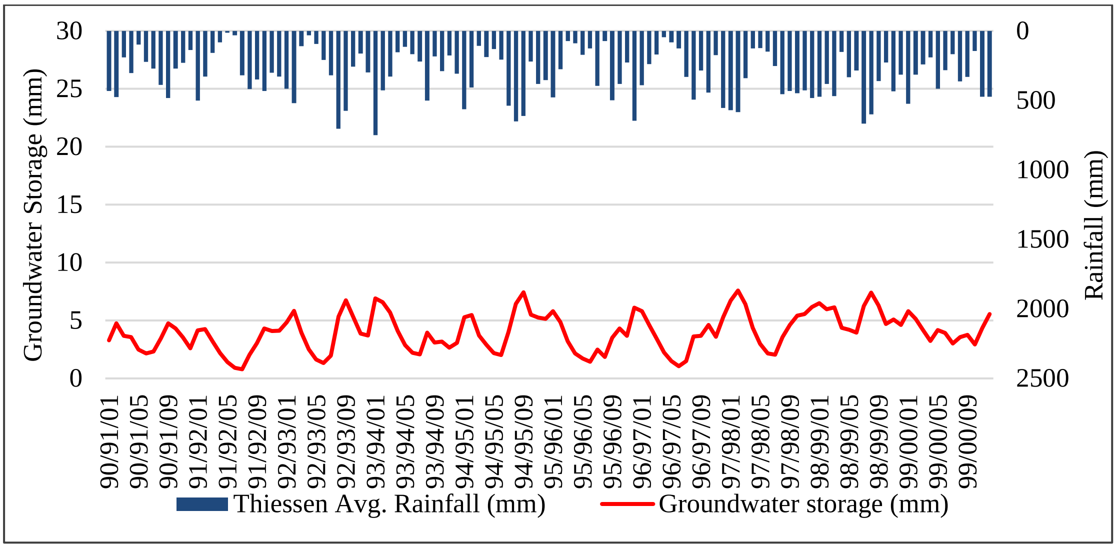

Figure 4-67: Ground water storage variation in Ellagawa watershed for validation period

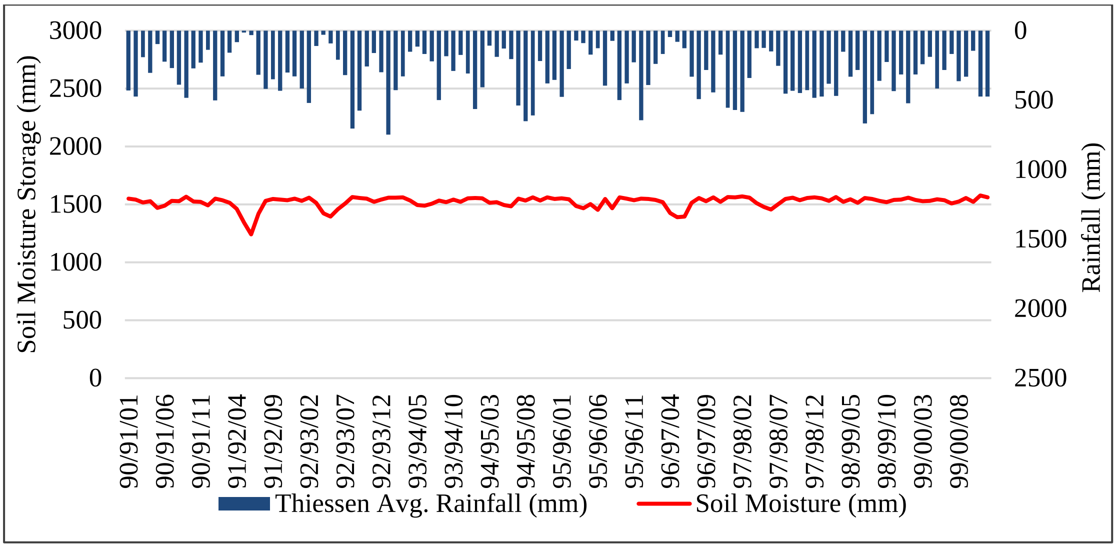

Figure 4-68: Soil moisture and variation in Ellagawa watershed for validation period

5 DISCUSSION

The “abcd” model was applied to Ellagawa and Thawalama watersheds in Kalu Ganga and Gin Ganga basins respectively and the model input data, model performance, behavior of model parameters, parameter sensitivity, challenges in the modelling work and the model limitations have been discussed herewith with reference to the related literature.

5.1 Model inputs

5.1.1 Thiessen averaged rainfall

Rainfall is one of the main inputs of the “abcd” 4-parameter model. For better representation of rainfall, number of rainfall stations were used considering WMO (2009) guidelines for both watersheds. In interpolation of rainfall, Thiessen polygon method was used with the aid of Arc GIS as most of the modelers had used this method even for distributed models.

For Thawalama watershed, four rain gauging stations were used as shown in Figure 3-9 and their corresponding Thiessen weights are as shown in Table 3-12. According to that, Kudawa and Mellewa Estate have higher Thiessen weights which are more or less equal, and dominate the Thiessen averaged rainfall of the watershed. Dependene Group rain gauging station has the lowest effect on the Thiessen averaged rainfall which has a value less than 0.05. For Ellagawa watershed, Rathnapura and Wellandura Estate is having the highest Thiessen weights while having the lowest in Galathura Estate.

For the selected data period after data checking, statistical parameters of Thiessen averaged rainfall were calculated for both watersheds as shown in Figure 3-26 and Figure 3-27. Gin Ganga and Kalu Ganga basins are located in the wet zone with an average annual rainfall recorded with 3869 mm/year and 3865 mm/year, respectively, an average monthly rainfall recorded with 322 mm/month and 322 mm/month, respectively and an average seasonal rainfall for Yala season with 2183 mm/season and 2255 mm/season and while for Maha season with 1686 mm/season and 1609 mm/season respectively. In comparing the average seasonal rainfall, it can be observed higher averages in Yala than

Maha due to the South West Monsoon. Variation of standard deviation was plotted as shown in Figure 5-1and Figure 5-2 to identify the variation of rainfall of each month in the selected data set. Lowest standard deviation of monthly data was observed in January for the both watersheds while observing the highest in June for Thawalama and September for Ellagawa. High standard deviations reflect high variations in the data set while low standard deviations reflect low variations in data. Especially high standard deviations were observed in the months having high rainfalls while low standard deviations observed in the months having low rainfalls. This was observed in the simulated flow results also, since low accuracy in the estimated high flows.

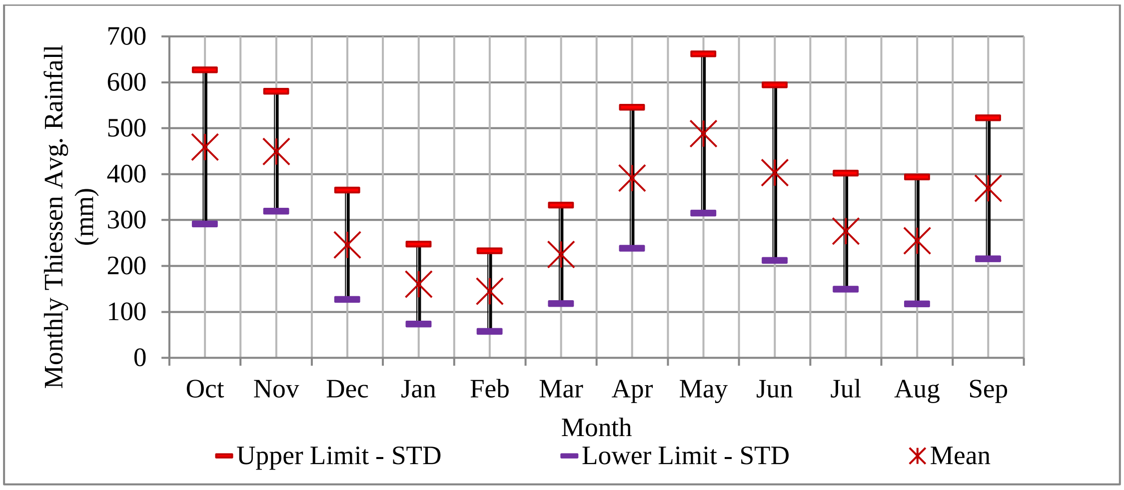

Figure 5-1: Monthly variation of Standard Deviation of rainfall - Thwalama

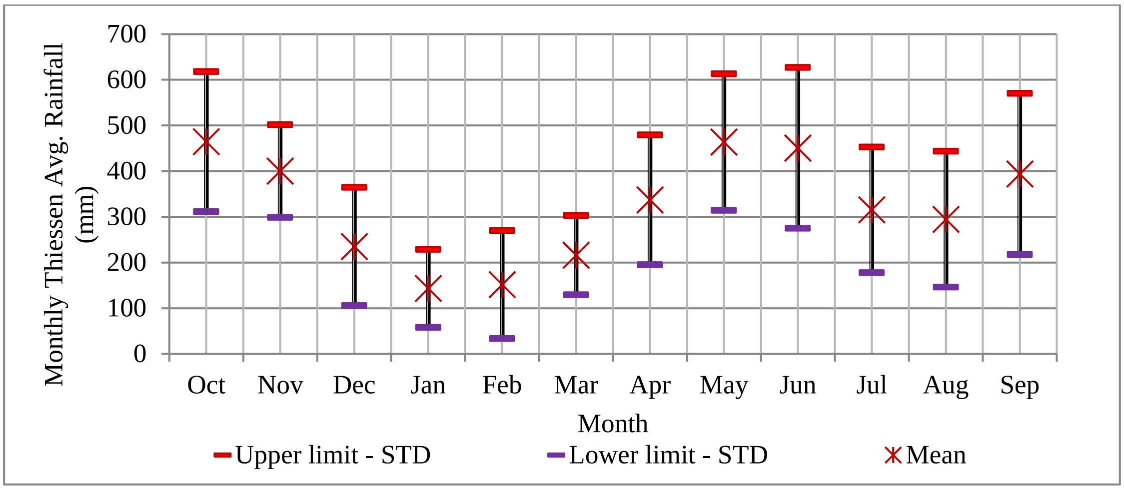

Figure 5-2: Monthly variation of Standard Deviation of rainfall – Ellagawa

5.1.2 Stream flow

The average annual streamflow of Thawalama and Ellagawa had recorded as 2976 mm/year and 2866 mm/year, average monthly stream flow had recorded as 248 mm/month and 239 mm/month and average seasonal streamflow for Yala season as 1664 mm/season and 1699 mm/season while for Maha season with 1312mm/season and 1167 mm/season, respectively. The monthly variation of standard variation of stream flow data was plotted as shown in Figure 5-3 and Figure 5-4 to check how much the stream flow data has deviated from mean. In Thawalama watershed, highest standard deviation was observed in June for stream flow data which was the same observation for rainfall data while observing the minimum in February which was January in the rainfall data set. For the Ellagawa watershed, highest standard deviation for stream flow data was observed in June while observing the minimum in February. But the corresponding months for the rainfall data are September and January respectively which may have affected the modelling process of Ellagawa watershed.

