TRANSFERABILITY OF MODEL PARAMETERS FOR MONTHLY STREAMFLOW ESTIMATION IN UNGAUGED WATERSHEDS IN KALU RIVER BASIN

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DECLARATION

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Professor N.T.S.Wijesekera	Date

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Transferability of Model Parameters for Monthly Streamflow Estimation in Ungauged Watersheds in Kalu River Basin

Abstract

Prediction and forecasting of ungauged streamflow have become a challenge to watershed modelers especially when practical water resources planning and management are a major concern. Over the years, researches have experienced and executed various methodologies and approaches to find a way to estimate streamflows at ungauged locations where they found that transformation of model parameters can be used effectively in this regard, which still requires further research. The present study targeted to find the adequacy of parameter transferability options to estimate streamflow at ungagged outlets. Two parameter monthly water balance model which was developed by Xiong and Guo (1999), is used for the modeling of two gauged watersheds at Ellagawa and Rathnapura which are located in Kalu river basin, Sri Lanka. Three model parameter transfer schemes have been tested under the study. They are namely, temporal, spatial, and spatio-temporal. The transferability of model parameters within Kalu River basin showed that the temporal transfer scheme has the highest capability of predicting overall flows with the average MRAE values of 0.34 while it is 0.42 and 0.35 in spatial and spatiotemporal transfer schemes respectively. Spatial and spatiotemporal transfer schemes perform at the same accuracy level for predicting high flows with an average MRAE value of 0.27 while it is 0.30 in temporal transfer scheme. The temporal transfer scheme has the highest capability to predict intermediate flows with an average MRAE value of 0.32 while it is 0.41 and 0.36 in spatial and spatiotemporal schemes respectively. Spatio-temporal transfer scheme performs best for low flows with an average MRAE value of 0.35 while it is 0.43 and 0.52 in temporal and spatial transfer schemes respectively. Further, compared to high and intermediate flows, low flow estimation has the highest MRAE values in all three considered transfer schemes.Results of seasonal flow analysis indicated that spatiotemporal scheme has the highest capability to predict Yala season streamflows with a 13% of average error for Ellagawa watershed and spatial transfer scheme has the highest capability to predict Maha seasonal flow with an average error of 13.29%. Model parameter C is 2.09 for Rathnapura watershed and it is 2.38 for Ellagawa which is having a 13% difference in each other.SC is 1420 for Rathnapura and 1461 for Ellagawa having a 3% difference from each other, indicating that model parameters do not vary across the catchments in Kalu River Basin and they are stable in a spatial domain. Transferability option 3, which used 19 years total data has the high capability to predict streamflows with a high accuracy level by giving MRAE values 0.35, 0.27, 0.36 and 0.35 for overall, high, intermediate and low flows respectively compared to transferability option 2 which used 12 years of common data period giving MRAE values 0.42, 0.27, 0.41 and 0.52 for overall, high, intermediate and low flows respectively indicates longer the data period, the higher the accuracy of streamflow predictions irrespective of the transfer scheme used. Since high and intermediate flow predictions are in higher accuracy level with lower MRAE values compared to that of for the low flows, streamflows predicted by transferred model parameters are sufficient and adequate to design and planning of water resources infrastructure and their management in ungauged watersheds within Kalu river basin.

Key Words: Ungauged watersheds, Parameter, Transferability, Model, Sri Lanka

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1 INTRODUCTION

Freshwater has become the most important resource which now requires sustainable management strategies to assure the availability and water security for future generations. UNSECO has identified the water securing and quality maintenance as major challenges faced by both developed and developing countries who are on the way to reach their sustainable goals. Massive-scale industrialization, the rapid growth of population, increased rates of deforestations, urbanizations, and climate change impacts have accelerated the scarcity of water in the present world. Therefore the gap between supply and demand of freshwater keep widening (Martin,2013; Porkka and Gerten, 2016).UNESCO further reported and stated that if managed properly, the planet's freshwater quantity is enough for the fulfillment of the water demand of living beings and their development activities.

Water resource modelers and water managers use hydrological models for accurate quantifications of water resources and their assessments. The type of hydrological model varies from a simple regression-based model to complex physical process-based distributed models. Over the recent past, various kinds of distributed water resources models have been developed and are now in practice. HEC-HMS, HEC-RAS, IRIC, LISFLOOD MIKE SHE, MIKE FLOOD, SWAT, SWIM are some of those models which have not yet been largely applied to Sri Lankan basins. These distributed models have drawbacks on computation time, lack of availability of high-resolution spatial data for model set up, initial parameter definition methods, and lack of continuous hydrological data for longer durations. In essence, these models require quality data, longer data periods, they are hard to setup and configure, and they need more digital space, capacities, and computation times. The performance of these models is quite low, especially for the data-scarce regions. Byeon (2015) has stated that lumped hydrological models still perform as well as distributed models when sufficient calibration data exists.

Xiong and Guo (1999) and Andreassian (2006) identified and reported that the monthly time scale is the commonly utilized and most suitable time resolution for the practical water resources planners to use for their planning and management activities. Therefore, conceptual monthly water balance models play a major role when watersheds are mathematically modeled and streamflows are quantified.

Essentially, an effective planning and proper management of water resources require water infrastructure which are designed properly and which functions efficiently. These water infrastructures are spatially distributed within a river basin. Often many river basins are gauged either at one or two locations. Though it is possible to calibrate and verify models for gauged watersheds, it is necessary to extrapolate streamflow at other small-scale watersheds within the same river especially for the design of water infrastructure for irrigation purposes, water supply schemes and for other water drainage activities. Since there exist lower spatial distances between sub-watersheds in the same river, it reduces the variability of hydrological behavior in a spatial domain (Oudin et al., 2008).To overcome this unavailability of streamflows researchers have used various approaches and methodologies to transfer hydrological model parameters from donor catchment to receiver ungauged catchments to predict and forecast ungauged streamflows.

However, a limited amount of literature had attempted to find how accurate can be the prediction of streamflows in ungauged catchments especially for planning and design purposes. No exact way to select a suitable method to streamflow predictions at ungauged watersheds with the required accuracy. One way to find a solution is to carry out case studies and experience the methods commonly used to estimate ungauged streamflow. It is necessary to compare with the observed streamflow for accuracy checking. The present study, therefore, targets to contribute towards the evaluation of the adequacy of transferring calibrated model parameters by optimizing model parameters for two basins and then comparing the results with observations.