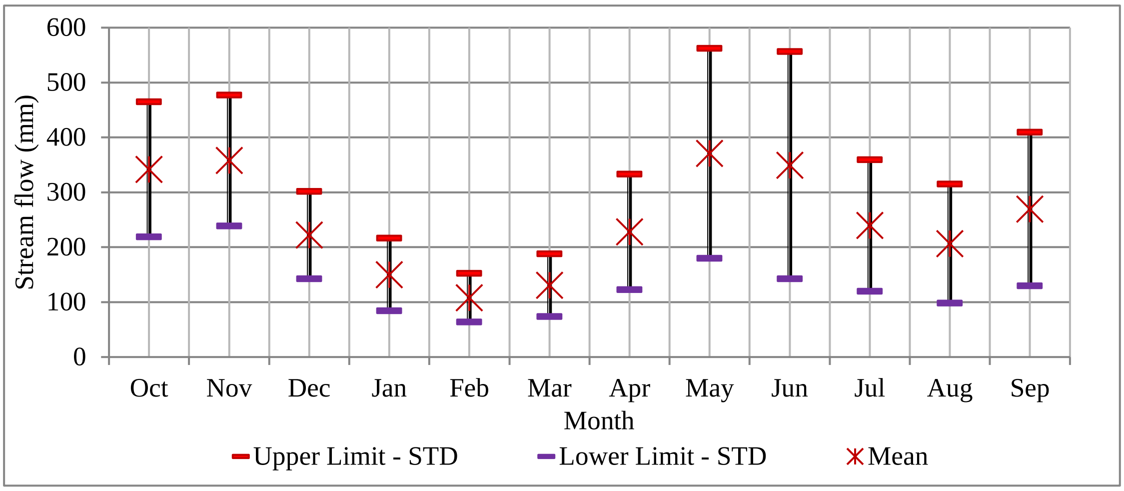

Figure 5-3: Monthly variation of Standard Deviation of Stream flow- Thawalama

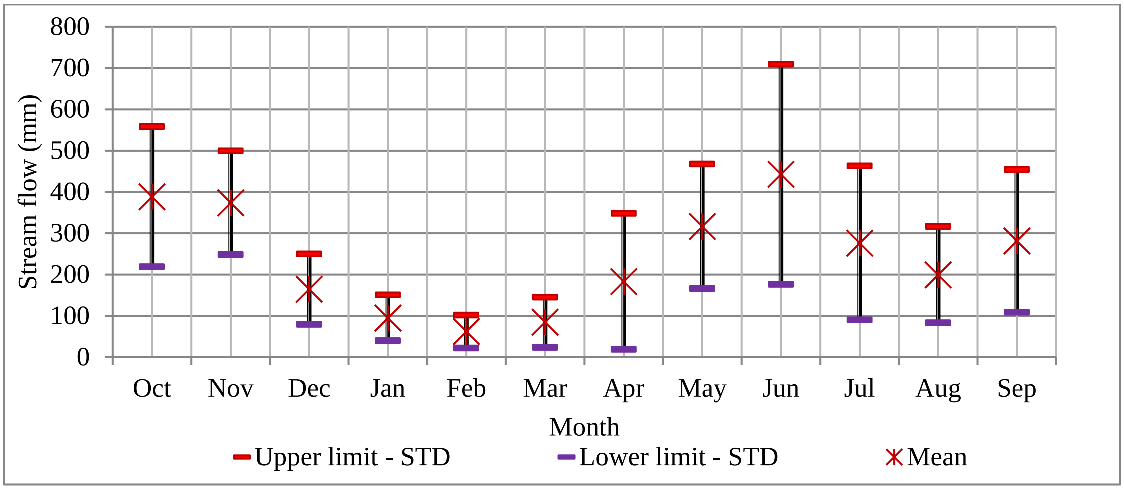

Figure 5-4: Monthly variation of Standard Deviation of Stream flow- Ellagawa

5.1.3 Evaporation

For the both Ellagawa and Thawalama watersheds, Rathnapura was used as the evaporation station under different data periods. The monthly variation of standard deviation of evaporation data was plotted as shown in Figure 5-5 and Figure 5-6 to check how much evaporation data has deviated from mean. Considering the pan evaporation data set for Thawalama (1980-2005) and Ellagawa (1980-2000), average annual pan evaporation of Rathnapura had been recorded for respective periods as 1283 mm/year and 1332 mm/year, average monthly pan evaporation had been recorded as 107 mm/month and 111 mm/month, while average seasonal pan evaporation for Yala season was 627 mm/season and 646 mm/season and for Maha season was 657 mm/season and 685 mm/season, respectively.

For the both watersheds, the highest standard deviation was observed in March while observing the minimum in December. Since the contribution of evaporation for the water balance is less, there is a less effect on the simulated results.

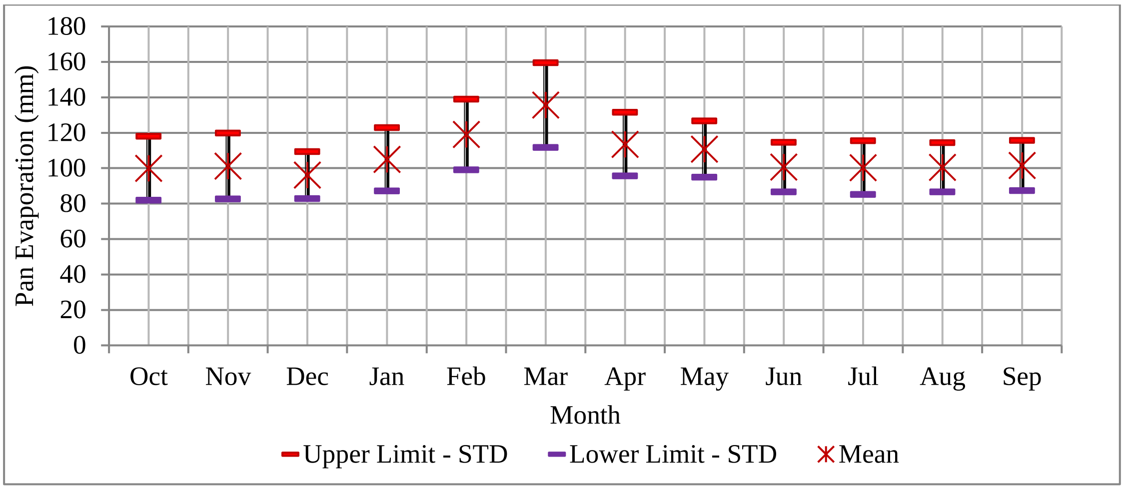

Figure 5-5: Monthly variation of Standard Deviation of Pan evaporation- Rathnapura (1980-2005)

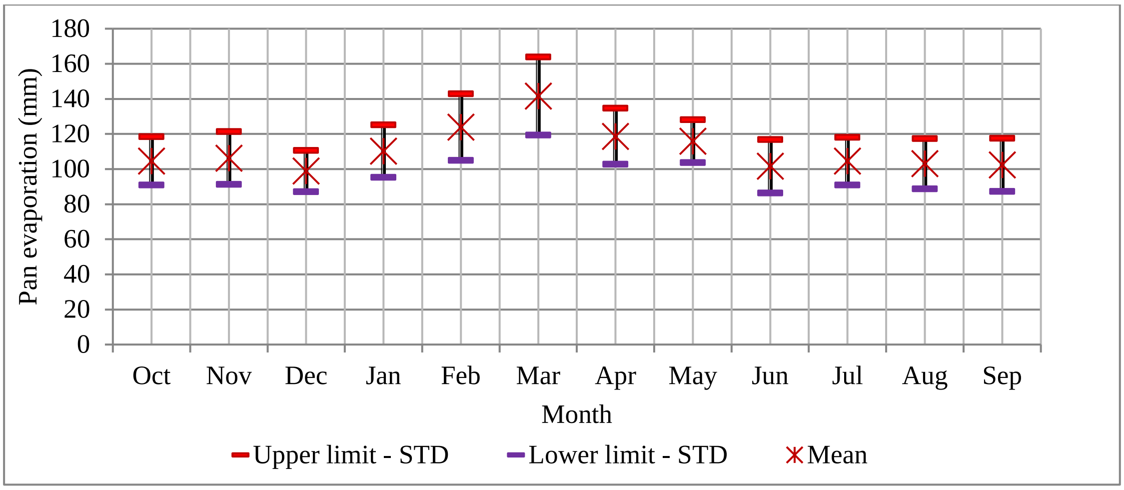

Figure 5-6: Monthly variation of Standard Deviation of Pan evaporation- Rathnapura (1980-2000)

5.2 Model performance

The correlation between the observed stream flow and simulated stream flow was observed for both watersheds considering overall data as shown in Figure 5-7. In both watersheds, low flows have been slightly over estimated while very high flows have been underestimated. But a balance distribution of simulated flow results can be observed in intermediate flows. Comparatively high dispersion of simulation results can be observed in Ellagawa watershed than Thawalama watershed. For further interpretation, graphs were regenerated with simulated flows verses observed flows for calibration and validation periods separately as shown in Figure 5-8 and Figure 5-9. In Kalu Ganga basin specially for validation period, the high flows have underestimated while low flows have overestimated, and high dispersion of simulated results were observed in validation period than in calibration period. In Gin Ganga basin, same kind of over estimations in low flows and under estimates in high flows in validation period were observed but relatively low in comparing with Kalu Ganga. Both watersheds showed excellent performance in their calibration with low dispersion with respect to 45^0 line. The dispersion of points was observed to be further scattered when the flow was increasing.

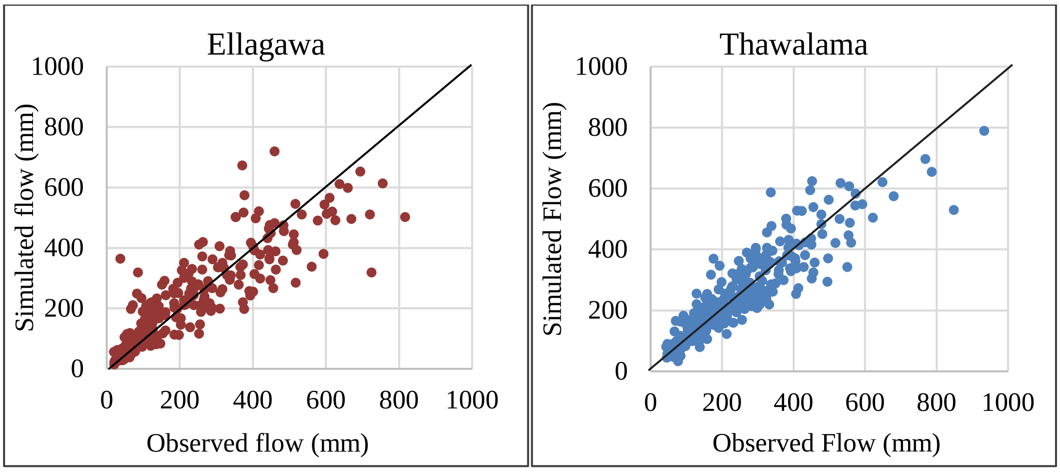

Figure 5-7: Observed flow Vs Simulated flow for Ellagawa and Thawalama watersheds

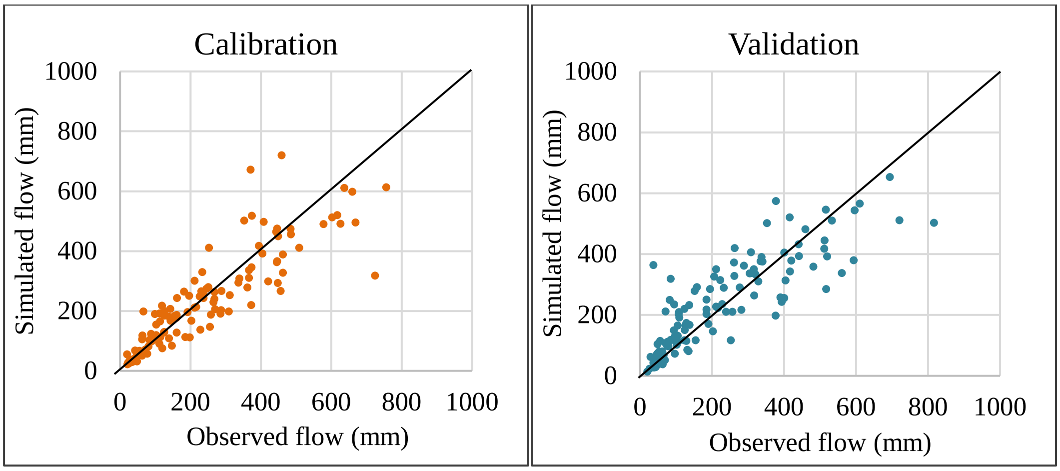

Figure 5-8: Simulated flow Vs Observed flow in Kalu Ganga for calibration and Validation Separately

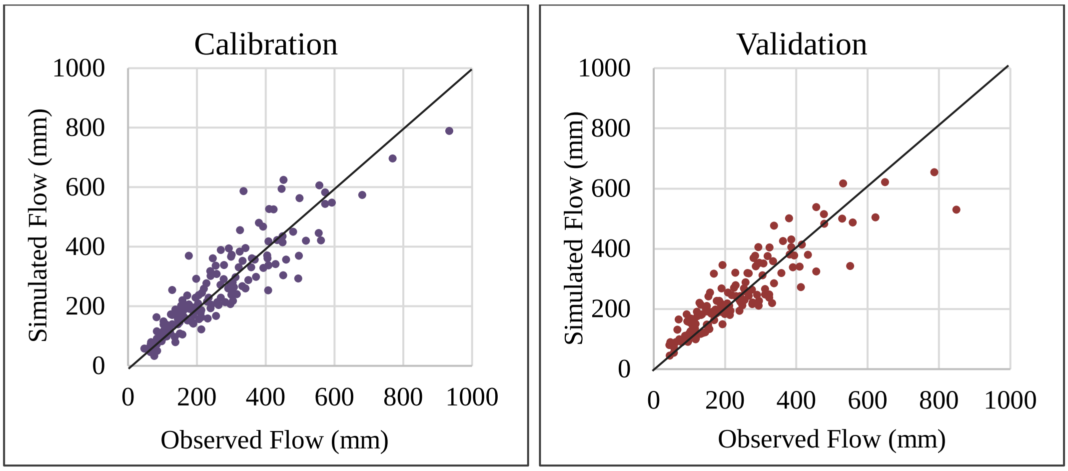

Figure 5-9:Simulated flow Vs Observed flow in Gin Ganga for calibration and Validation Separately

Even in the flow duration curve analysis, the same scenario was clearly observed which have been shown in Figure 4-30, Figure 4-32, Figure 4-34 and Figure 4-36. Specially these underestimations in high flow regimes and over estimations in low regimes are dramatically observed in validation periods in both watersheds.

The overall performance of the model was measured by using the MRAE, which is an objective function especially suitable for low and moderate flows. But for the comparison purposes, Nash Sutcliff Efficiency value was used which is especially suitable to evaluate high flows. As a consensus, MRAE values close to zero and Nash Sutcliff Efficiency values close to one are considered as good simulations. The Table 4-6 shows the optimized MRAE and Nash values for calibration and validations in corresponding watersheds. The MRAE in calibration and validation of 'abcd' model for Thawalama watershed are 0.21 and 0.23 which can be considered as an excellent performance. But the corresponding MRAE values for Ellagawa watershed are 0.26 and 0.43 which shows relatively low performance than Thawalama watershed but also can be considered as a satisfactory referring to previous modelling work in literature. The Nash Sutcliffe efficiency values in calibration and validation of 'abcd' model for Thawalama watershed are 0.81 and 0.80, which can be considered as a satisfactory performance while the corresponding values for Ellagawa watershed are 0.77 and 0.73, which also can be considered as satisfactory. In overall comparison of both watersheds, it can be concluded that ‘abcd’ model for Thawalama watershed shows better performance than for Ellagawa watershed.

The model performance was checked separating the high, medium and low flows in the data set separately for calibration and validation. The high, medium and low flow regimes were identified by using the sudden deflection points in the flow duration curves and the results have been summarized in Table 4-7. The probability exceedance values of regime changing points were not same for calibration and validation data sets even though it is expected from a parent data set, but was in a satisfactory range.

In the model application for separate regimes, satisfactory performance was shown with relatively low MRAE values for high flows and medium flows while showing relatively low performance for low flows specially in validation periods as shown in Table 4-8. This observation, specially related to intermediate and low flows are well illustrated with visual comparisons, flow duration curve analysis and the plot between observed verses simulated flows.

Therefore, by considering the above facts, it can be concluded that the overall performance of the “abcd” model is satisfactory for the considered watersheds.

5.3 Model parameters and behavior

The mean a,b,c and d parameter values from literature was taken as the initial parameter values for the model in the calibration and validation process and ended up with optimized parameters as shown in Table 5-1. No deviations in the optimized a,b,c and d parameters were observed with respect to the range from literature.

According to the model structure of “abcd” model as shown in Figure 2-1, the parameter “a” reflects the propensity of runoff to occur before the soil is fully saturated. According to Thomas (1981) the parameter “a” will reduce with the urbanization and deforestation while reaching unity in flat terrains with low drainage density. In comparing the land use of both watersheds, Thawalama watershed has a higher forest density, low drainage density and low home steads percentages than Ellagawa watershed which shows comparatively low urbanization. But in comparing the parameter “a”, Thawalama has a lower value than Ellagawa, which is contradictory with literature. This scenario must be further investigated.

The parameter ‘b’ is an upper limit on the sum of actual evapotranspiration and soil moisture storage in each month. This parameter reflects the ability of the catchment to hold water within the upper soil horizon. In comparing the optimized values for parameter “b” of the two watersheds, Ellagawa is having a high moisture storage capacity than Thawalama as shown in Table 5-1. The reason should be due to the differences of soil type in two watersheds.

The parameter ‘c’ is equal to the fraction of groundwater recharge and the balance (1-c) for the direct runoff. The timely changes in the land use and the slope will affect the magnitude of “c”. In case of urbanization and deforestation, value of parameter “c” will reduce while increasing the fraction for surface runoff which is (1-c). In considering the optimized “c” values for both watersheds, those are lesser than 0.1 which shows a lower recharge while showing a high fraction for run off. The reason might be the mountainous terrain existing in both watersheds. In comparing both watersheds, Thawalama watershed shows a lower recharge than Ellagawa, which reflects a comparatively low recharge.

Parameter “d” is relevant to the ground water discharge. Thawalama watershed has a higher value for parameter “d” than Ellagawa watershed as shown in Table 5-1. Since the recharge is a lesser fraction in both watersheds, groundwater storages and the contribution to the runoff, both watersheds show very low values as shown in Figure 4-65 and Figure 4-67. The reason may be the existence of both watersheds as upstream watersheds in Kalu and Gin river basins.

Table 5-1: Model parameter comparison

Model Parameters	Range from literature	Model initial values	Optimum parameter value (Thawalama)	Optimum parameter value (Ellagawa)
a	0.873-0.999	0.936	0.961	0.998
b	14-1900	957	1066	1644
c	0-1	0.5	0.003	0.013
d	0-1	0.5	0.813	0.741

5.4 Model parameter sensitivity

Sensitivity analysis was carried out as overall sensitivity analysis and local sensitivity analysis considering the MRAE, NSE, average of annual water balance difference and standard deviation of annual water balance difference as out puts when the parameters are varied individual one at a time.

In the overall sensitivity analysis, sensitivity index (SI) was calculated for each parameter and ranked from the highest to the lowest sensitivity as shown in Table 4-13 and Table 4-14.

From those results it was observed that for certain outputs, rank is different in calibration and validation periods which indicates the loss of stationarity in hydrologic modelling. To get away from this confusion, multiplication of the SI of calibration and validation periods were considered in the ranking process. Even though the both watersheds are wet zone watersheds, the sensitivity ranks of the parameters were different. For examples, “b” is the most sensitive parameter for MRAE in Thawalama watershed while “a” is the most sensitive parameter in Ellagawa watershed. In case of average annual water balance difference, “a” is the most sensitive parameter for both watersheds which shows some similarity. The parameter “d” is the least sensitive parameter considering overall sensitivity for both Ellagawa and Thawalama watersheds.

The Figure 4-45, Figure 4-46, Figure 4-47 and Figure 4-48 show the behavior of all the four parameters when it was given a % value change from the optimized parameter set under the local sensitivity analysis. The results show, the parameter “a” is the highest local sensitive parameter which alarms that the timely changes in the catchment related to deforestation and urbanization can adversely affect the validity of the model.

In considering all the above, parameter “a” and “b” are the most sensitive parameters, which are related to the surface flow while having low sensitivity from the parameters related to the ground water flow for the both watersheds.

5.5 Challenges faced in modelling

With regarding the model development, calibration and validation, difficulties were found regarding data and to set the initial conditions of the model which can affect the model performance.

5.5.1 Difficulties with data

The problems related to data can be divided into two categories as data availability and the data accuracy. In selection of rainfall stations and evaporation stations, the initial concern was to select the stations within the catchment which could obviously reflect the exact rainfall conditions. But unfortunately, data was not available continuously for number of years for some of the stations which falls within the watersheds. Certain rainfall stations had started recently and some of the stations were not functioning. But for the Ellagawa watershed, all the stations were found within the catchment while Thawalama is having only one station which is Anningkanda within the catchment. All the other three stations are located outside of the catchment. In addition to that, there were missing values of rainfall data for certain stations which can affect the model performance and the missing data percentage was kept below 10% for each station to reduce initial data distortion. The rainfall missing values were filled by using the linear regression method which is considered as one of the accepted methods in hydrological studies while filling the missing values of stream flow and pan evaporation data by using monthly mean values of 30 years data. The selected evaporation station for both watersheds is Rathnapura which is located within the Ellawaga watershed of Kalu Ganga while it is located outside of Thawalama watershed of Gin Ganga. Even though Rathnapura is situated outside of Thawalama watershed, it was used considering the data availability, data cost, satisfactory water balance and other similar climatic conditions. Nonetheless, still there might be an error due to this distant proximity but it is presumed to have a minor effect on the model due to the low contribution of evaporation to the water balance.

In addition to the above, there had been problems regarding the accuracy of available data. Especially in the stream flow data of Kalu Ganga, a sudden reduction was observed after year 2000 as shown in Figure 3-11and Figure 3-19 which affected the water balance immensely and led to the removal of the data after 2000 from the study. In the same way, in Thawalama watershed a sudden deflection was observed after 2005 in the single mass curve of Millawa state rainfall data as shown in Figure 3-18 which affected the single mass curve of Thiessen averaged rainfall due to its high Thiessen weight. This phenomenon has adversely affected the water balance of Thawalama watershed and led to the removal of data after 2005 from the model.

Considering these limitations on data availability, data accuracy, time and cost, 20 years data (1980-2000) was used for the Ellagawa watershed while using 25 years (1980-2005) data for the Thawalama watershed. But still this data period is enough for a monthly model, according to Martinez and Gupta (2010).

5.5.2 Initial conditions for the model

In the calibration, it was required to set initial values for the soil moisture (S_{t-1}), ground water (G_{t-1}) and for a,b,c,d parameter values which was little bit challenging. Initial values for soil moisture and ground water were assumed in the calibration as the other modelers had done, while using the mean values in the literature, for the a, b, c, d parameters. By running the model number of times, the initial soil moisture and ground water values converged to a quasi-steady state and could got away safely from the issue with the initial values.

5.6 Limitations of ‘abcd’ model

One of the major requirements in the application of “abcd” model is not to have any large water storages and flow regulatory structures in the watershed which will affect the response of the flow to the rainfall. For the selected watersheds, Thawalama and

Ellagawa, it was observed that there are no such large surface storages and this fact was verified in the visual data check by observing an appropriate response of stream flow to rainfall without having a considerable lag except few months which had rained in the last day of the month. In addition to that, according to Martinez and Gupta (2010), model does not perform well with its conventional model structure for the catchments which has snow falling and the model structure need to be modified accordingly. The reason may be the lag that is created in the runoff of snow. This was not a problem for the selected watersheds, since snow is not a mode of precipitation in Sri Lanka.