1.1 Problem Statement

In Sri Lanka, major rivers are mostly gauged only at two or three locations for streamflow measurements. Therefore, this unavailability of an appropriate amount of gauging stations to measure streamflows limits the proper infrastructure designs at sub-watersheds while it restricts the effective management and planning of the water resources in both basin sub-basin levels. As a solution to this unavailability of measured streamflow at ungauged watersheds, gauged catchments can be modeled and can identify a set of model parameters that are applicable to estimate the streamflow at ungauged catchments. Further, it is required to check these estimated streamflows represents the hydrological behavior of the ungauged catchment adequately. Through a comprehensive literature review, it has been revealed that in Sri Lankan context none has checked whether the transferred model parameters from gauged to ungauged catchments predict the streamflow adequately for the planning and design purposes by comparing them with an observed time series. Therefore, evaluation of the adequacy of transferring calibrated model parameters by optimizing model parameters for gauged basins and then comparing the results with observations will solve the number of difficulties of hydrological modelers, designers, and planners who attempt to do sustainable water resources planning and management.

Under the present study, two gauged catchments within the Kalu river basin were selected for the adequacy checking of model parameter transferability for the streamflow predictions at ungauged catchments. The 2P monthly water balance model was applied for Ellagawa and Rathnapura basins separately and parameter transferability options were checked and recommendations were given to facilitate streamflow estimations in ungauged basins for proper management and planning of water resources.

1.2 Objectives

1.2.1 Overall objective

To evaluate the adequacy of transferring calibrated model parameters by optimizing model parameters for two gauged basins and comparing the results with observations using the 2P monthly water balance model.

1.2.2 Specific objectives

1. Review of recent studies carried out to assess the parameter transferability and identification of state-of-the-art methods available for streamflow predictions at ungauged basins.
2. Identifications of the merits of the 2P monthly water balance model for the parameter transferability assessment over the other available models and methods.
3. Execution of 2P monthly water balance model simulations for Ellagawa watershed and Rathnapura watershed and identification of an optimized set of model parameters for both watersheds separately
4. Execution of model parameter transferability methods on both watersheds and analysis of results and summarization.
5. Giving recommendations about the adequacy of transferring calibrated model parameters within the Kalu river basin for the modelers who intended to do hydrological modeling for planning and management of water resources

1.3 Project Area

The present study concentrates on Ellagawa and Rathnapura sub-basins within the Kalu river catchment which covers 2766 km² in area. Most land areas are covered by forests, home settlements, paddy and rubber lands, and lands of other agricultural plantations. Kalu River falls freely into the sea at Kalutara by capturing a huge amount of rainfalls from central highlands to the southwestern coastal area. The Kalu Basin receives an annual average rainfall of 3600 mm which is a large wetter catchment in the country. It's annual average rainfall varies from 2800 mm in lower reaches to 5300 mm in higher elevations. The Kalu river basin is located between the 6.32°N and 6.90°N, and 79.90°E and 80.75°E. Kalu River originated from Samanala hills in central highlands which is approximately high about 2250 m to MSL. Major tributaries of Kalu River gather rainwater from Sri Pada and Sinharaja rainforests and encompass a quick drain on its upper catchments. River flow from the Sri Pada flows over a 36 km from an elevation of 2250 m MSL and reaches 14m of MSL at Rathnapura town which indicates the steepness of upper reach of the river which is given as the reason for the frequent flash floods in the Rathnapura area. Afterward, Kalu River flows on considerably flat terrain for about 70 km and finally reaches the sea by supplying a large amount of fresh water to the sea. The average runoff coefficient for the Kalu river basin is found to be 0.49 with the consideration of the spatial variation of the basin. (Wijesekera et al., 2016).

Ellagawa basin has an area of 1390km² and the Rathnapura basin has an area of 627km². These two catchments were considered under the present research and their placement within Kalu catchment is illustrates in Figure 1-1. Six rainfall gauging stations were considered and Table 4-1 presented the location coordinates. Ellagawa basin experiences average annual rainfall of 3600mm and it is 3500mm for Rathnapura. The average annual pan evaporation is around 950mm for Rathnapura which is the evaporation station used for the modeling of both Ellagawa and Rathnapura basins.

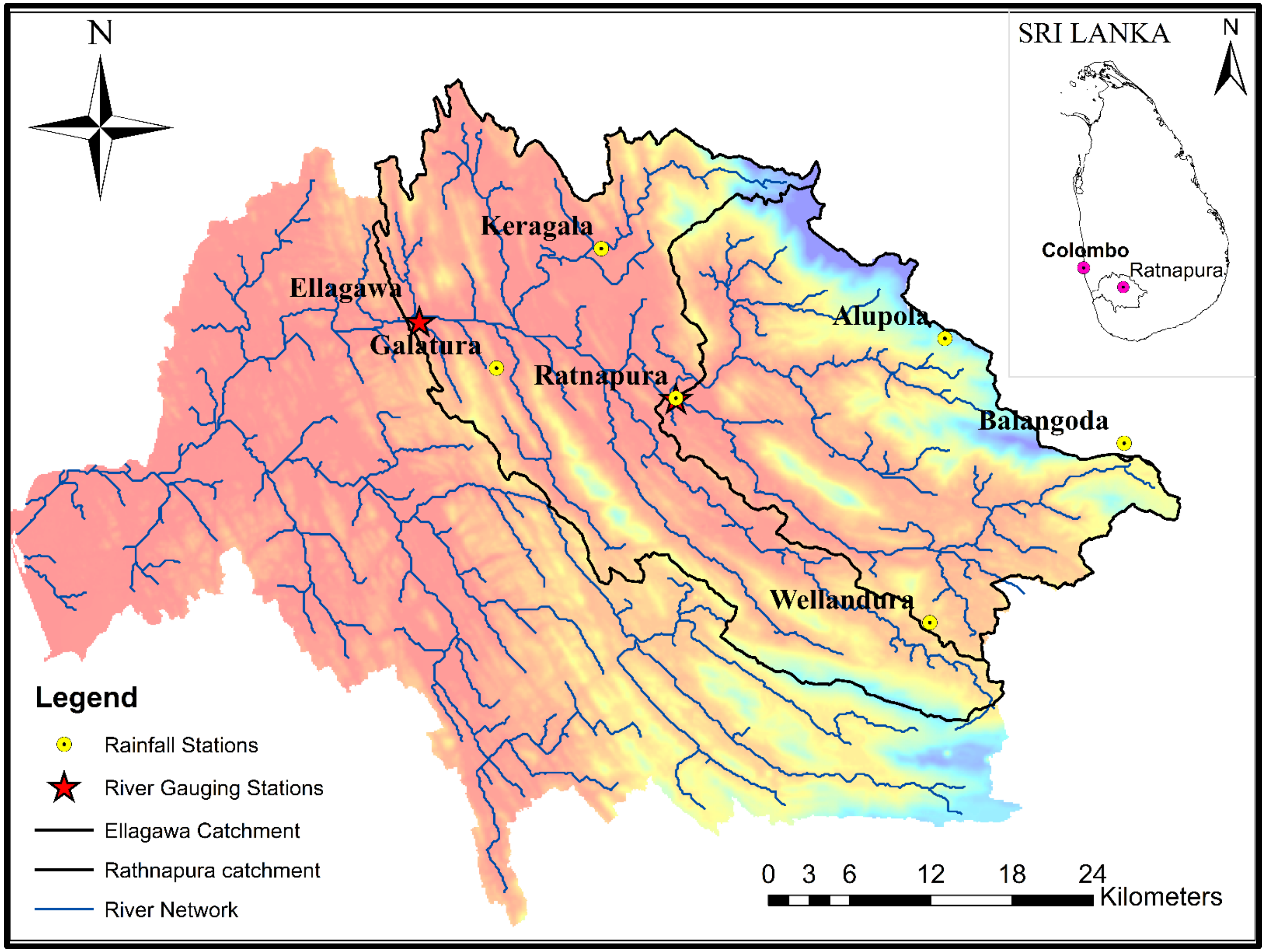


Figure 1-1: Project Area Map

2. LITERATURE REVIEW

The main target of the detailed literature review is to recognize and understand the available research findings, methods, and guidelines regarding the transferability assessment of model parameters. Literature review supports to explore the step by step procedures followed by researchers to do modeling of water resources mathematically to evaluate the accuracy and adequacy of transferability of model parameters streamflow prediction and furcating at ungauged watersheds.

2.1 General

Under the present literature review, it has been identified that appropriate tools, methods, schemes, and techniques which are experienced by researchers to transfer model parameters from a gauged catchment to an ungauged catchment for streamflow predictions and forecasting. There were some reviewed publications which directly addressed the parameter transferability options, schemes and at the end recommend the most accurate method which can be practice to transfer model parameters for general applications whereas some other reviewed publications were there which are explained method and techniques which can be used to transfer model parameters for a specific application related to planning and management of water resources. Some studies were concentrated in low flows, some were concentrated in high flows and some were concentrated in overall flows. The literature review consists of more than 11 major publications which address the model parameter transferability in both monthly and daily time scale. Other than the learnings about model parameter transferability, this literature review was expanded to more than 30 peer-reviewed papers, all together which facilitate to learn about water balance models, selection of data lengths for calibration and validation, model performance evaluation criteria, details about objective functions, etc.

2. 2 Predictions at Ungauged Catchments

Freshwater is the most precious natural resource found in the earth and the unavailability of measured streamflows at ungauged catchment has become one of the major challenges faced by hydrological modelers, scientists, and experts (Sivapalan, 2003). This is known as PUB – predictions at the ungauged basin after Sivapalan (2003). Streamflow time series at a watershed level has a wide variety of applications in multiple sectors like hydropower generations, irrigation water scheduling, low flow analyzes, water supply schemes and planning, flood mitigation efforts, environmental flow assessments, trans basin diversion studies and various kind of activities related to planning and management of water resources in a sustainable manner. Especially for flood studies, and low flow studies, nowadays computer-based numerical models have become an essential tool for hydrologists. These numerical models required accurately measured streamflow time series for their model calibration and validations.

Various kinds of approaches and methodologies can be found which were attempted to estimate streamflow time series at ungauged catchments. They differ from each other due to the complexity, data requirement, and applicability in different areas. Process-based models and hydro-statistical models are the major two aspects found which have been used by specialists to predict ungauged streamflows. Under process-based models, it calibrated a deterministic model at the ungauged site by a regional approach whereas under hydro statistical approach gauged catchments were modeled to predict streamflows at nearby ungauged sites.

Archfield and Vogel (2010), Skoien and Bloschl (2007) have performed direct transformation of streamflow time series from nearby gauged catchments to ungauged catchments without executing rainfall-runoff models. Drainage area ratio method by Hirsch (1979), Wiche et al. (1989) is found to be the oldest method used to direct the transformation of streamflow to ungauged watersheds. Under this method first identifies a nearby gauged catchment that is hydrologically similar to the ungauged catchment and then area normalized streamflow values have been transferred from gauged to the ungauged catchment. According to Archfield and Vogel still, this drainage area ratio method is the most widely used for streamflow estimations at ungauged watersheds. This is especially because of its requirement of a limited number of inputs data such as streamflow at index catchment and area of both index and other ungauged sites. This is simply a default because it is not data-intensive and less time consuming and simplicity whereas other methods require too much data and only local applications can be found on them (Emerson et al., 2005). However the performance of the DAR method has been rarely compared with other methods for estimations of streamflow at ungauged sites.

By assuming the probability of exceedance of flow regimes are the same for both sites, daily flow duration curves have been used to estimate streamflow at ungauged watersheds by Fennessey (1994), Smakhtin, and Hughes (1996) and Archfield et al. (2009 & 2012). The authors have named this method as the QPPQ method. In 2000 Smakhtin and Masse has presented an improved version of this above same method with flow duration curves associated with wetness indicators to estimate ungauged streamflows.

In 2006, Mohamoud has developed a modified drainage area ratio-based method and a regional regression equation for the Mid-Atlantic region to estimate ungauged streamflows. Its prediction capability and accuracy has tested using observed data. Two equation has been proposed to estimate streamflow when streamflow to drainage area remains constant and when it varies due to increased drainage. The author has concluded that those two mathematical equations can be used reliably for estimate ungauged streamflows in the Mid-Atlantic region.

Mohamoud (2008) again presented a new method to predict FDCs and streamflow time series at ungauged sites of the USA and Mid-Atlantic region and also showed the reconstructed streamflows and FDCs are closely matched with the observed values and same predictions gain from DAR method. Under the study, they finally recommend that the method can be adapted to anywhere in the world if the regression equation is developed by using the method presented under their study.

Archfield and Vogel (2010) have reported the development of a Map correlation method which is useful to identify the most suitable donor gauged catchment which has a better correlation with receiver ungauged catchment to donate streamflows directly. Skoien et al. (2006) have found under their streamflow predictions studies by using topological kriging concepts, the closest gauge is not the always which has the best correlation with the nearby ungauged site to be predicted streamflows.