6 CONCLUSION AND RECOMMENDATION

6.1 Conclusions

1. The “abcd” monthly water balance model can be used successfully to represent the catchment hydrology and to investigate the water resources of the two wet zone watersheds, Thawalama and Ellagawa in Gin Ganga and Kalu Ganga, respectively.

2. Monthly rainfall, stream flow and evaporation data from 1980 ~ 2005 (25 years) and 1980 ~ 2000 (20 years) can be used successfully for modelling of Thawalama and Ellagawa watersheds, respectively.

3. The optimized average a, b, c, d parameter values considering Thawalama and Ellagawa watersheds are 0.980, 1355, 0.008, 0.777 with corresponding average MRAE and Nash–Sutcliffe efficiency values of 0.24, 0.79 and 0.33, 0.77 in the calibration and validation, respectively.

4. Thawalama watershed shows better performance than Ellagawa watershed in calibration and validation, in the presence of MRAE and NSE as objective functions.

5. The “abcd” model shows better performance for high and intermediate flows than low flows when the MRAE is used as the objective function.

6. The parameter “a” and “b” are the most sensitive parameters considering overall sensitivity of Ellagawa and Thawalama watersheds for MRAE , average of annual water balance difference, and the standards deviation of annual water balance difference.

7. The parameter “d” is the least sensitive parameter considering overall sensitivity for both Ellagawa and Thawalama watersheds.

8. Parameter “a” is the most local sensitive parameter for the considered range for both Ellagawa and Thawalama watersheds.

6.2 Recommendations

1. The “abcd” hydrologic model can be recommended to use for streamflow simulations and water resources investigations in monthly temporal resolution for the watersheds which are having similar characteristics with parameter values of a (0.961-0.998), b (1066-1644), c (0.003-0.013), d (0.741-0.813).
2. It is recommended to apply the “abcd” model for several additional wet zone watersheds and confirm the behavior of a, b, c and d parameters.
3. It is recommended to apply the “abcd” model for several dry zone watersheds and confirm the behavior of a, b, c and d parameters under dry weather conditions.
4. The model is recommended to apply only for the watersheds which are free from large water bodies and snow.
5. It is recommended to do verifications for soil moisture storage and groundwater storage which are given as out puts from the model, by conducting appropriate field tests.

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APPENDIX-A

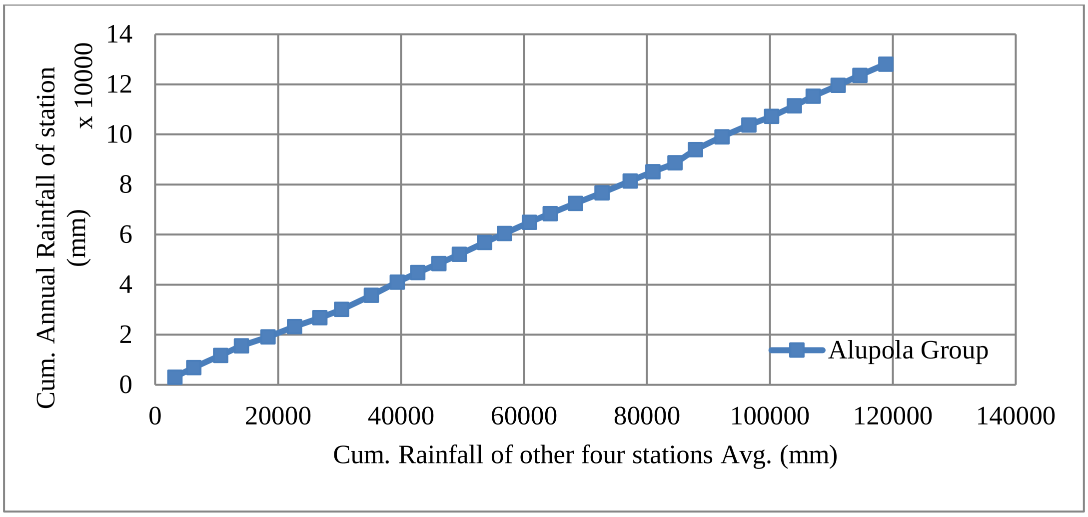
DATA CHECKING FOR KALU GANGA WATERSHED

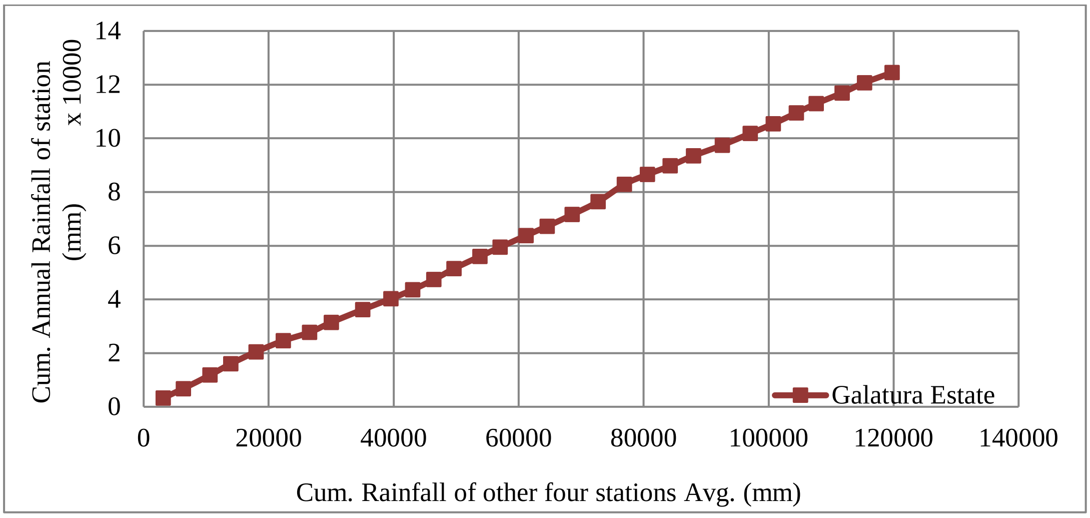
A-1- Double mass curve analysis for Kalu Ganga

A-2-Visual checking of rainfall and stream flow for Kalu Ganga

A-3-Monthly comparison of Thiessen Averaged Rainfall, Stream flow and Evaporation for Kalu Ganga (1980-2010)

A-4- Monthly, Annual and Seasonal Runoff Coefficients for Ellagawa Watershed (1980-2000)





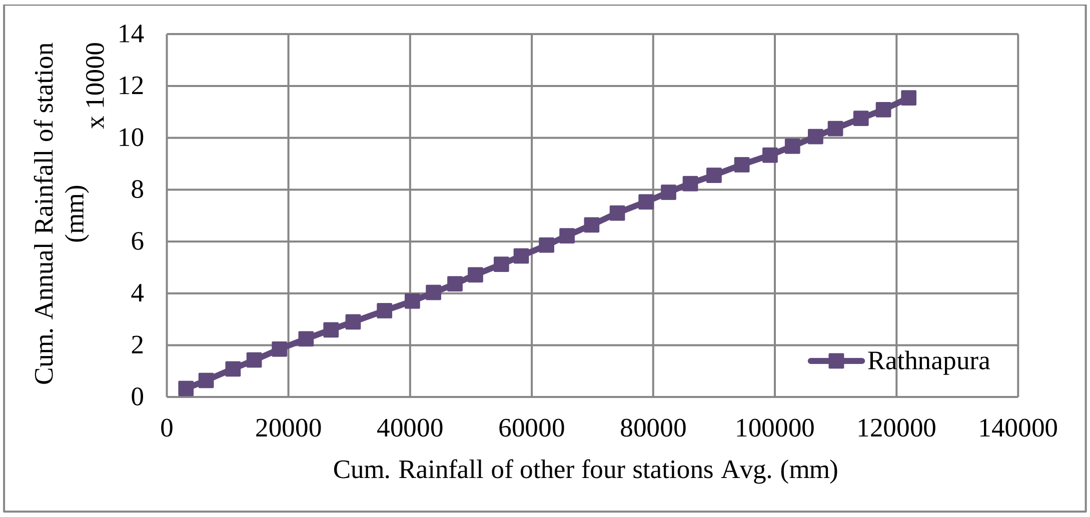
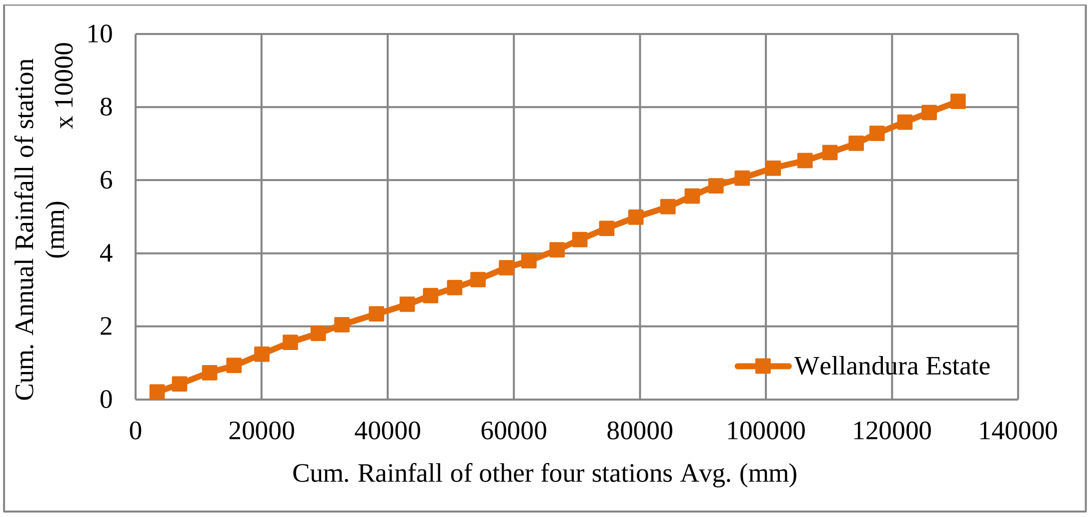