Former and Voger have experienced three methods to estimate ungauged streamflows namely DAR, and two other regression equations with standardizations. Standardization by means (SM) and standardization by means and standard deviation (SMS) are the two standardization methods. However, it has been finally found that none of the two methods are superior to the DAR method. More 50% of sites have given better estimation with the DAR method than the other two methods. The other methods have shown greater biasness than DAR.

2.3 Parameter Transferability

Most of the watersheds in the world have a lack of streamflow observations, remain ungauged. Therefore it’s a challenge and a duty of hydrological researches to develop tools methodologies and strategies to predict and forecast streamflows at ungauged outlets. (Sivapalan et al., 2003; Wagener and Montanari, 2011).The most common and practiced method of streamflow predictions at ungauged watersheds involves two major steps. First is the calibration and validation of model parameters for gauged watersheds by comparing their simulated flow values with observed flow values. The second step is transferring calibrated and validated model parameters from gauged to the ungauged catchment that found to be hydrologically similar in various aspects. (Oudin et al., 2010)

A considerable amount of studies and comprehensive researches were found which has tried to transfer model parameters from gauged to ungauged catchments in different ways to predict and forecast streamflows. Some of them can be found under references Patil and Stieglitz (2014), Bloschl et al. (2013), Zhang and Chew (2009), Oudin et al. (2008), Young (2006), Mcintyre et al. (2005), Kokkonen et al. (2003), Post and Jakeman (1999).

Oudin et al. (2008) have used spatial proximity and physical similarity approaches to firstly identify the donor gouged catchment and receiver ungauged catchment for the model parameter transformation. The author has checked the spatial proximity approach and physical similarity approach on 913 catchments in France and finally found the spatial proximity is outer-performed the physical similarity approach for the selection of donor gauged catchment for ungauged streamflow estimation. In 2009, Zhang and Chiew have executed multiple parameters transferring methods over 210 southeast Australian catchments and found the integrated method of physical similarity and spatial proximity approach has lightly overperformed the spatial proximity approach. In 2014 Patil and Stieglitz, has checked two different methods of spatial transferring of model parameters on 323 USA catchments and findings concluded that prediction performance at ungauged watersheds is more sensitive to the parameters which are transferred rather than to the methods used to transfer them. Further, conclude that spatial transferring of model parameter resulted in some deterioration during model simulations compared to model calibration due to variation of physical properties and hydro-meteorological inputs of donor gauged and receiver ungauged catchment.

Using a spatially lumped hydrological model named EXP-HYDRO on 294 USA catchments Patil and Stieglitz (2015) evaluated three major schemes of hydrological parameter transformations and summarized their performance separately. The three major schemes are temporal, spatial, and spatiotemporal. They have concluded that among these three methods, the temporal transfer scheme is perform best over other two methods with a lowest variation during model simulations compared to calibration. Negligible differences has observed in model performance and predictions from other two schemes. Their results also suggested that parameters show greater stability in a temporal domain rather than a spatial domain and which is consistent with other findings in the world. It further said relative superiority of the temporal transfer scheme is preserved when the distance between donor gauged and receiver ungauged catchment been reduced and the temporal lag between calibration and verification data period increased. The difference of performance of the three transfer schemes become reduce and come to same level when the temporal lag between calibration and verification data durations increased. Authors at the end suggested that further researches need to be conducted to better understanding about the schemes and their performance with the various hydrological behaviors of catchments and the various time lags. In Sri Lankan catchments no reviewed studies has been reported which assess the available methods of parameter transformations and not assessed how accurately one can used transferred model parameters to predict streamflow at ungauged basins for water resources planning and management.

2. 4 Water Resources Models

Water resources models comes in two different ways. They are distributed models and lumped model. Main feature of distributed models are their capability of incorporation of spatial variability of catchment hydrology by using series of data such as land use, soil properties, precipitation, temperature, evaporation and some other hydrological parameters. This facilitate to make predictions in accurate and operational scales by considering inherent spatial variability which has been lumped in to average characteristics of the watershed over a years. (Smith et al., 2004, Boyle et al., 2001, Beven, 1994).No matter it is lumped or distributed, all hydrological models comprises of model parameters which need to be well calibrated with observed data and well optimized with suitable objective function. This each calibrated and optimized model parameter represents a unique combination of hydrological, geographical, meteorological and climatological influence and the behavior of catchment hydrology. However the determination, calibration and optimization of model parameters for each and every catchment is a procedure of data intensive and time consuming.

Over the recent past years various kind of distributed water resources models has been developed and now in practice well. HECHMS, HECRAS IRIC, LISFLOOD MIKESHE, MIKEFLOOD, SWAT, SWIM are well known models in the field of hydrology which has not yet been largely applied to Sri Lanka basins. This all kind of distributed models have a drawbacks on computation time ,lack of availability of high resolution spatial data for model set up ,initial parameter definition methods and lack of continuous hydrological data for longer durations. In essence these model requires quality data, longer data, hard to setup and configure, and need more digital spaces, capacities and computation times. The performance of these models are quite low especially for the data scarce regions (Hydrologically remote areas). Byeon (2015) has stated that lumped hydrological models as well as distributed models when concern about rainfall runoff simulations with the availability of sufficient calibration data exists. However Patil and Stieglitz (2015) stated that for the operation use of these lumped hydrological models requires transfer of calibrated and validated model parameter either in time or space of both for ungauged streamflow estimations.

2. 5 Monthly Water Balance models

From history to present water balance models have been developed in many ways and they have comes in various time scales like hourly, daily, monthly and annually. Based on their time scale their complexity also varies. In 1940s, the first water balance model was developed by and afterwards it has been modified by Thornthwaite and Mather on 1955-57.These models then modified time to time and applied and utilized for various kind of studies related to streamflow forecasting and predictions. Some of those studies are Xu and Halldin (1996), Xu and Vandewiele (1995), Arnell (1992). Since these models were on daily scale, they are data intensive compared to corresponding monthly models.

There are major two sound reasons for the usage of monthly time scale for models. First one is, monthly streamflows are sufficient for the planning and management activities of water resources and climate change impact assessment related studies. Second one is hydro-meteorological data is readily available on monthly time scale compared to daily and hourly time scales. Most monthly models requires fewer number of model parameter to explain catchment hydrological behavior. The hydrological and catchment information per model parameter is increased due to that and it facilitates more accurate determination of model parameters and ultimate they becomes more reliable parameters which possess good correlation with catchment characteristics.

Literature recommended that a simple monthly water balance model still can be used efficiently to streamflow estimations just like conceptual hydrological models still in greater use in the sector of flood forecasting despite the arrival of process based physical models (Woolhiser, 1996).Ye et al.(1997) found that a six parameter conceptual model has given similar or not less superior results compared to a model with twenty two parameters for streamflow estimations in monthly time scale. Therefore a simple model with lesser number of model parameters still can be used for practical water resources planning activities. Under present case study, the two parameter monthly water balance model which developed by Xiong & Guo (1998) is used to check the adequacy of transferability of model parameters for streamflow estimation especially in ungauged catchments for the effective planning and management of water resources.

2. 6 2P Monthly Water Balance Model

Xiong and Guo (1998) developed and executed a two parameter monthly water balance model over a seventy cathcmenents belongs to three major river basins in the south of china. The results obtained after the application of developed model in above catchments concluded that the model efficiencies are high in both calibration and validation periods. Comparative study of monthly water balance models revealed that this 2P models gives similar performance to a five parameter model as well. At the end authors recommended that this2P model can be easily and efficiently applied for the programs of water resources planning and climate impact related case studies to simulate monthly rainfall runoff conditions especially in humid and semi humid regions. This model consist of two major model parameters called C and Sc. C accounts for the conversion of time scale from year to monthly while Sc stands for the field capacity of the catchment. Major hydrological data inputs require for the model development are rainfall and evaporation. Soil moisture content also required as an initial condition for the commencement of the model simulations. A unique way of model parameter optimization also described in the original paper and further descriptions and its application in the present study is comes under section 5.2.2 in chapter 5.

2.7 Model Calibration and Verification Data Durations

Model calibration and verification procedures are the essentials of hydrological models which decides the accuracy and which assures the reliability of the models for their future applications. Models can give erroneous results unless they calibrated well. The model calibration can be done either manually or automatically or for both methods.

It is difficult to obtain unique set of model parameters during model calibrations when there is limited information, limited data and unrealistic measurements of hydrological inputs. Spatial variability of rainfall and other catchment properties are poorly represented by point measurements. The quality and consistency of final set of calibrated model parameters are always depends on the optimization algorithm or procedure, objective function, model structure and calibration data set. Therefore care must be taken during the selection of calibration data set since it decide the final quality of the model performance and outputs.

Table A-1 and Table A-2 under Appendix A shows that the calibration data durations used for various kind of local and international studies and their recommendations. Most of the studies has used 5 to 10 years period of data for model calibration. Within this considered duration there should be several wet years dry years and average years to encompass a variety of hydrological events in order to activate all the model parameters during model calibrations. Theoretically it has been proved that the data set is longer the calibration performance also getting better since its experiences considerable amount of hydrological events under the considered longer period. In 1994 under their study Michaud and Sorooshian (1994) stated that at least 15 years of monthly data is required for better model calibration. Haans (1972) presented a study over a 7 USA catchments and concluded that at least one and favorably two or three years of measured monthly streamflows are necessary for proper parameter estimations. Xu and Vandewiele (1994) has checked the data lengths of 2,5,10,15 20 years of monthly data on 91 Belgium catchments and concluded that at least a 10 years of data set is required for an adequate and reliable model calibration. Therefore no exact indications to have a calibration data length for proper model performance .Sometimes 2 years set of data would do better parameter estimations rather than 10 years data set. The importance is its hydrological representativeness of the watershed and the richness with the information of catchment responses. Considering all findings from literature, the present study selected calibration data length as 12 years and verification data length as 7 years for Ellagawa and Rathnapura watersheds as it represents a good sample of hydrological events including wet years, dry years and average years with respective to observed rainfall and streamflow variability. See Figure C-3 and Figure C-4 in Appendix C.

2. 8 Model Performance Evaluation Criterion

There are two major criteria that used by experts to evaluate model performance can be found in literature.

1. Graphical Verification Criteria
2. Numerical Verification Criteria

2. 8.1 Graphical verification criteria

Graphical verification criteria recommended to be used to evaluate and compare the simulated discharge as follows

- Linear scale plots with the time in x axis - Simulated and observed hydrographs for verification period
- Double mass plots - Simulated versus observed discharge volumes for the verification period
- Flow Duration Curves (FDC)– For both simulated and observed streamflows for calibration and verification period

2. 8.2 Numerical verification criteria

The verification formula used to evaluate and compare the simulated and observed discharge know as objective function. The objective function act as the main and essential element during the calibration of conceptual rainfall runoff models automatically. There are some objective functions which gives better indications with high flows whereas gives more better figures with low flows. Depending on the study, it is up to modeler to decide one or multiple objective functions are going to be used or not.

Well known statistical approaches to evaluate model performances are Mean Ratio of Absolute Error (MRAE),Nash & Sutcliffe (1970), Ratio of Absolute Error to Mean (RAEM), Relative Error (RE) and Correlation Coefficient (R2).Detail descriptions of these objective functions and their performance with different flow regimes can be found in the references of Wang et al.(2011),Chen et al.(2007),Wijesekera (2000),Xiong and Guo (1999), and Xu and Singh (1998).In 2000 , Xiong and O'Connor stated that "the goodness of the estimated optimum parameter set is determined more by the shape of the response surface, which reflects both the rainfall–runoff relation expressed by the data and the structure of the selected model, rather than by the optimization methods used to calibrate the model". Table A-3 in Appendix A gives the summary of different numerical indicators and their performance on various flow regimes.

2. 9 Objective Functions

Objective functions are the indicators that give a numerical figure to the modeler to decide whether the model performance is adequate for the considered application under the study. It helps to assess the model performance and it decides the further commencement of the whole modeling activity. As mentioned earlier one objective function may more sensitive to low flow events while the other one is sensitive to flood peaks. The modeler has to select a suitable objective function based on the study going to conduct. The objective function enables one to reject or accept any modification or any changes during model simulations by giving a positive or negative indication.

Madsen (2000) concluded under his study that there should be an objective function in any hydrological model to assess the agreement between average values of observed and simulated runoff, to assess the overall agreement of shape of the observed and simulated total hydrographs, to assess the agreement of observed and simulated peak flows with time and quantity and finally to assess the agreement between simulated and observed low flows.

Table A-3 in Appendix A has summarized how each objective function performed and behave with the overall flow, intermediate flow, high flows, and low flows. Intermediate and overall flow matching is the major concern in water resources planning and management activities. Therefore it is found the MRAE is preferred over NSE when the major concern is given to intermediate flow matching.

Since MRAE is proved to be the most suitable for intermediate flow matching, under the present case study, the “MRAE” is used as the objective function to evaluate model efficiency and to obtain an acceptable level of agreement between observed and simulated hydrographs.