Figure A-1.1: Double mass curve analysis for Kalu Ganga



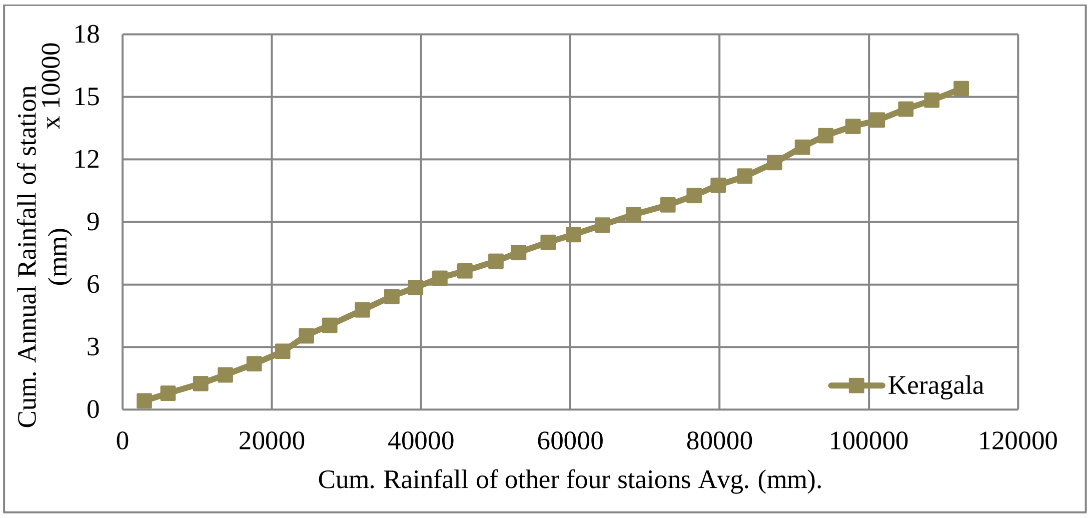


Figure A-1.2: Double mass curve analysis for Kalu Ganga

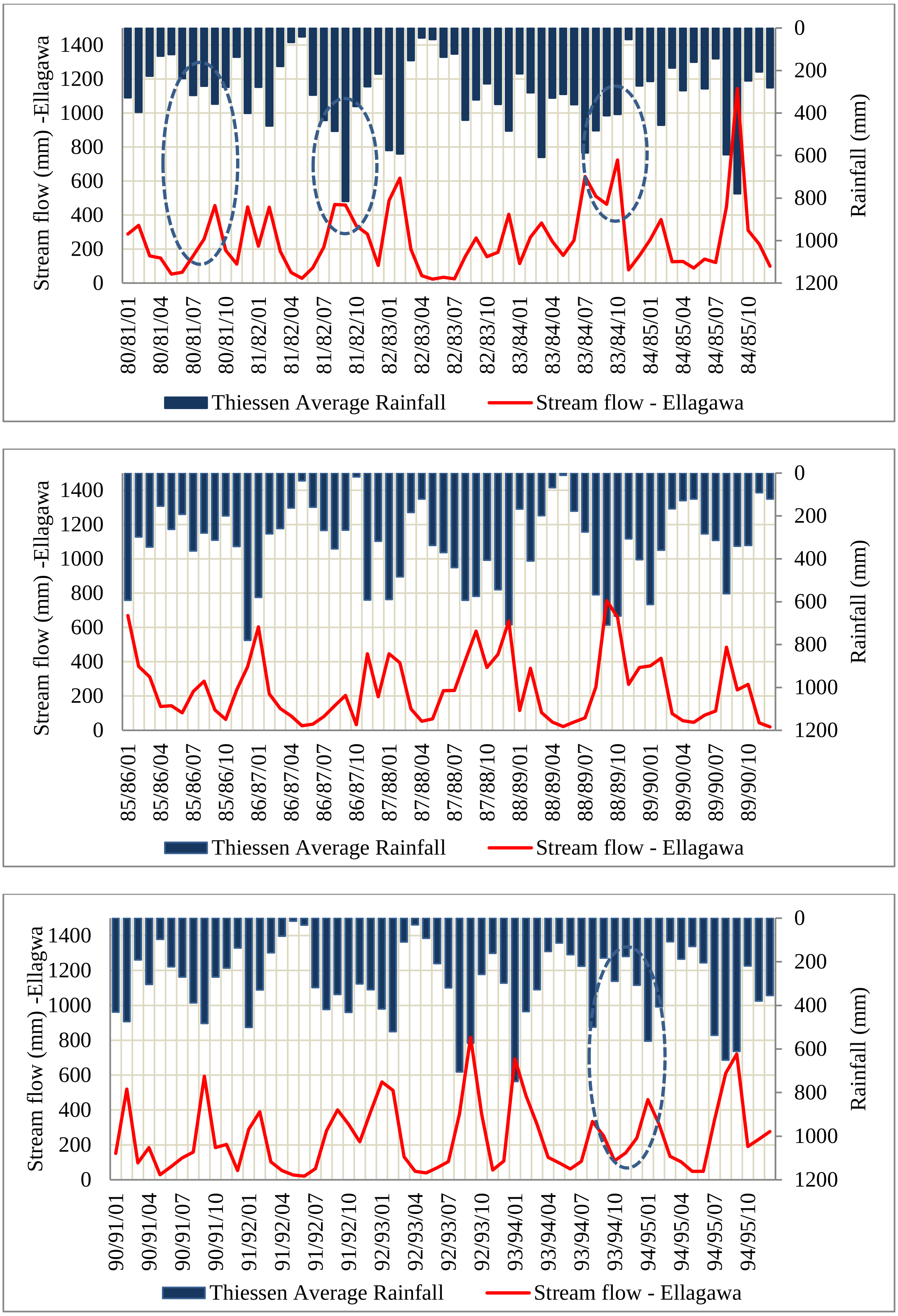


Figure A-2.1: Monthly Stream flow at Ellagawa with respect to monthly Thiessen averaged rainfall- 1980-1995

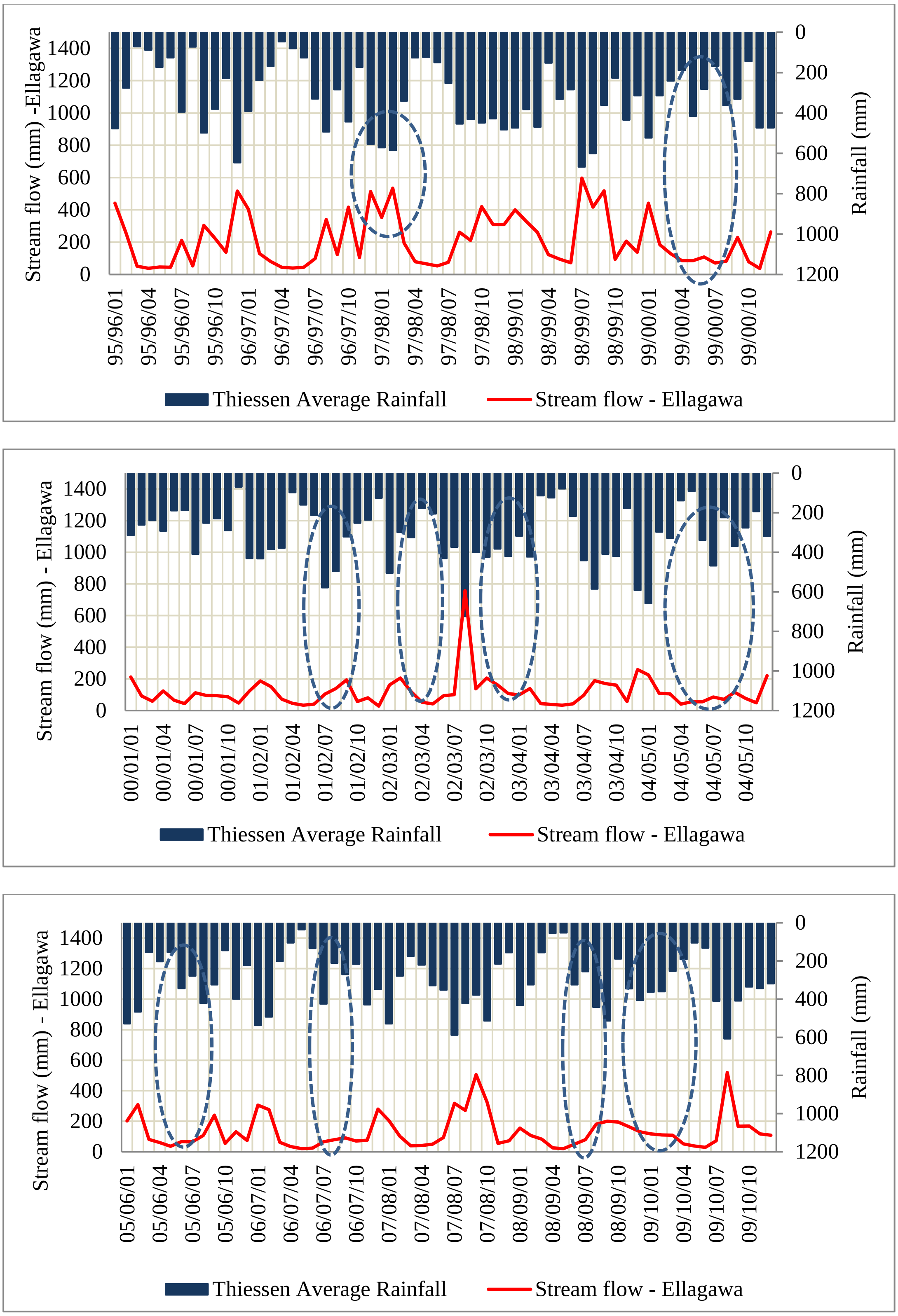


Figure A-2.2: Monthly Stream flow at Ellagawa with respect to monthly Thiessen averaged rainfall- 1996-2010

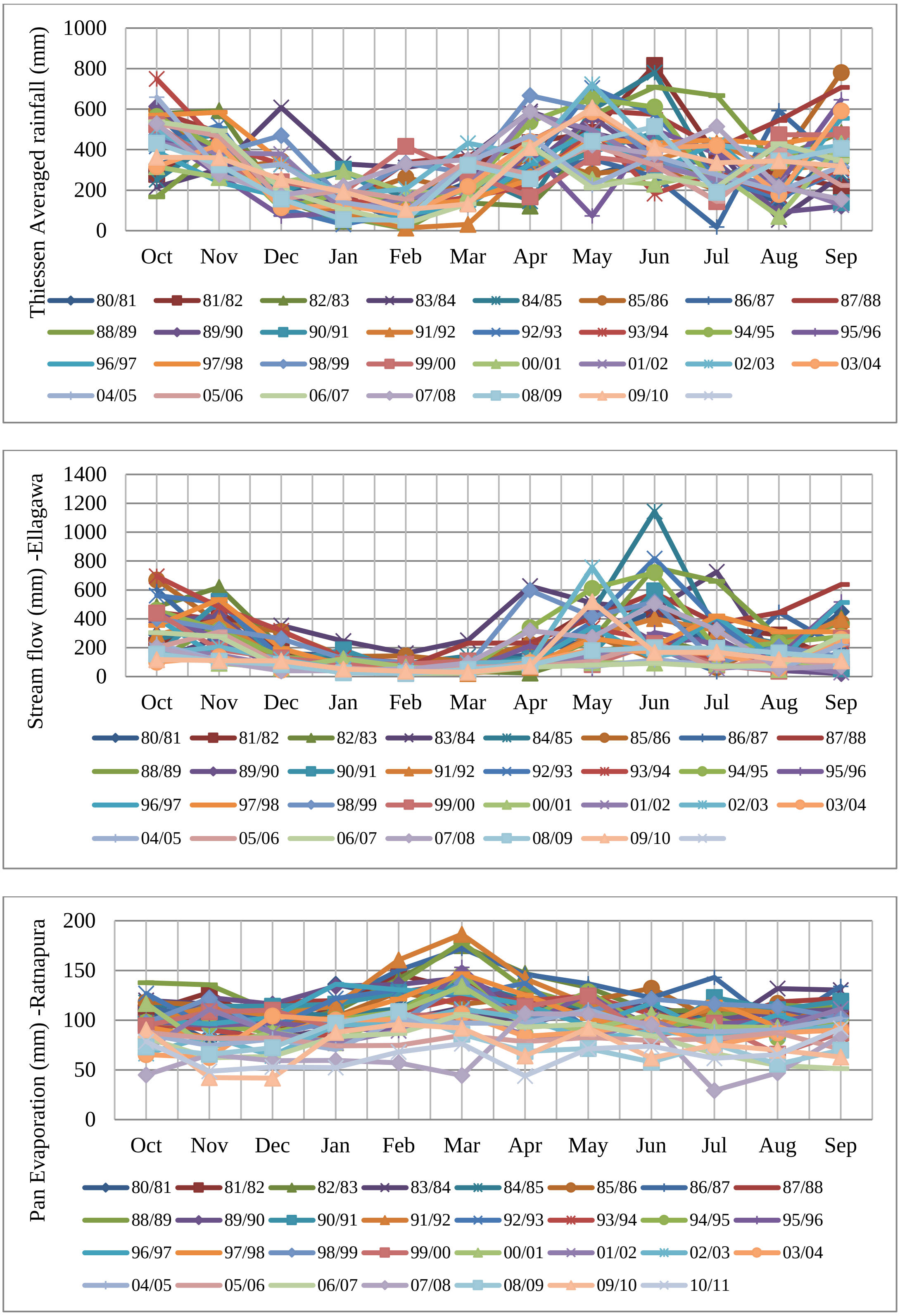
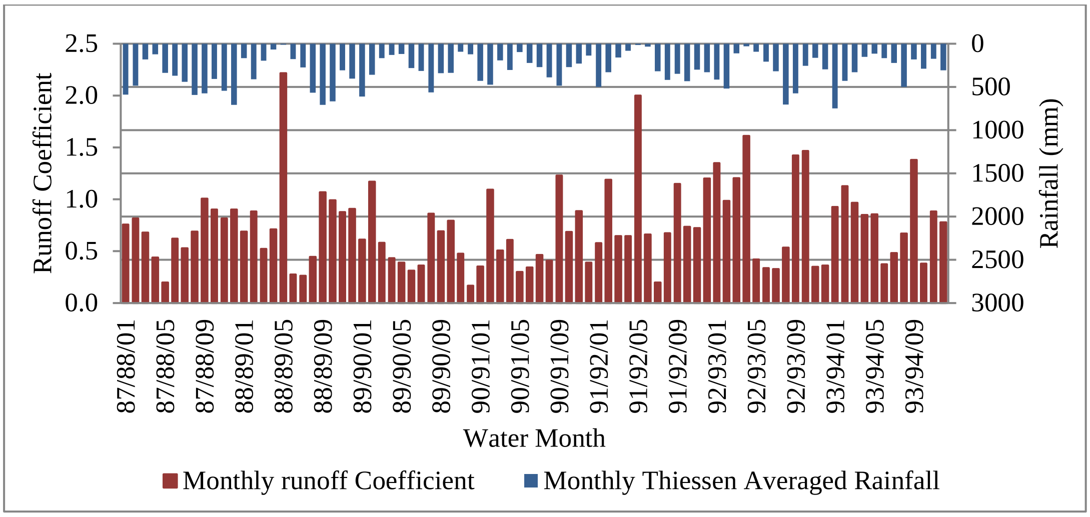
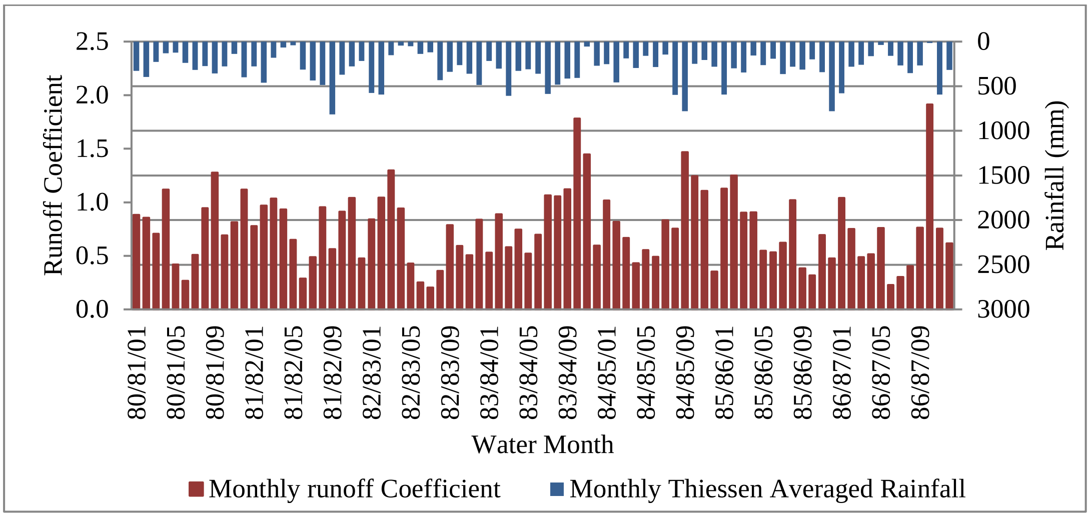