2. 9.1 Mean ratio of absolute error (MRAE)

MARE is a numerical indicator that considers the absolute mismatch of simulated streamflow to the observed value at each observation point and gives an average indication of the error at the end. MARE has been used for parameter optimization by Wijesekera (2010) and Perera and Wijesekera (2000) under their studies. Wanniarachchi (2013) has used MRAE as an objective function during calibration and verification under his case study on Attanagalu Oya.

Following is the numerical equation for the MRAE. Their Observed flow is indicted by Qobs and Qsim indicates the simulated flow and n is the number of data points in the considered periods.

$MRAE = 1/n\ [\sum|Qobs-Qsim|/Qobs]$………………*Equation 1*

MRAE is specific to considered observations only under the model simulations. Therefore when there is unrealistic observations are present, it is identifiable with the MRAE value. When MRAE closer to zero its indicated excellent performance of the models, while it reaches unity the model performance gets lower. MRAE values around 0.5 indicate the average model performance of runoff modeling.

3. METHODOLOGY

A comprehensive methodology flowchart is given in Figure no 2. The Problem has been identified as the first step of the study by paying attention to the planning and management of water resources in sub-basin levels of Sri Lanka. Then the overall objective and the targeted specific objectives to be covered under the study were concluded which are planned to achieve within the time frame. Data collection and literature review was done in parallel. Available methods for data consistency checking and data gap filling, monthly water balance models, studies related to spatial transferability of calibrated model parameters and role of selected objectives functions, and other evaluation criteria were reviewed under the detailed literature review and summarized under the chapter 2.

For both Ellagawa and Rathnapura Watersheds, the considered 2P monthly water balance model was established in a spreadsheet environment of MS Excel. To obtain an optimized set of calibrated and verified model parameters, model calibration and verification was then carried out for both Ellagawa and Rathnapura watershed. As the most important step, the verified set of model parameters interchanged and apply for both watersheds separately and streamflow is computed. Then a comparison of simulated flow was made for both watersheds with the observed streamflow data and assess the accuracy of simulated streamflow by using an objective function. Model performance was evaluated using three major evaluation criteria. Finally, conclusions & recommendations were made regarding the adequacy of spatial transferability of model parameters for streamflow estimation of ungauged watersheds for the planning and management of water resources.

In essence, this case study concluded that how accurately a modeler can transfer model parameters within watersheds which are in close proximity to estimate streamflow for infrastructure designs and future planning and management activities.

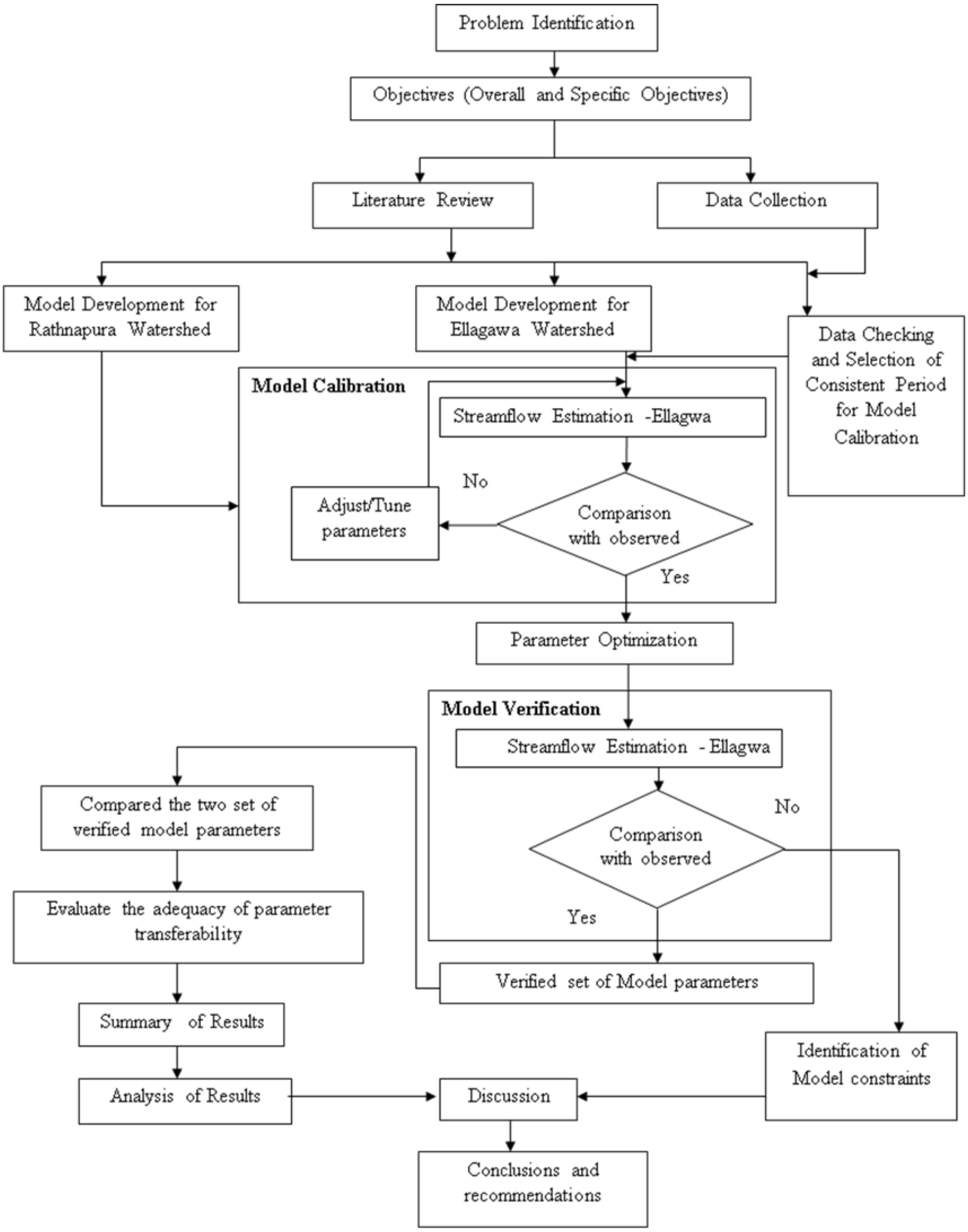


Figure 3-1: Methodology Flow Chart

3.1 Model development

Xiong & Guo, (1999) developed a two-parameter monthly water balance model which accounts for and lumped three major hydrological variables namely rainfall, streamflow, evaporation into three numerical equations which are given under Equations 1,2 and3.

$E(t)/EP(t) = C\times \mathrm{Tanh}[P(t)/EP(t)]$ …………………………....*Equation (2)*
$Q(t) = S(t-1)+\mathrm{Tanh}\{(S(t-1)+P(t)-E(t)/Sc)\}$………………....*Equation (3)*
$S(t) = S(t-1)+P(t)-E(t)-Q(t)$…………………………………*Equation (4)*

Where,
P (t): Monthly Rainfall (Observed)
E (t): Actual Monthly Evapotranspiration (Model Estimation)
EP (t): Monthly Pan Evaporation (Observed)
Q (t): Monthly Runoff
S (t-1): water content of the soil at the end of the (t-1)-Th month, at the beginning of the (t) Th month
S (t): Water content of the soil at the end of (t) Th month
C: Model parameter 1 which accounts time scale from year to month
Sc: Model parameter 2 which accounts for the field capacity of the catchment.

After the spreadsheet development of the 2P monthly water balance model using the above concepts, a manual calculation was also performed for several time steps to certain the model outputs and to assure its representativeness of the model concepts.

4 DATA AND DATA CHECKING

4.1 Data Requirement

Simulation of 2P monthly water balance model requires three major hydrological data as model inputs namely Rainfall, Streamflow, and Evaporation which are on a monthly time scale. Therefore, the following data were collected under the data collection. For the computation of the physically-based runoff coefficient, land use data of the project area also collected, and data sources and data resolutions are mentioned in the following Table 4-1. Station coordinates were given in Table 4-2.

Table 4-1: Summary of Collected Data with Sources

Data Type	**Data Resolution**	**Station**	**Data Duration**	**Source**
Rainfall	Monthly	Alupola Galatura Keragala/Kuruvita Rathnapura Balangoda Wellandura	1983 -2019	Department of Meteorology
Streamflow	Monthly	Ellagawa Rathnapura	1983 - 2019	Department of Irrigation
Pan Evaporation	Monthly	Rathnapura	1983 - 2019	Department of Meteorology
Topographic Maps	1:50000		Updated 2003	Survey Department

Table 4-2: Station Coordinates of Collected Hydrological Data

Data type	**Station Name**	**Location Coordinates (WGS 84, N/E in Decimal Degrees)**	
Streamflow	Ellagwa	6.90 °N	8.44 °E
	Rathnapura	6.68 °N	80.4 °E
Rainfall	Balangoda	6.65 °N	80.7 °E
	Kuruvita/Keeragala	6.78 °N	80.35 °E
	Wellandura	6.53 °N	80.57 °E
	Galatura	6.70°N	80.28° E
	Rathnapura	6.68 °N	80.4 °E
	Alupola	6.72 °N	80.58 °E
Pan Evaporation	Rathnapura	6.68 °N	80.4 °E

4.1.1 Landuse

Using 1:50000 topographic maps from the survey department, Landuse maps were prepared for Ellagawa, and Rathnapura Watersheds and areas were computed separately.

Table 4-3: Major Landuse Types of Ellagawa and Rathnapura Watersheds

Landuse Type	**Ellagawa**		**Rathnapura**	
	Area (km^2)	**percentage of Area**	**Area (km^2)**	**percentage of Area**
Forest area (Forest, Rubber, Coconut, Tea, Other cultivation)	722	51.9%	307	49.0%
Built up area (Built-up area, Home settlements)	249	17.9%	111	17.8%
Marshy area (Marshy, Paddy)	95	6.8%	25	4.1%
Grassland (Chena, Grass, Scrub)	300	21.6%	172	27.4%
Rocky area	6	0.4%	3	0.4%
Water area	19	1.4%	8	1.3%
Total	1390	100.0%	627	100.0%