Figure A-3:Monthly comparison of Rainfall, Stream flow and Evaporation for Kalu Ganga- 1980-2010





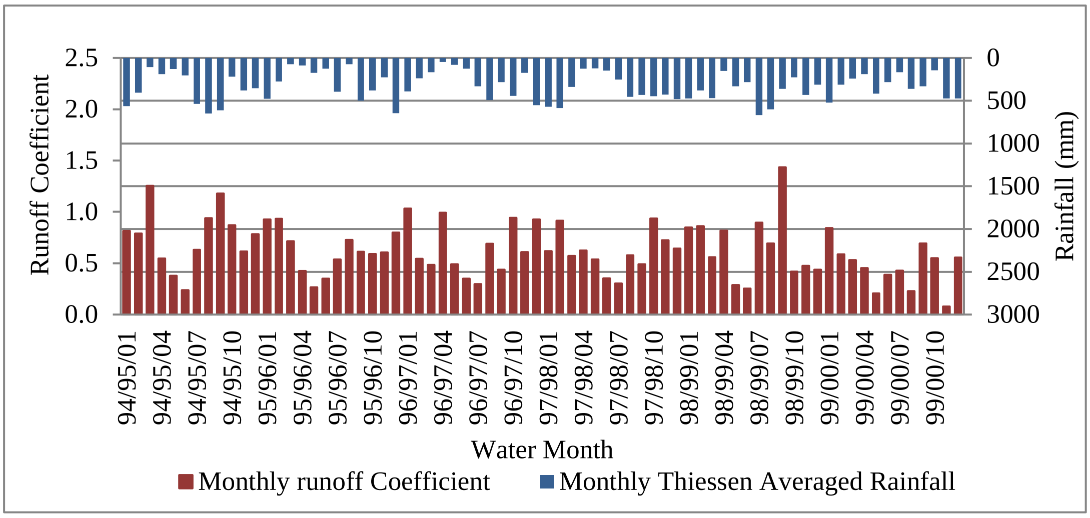


Figure A-4.1: Monthly Runoff Coefficients variation with rainfall in Ellagawa Watershed

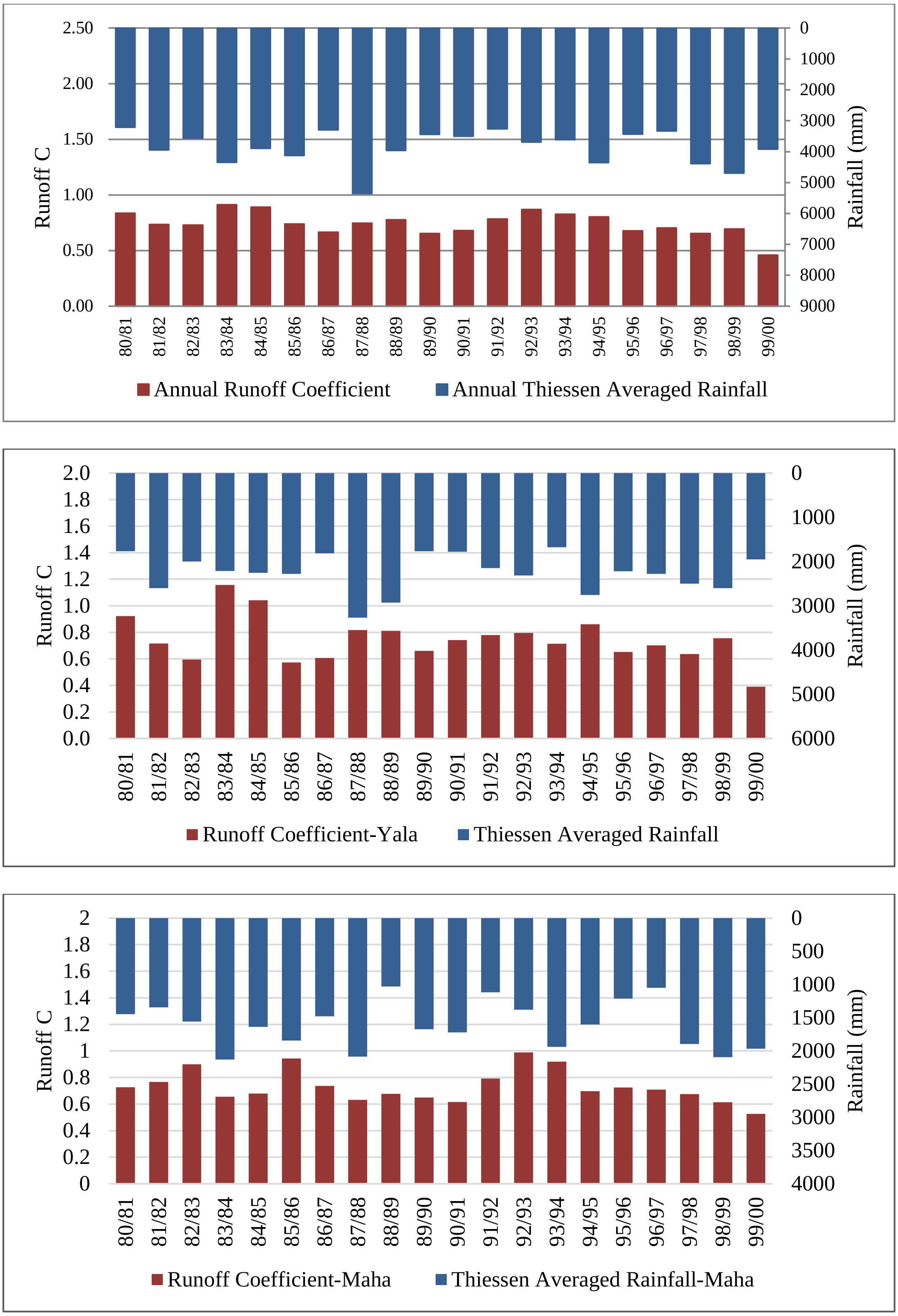


Figure A-4.2: Annual and Seasonal Runoff Coefficient variation with rainfall at Ellagawa watershed

APPENDIX-B

DATA CHECKING FOR GIN GANGA WATERSHED

B-1-Single mass curve & Double mass curve analysis for Gin Ganga

B-2-Visual checking of rainfall and stream flow for Gin Ganga

B-3-Monthly comparison of Thiessen Averaged Rainfall, Stream flow and Evaporation for Gin Ganga (1980-2011)

B-4- Monthly, Annual and Seasonal Runoff Coefficients for Thawalama Watershed (1980-2005)

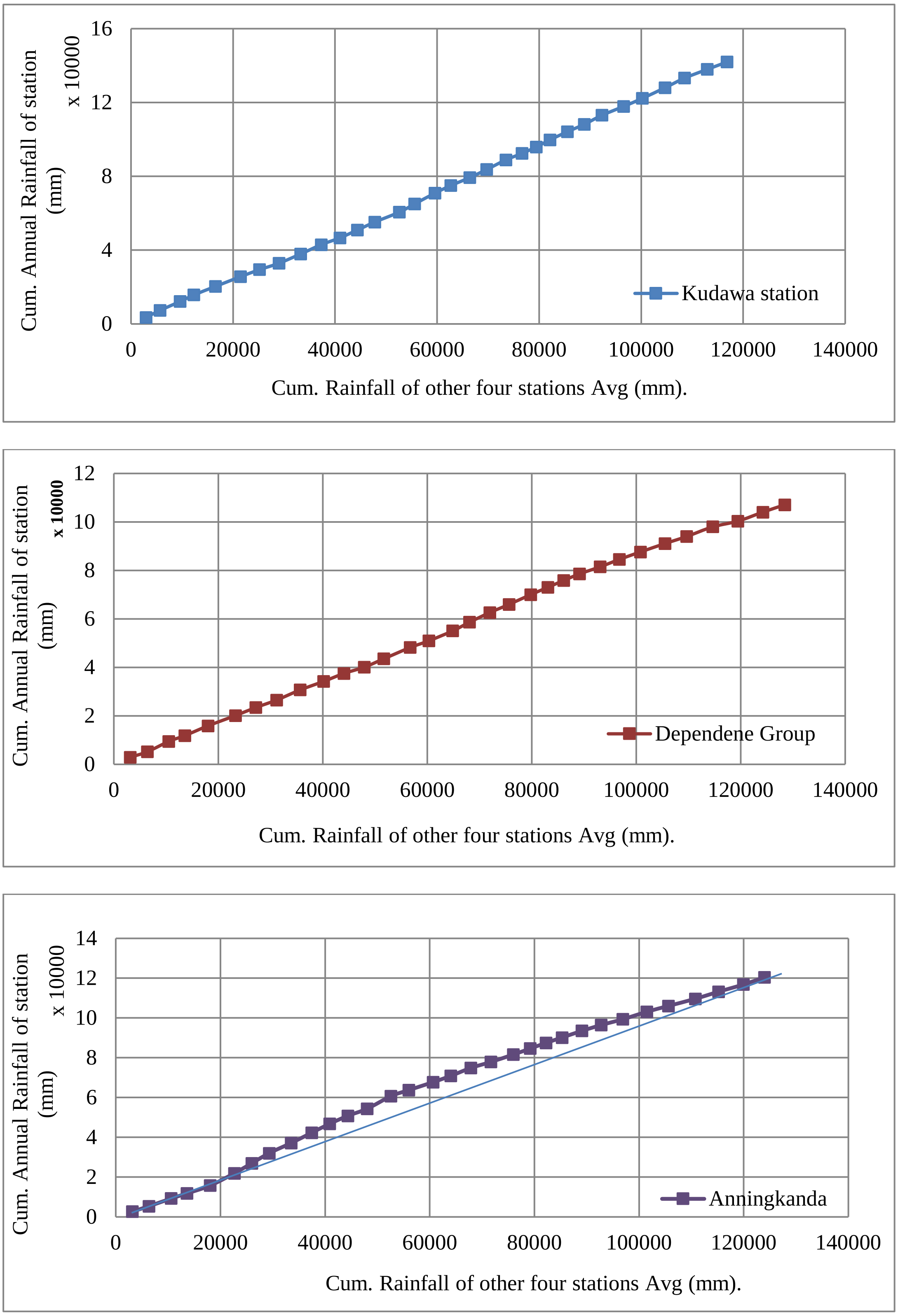


Figure B-1.1: Double mass curve analysis for Gin Ganga

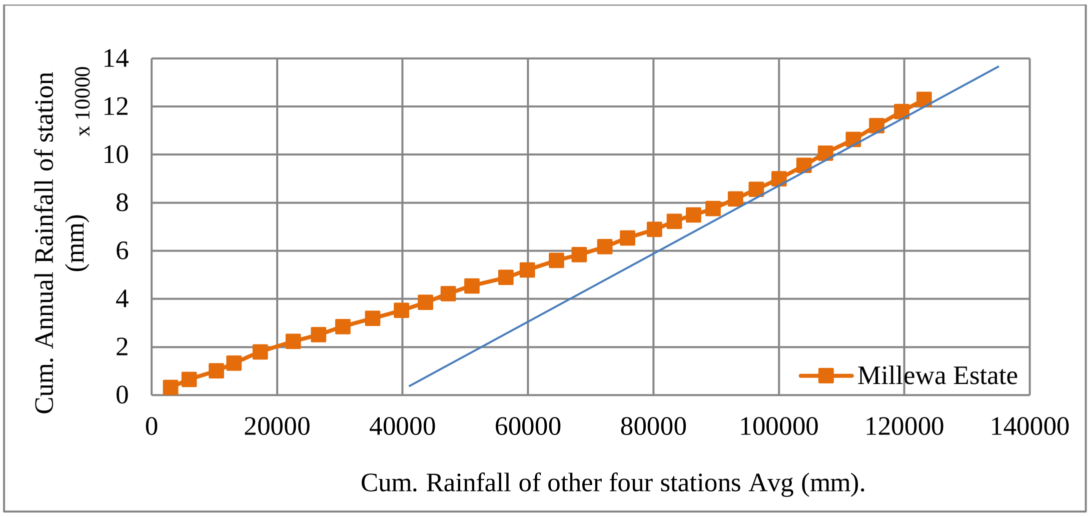


Figure B-1.2: Double mass curve analysis for Gin Ganga

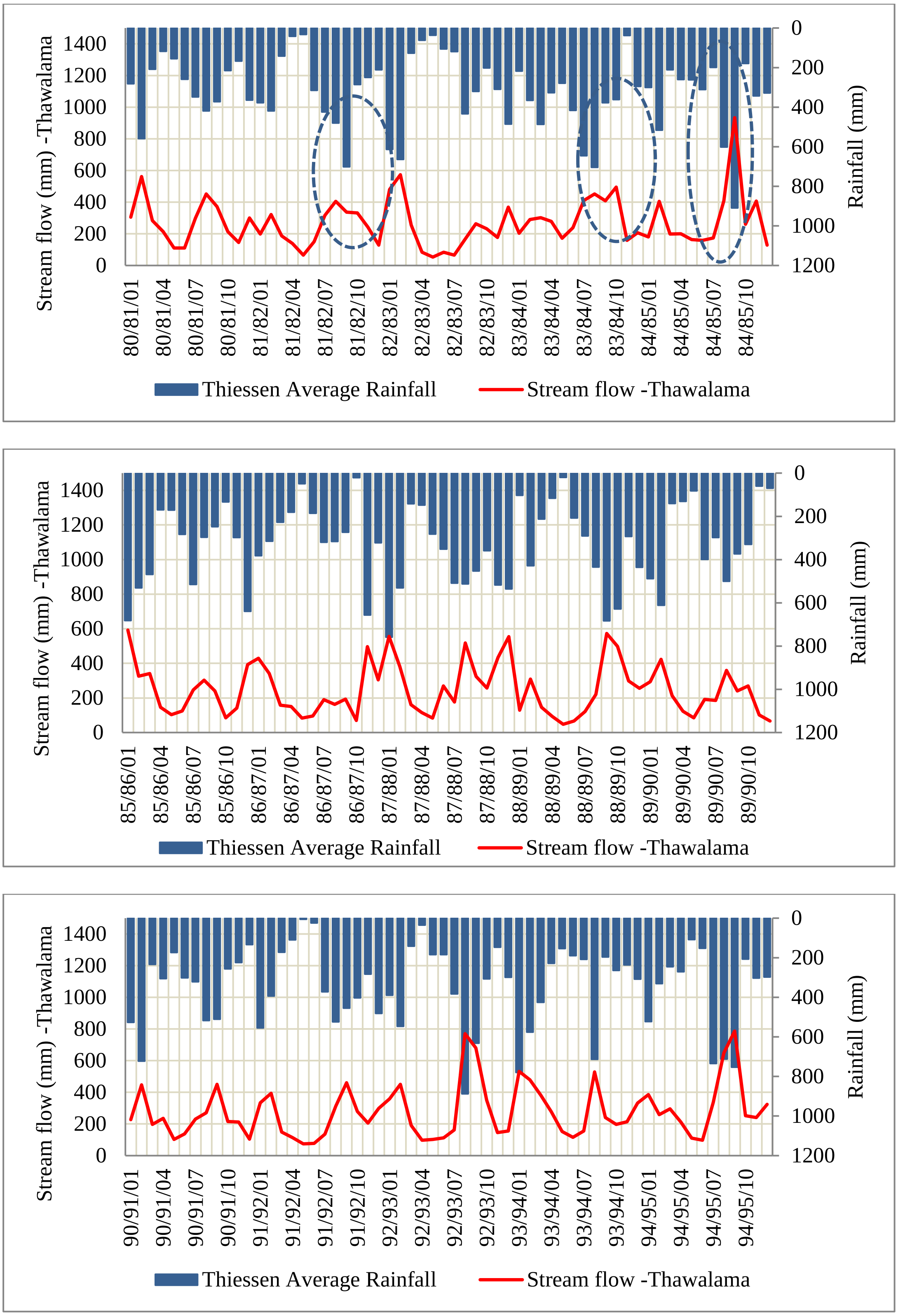


Figure B-2.1: Monthly Stream flow at Thawalama with respect to monthly Thiessen averaged rainfall- 1980-1995

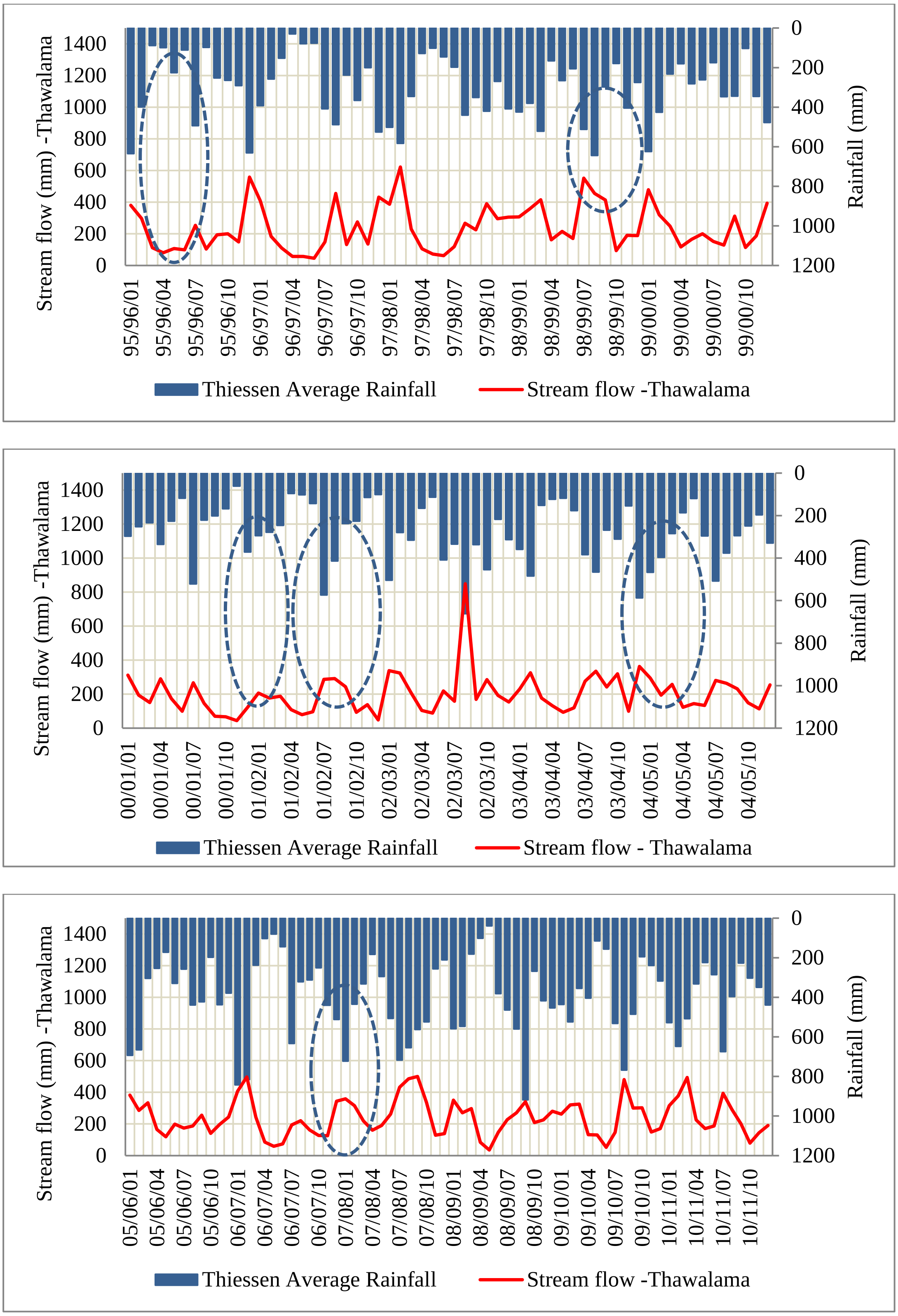


Figure B-2.2: Monthly Stream flow at Thawalama with respect to monthly Thiessen averaged rainfall- 1995-2011

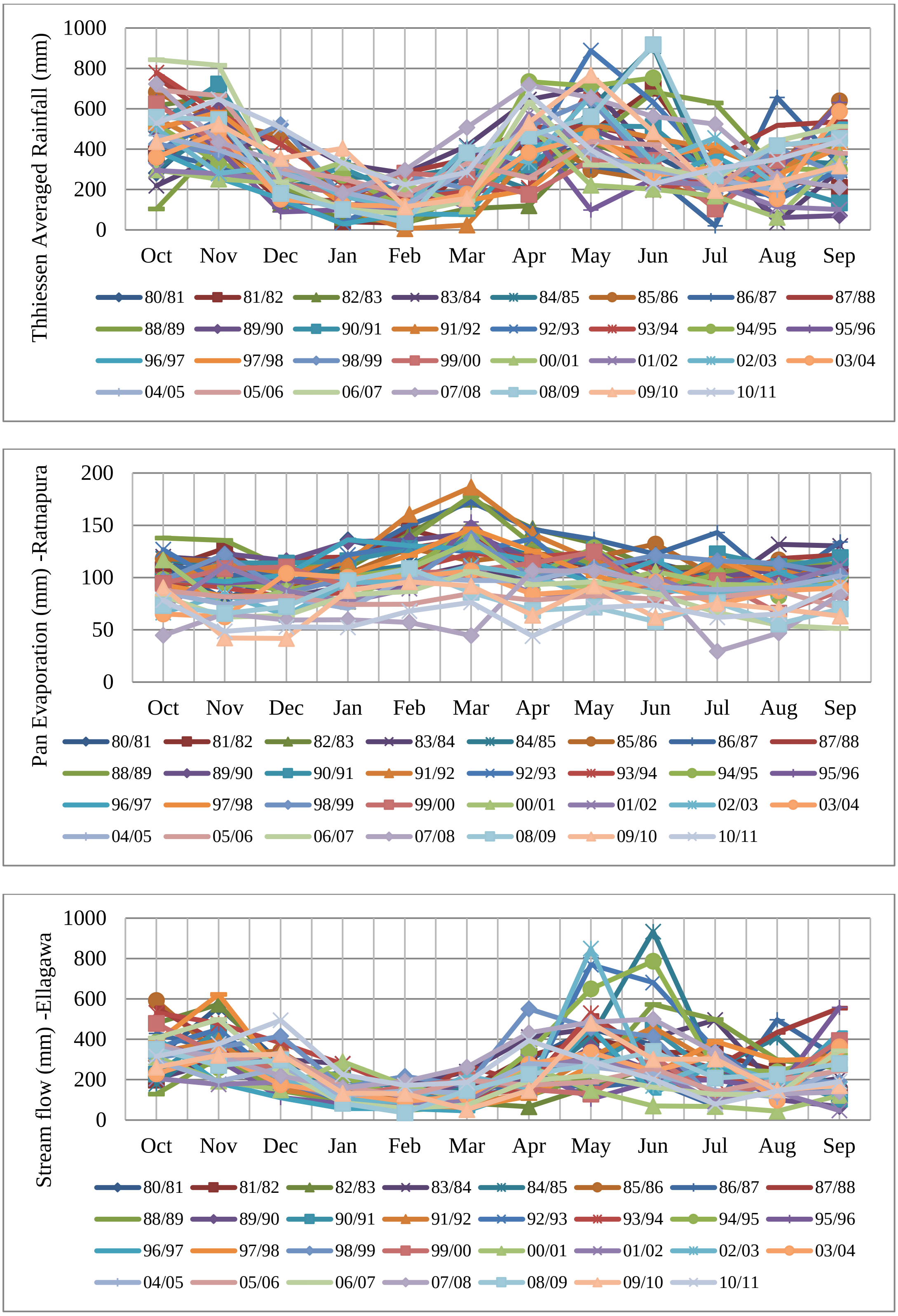


Figure B-3: Monthly comparison of Rainfall, Stream flow and Evaporation for Gin Ganga- 1980-2011

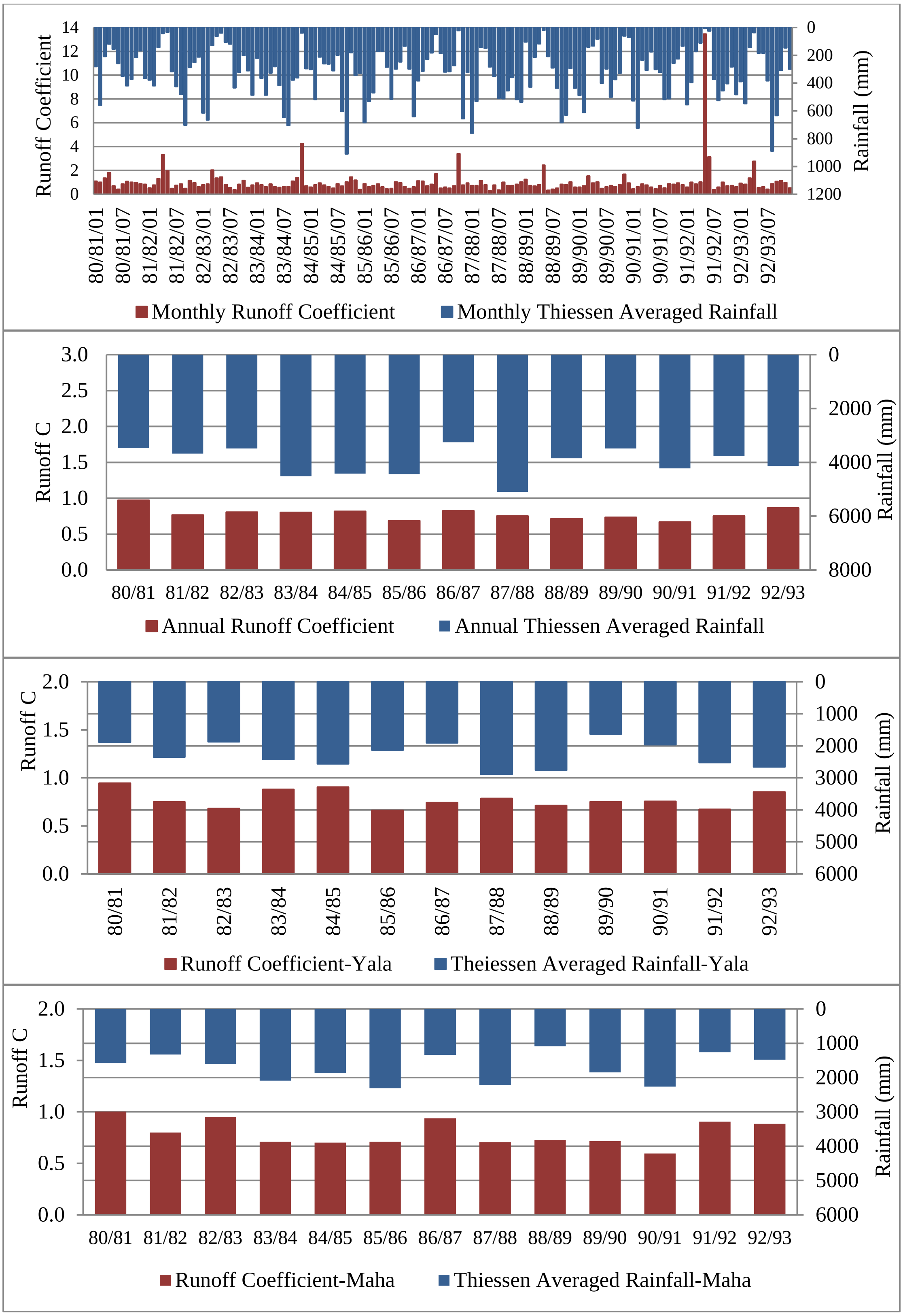


Figure B-4.1: Monthly, Annual and Seasonal Runoff Coefficients for Thawalama Watershed (1980-1992)

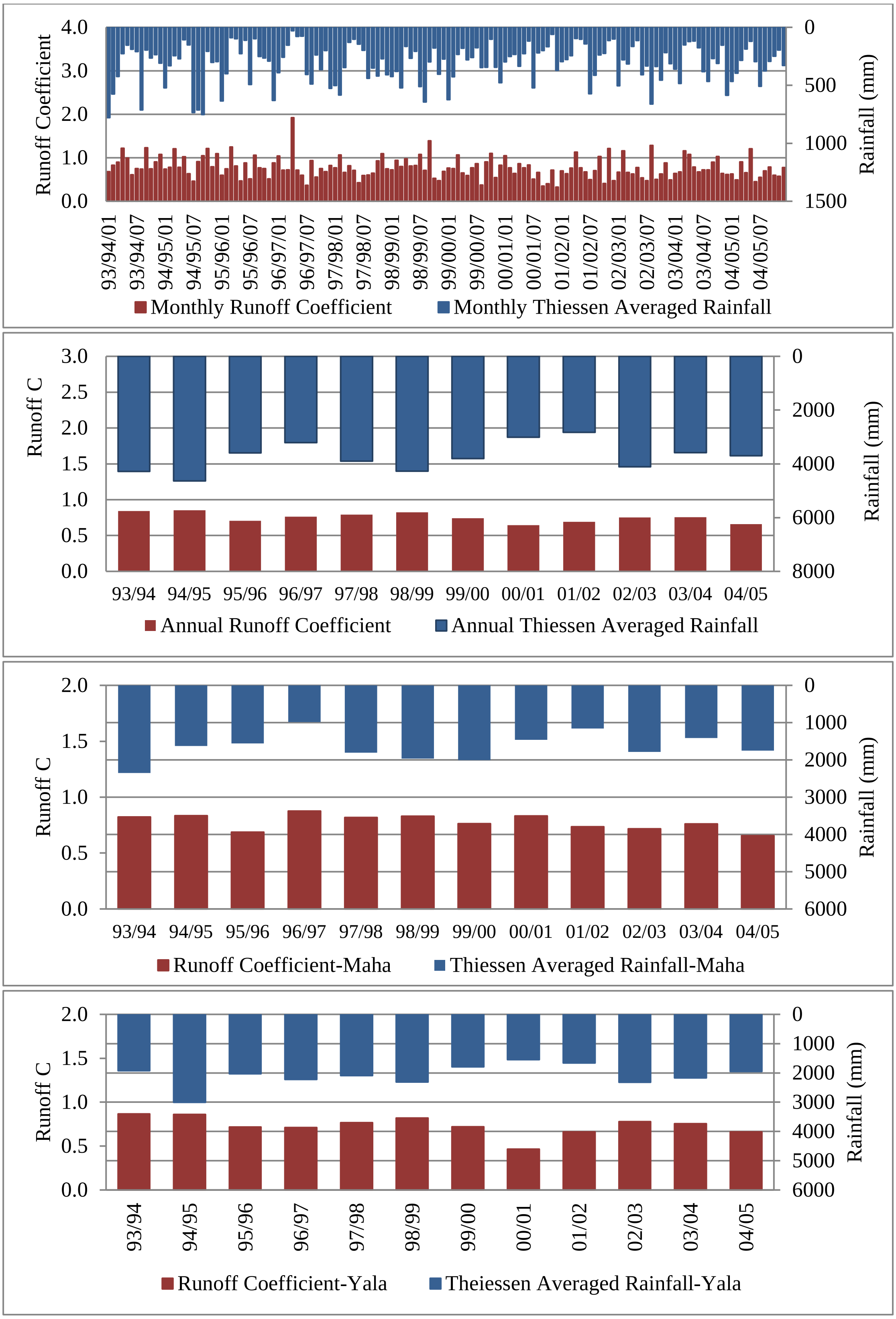


Figure B-4.2: Monthly, Annual and Seasonal Runoff Coefficients for Thawalama Watershed (1992-2005)