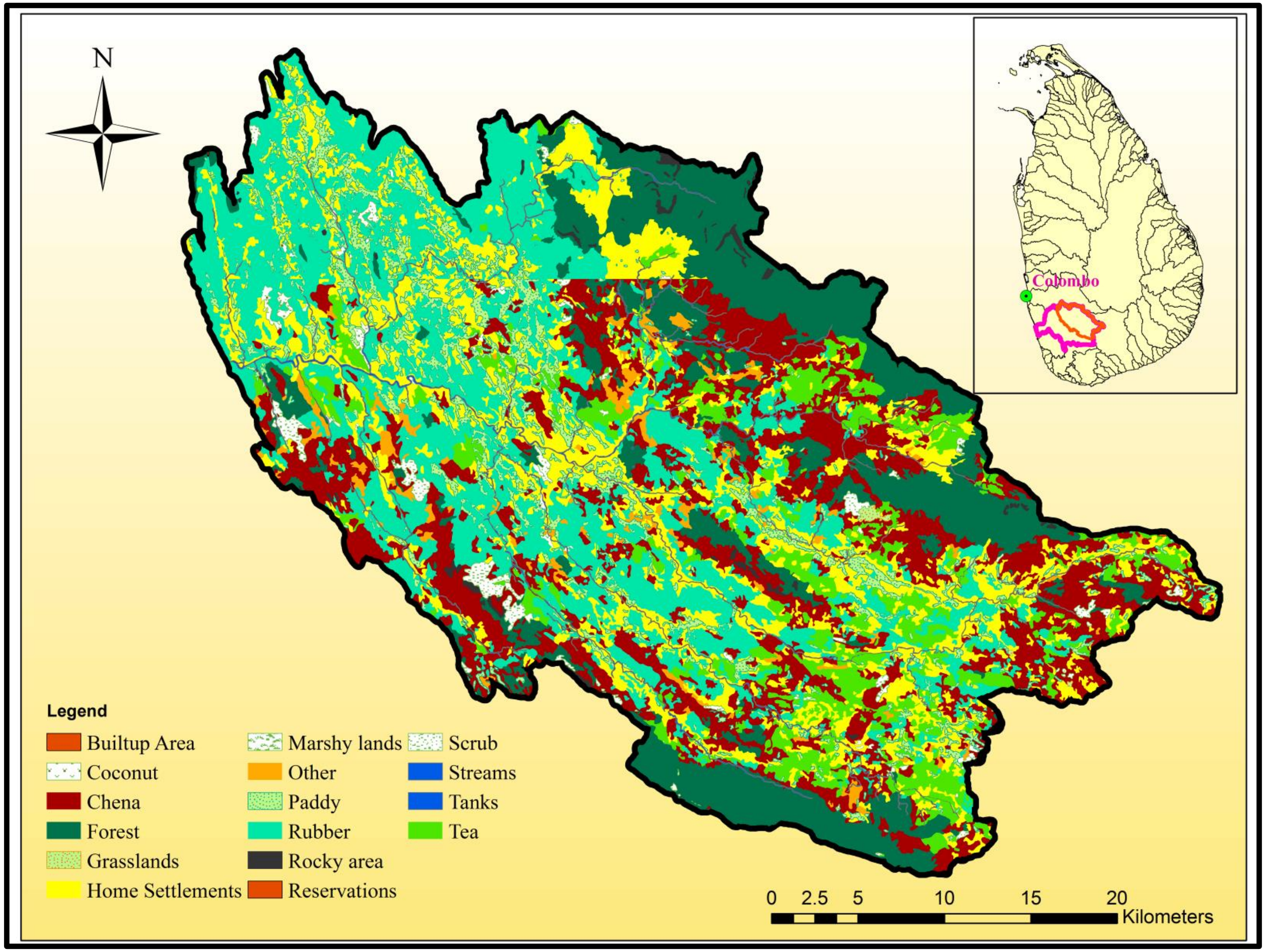


Figure 4-1: Landuse Map of Ellagawa Watershed

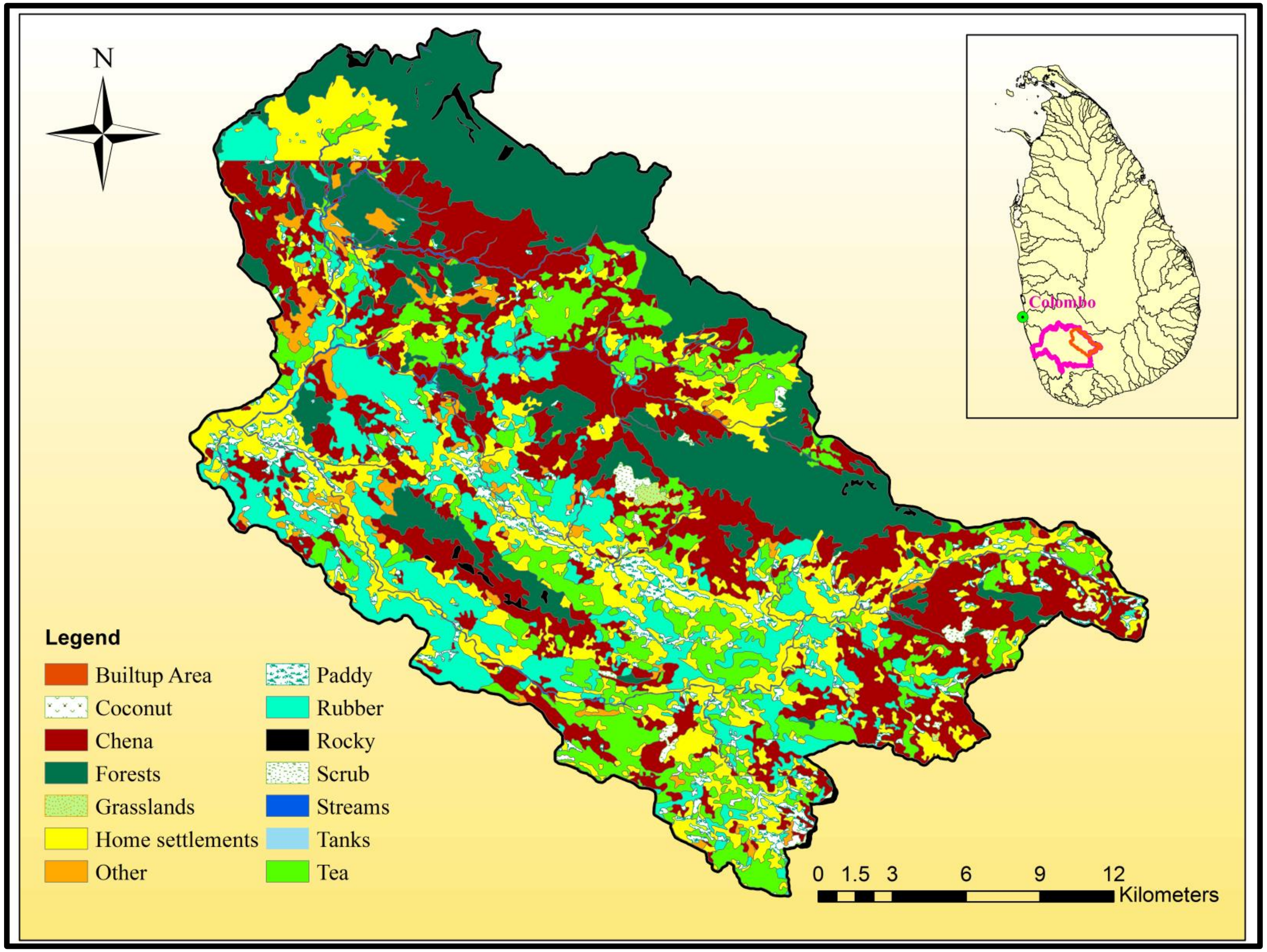


Figure 4-2: Landuse Map of Rathnapura Watershed

4.1.2 Rainfall

As mentioned in Table 4-2, rainfall data from six rainfall gauging points were collected in monthly resolution. The station density was selected based on the WMO standards for both rainfall and streamflow. (Table 4-4)

Table 4-4: WMO standards for Spatial Distribution of Gauging Stations

Gauging Stations	**No. of Stations**	**Station Density (km²/station)**	**WMO Standard (km²/station)**
Rainfall	6	232	575
Streamflow	1	1390 (Ellagawa) 628 (Rathnapura)	1875

Rainfall data were arranged against time and rainfall time series were prepared for each rainfall station separately. During that missing rainfall, values were detected and summarize as follows.

Table 4-5: Summary of Missing Rainfall Data

Station	**Missing Months**
Alupola	2019-February
Rathnapura	2019-September
Kuruvita/Keeragala	2018 - August
Galathura	1999 - October
	2007 - September
Balangoda	1994 - December
	1995 - July
	1997 - September
	2012 - January
	2019 -May to Sept
Wellandura	1990 - October
	2002 - May, July, September, October, November, December
	2006 - September
	2007 - February, March, September, October, November, December
	2008 - October, November
	2010 - April
	2011 - May, July, November
	2011 - January, December
	2018-December
	2019-January, February, September

4.1.2.1 Data gap filling

Many researchers have been carried out to study the methods of gap filling of rainfall data over the years. Depending on the rainfall patterns and its spatial distribution, the best method for estimating missing rainfall data can vary from place to place. (Caldera, 2016). Missing hydrological data can be filed by using the neighboring station to the station to be filled by considering their correlation with each other. Under the present study, the missing precipitation data were field by taking a simple average of rainfall of other surrounding gauging stations.

4.1.2.2 Consistency checking of rainfall data

The literature emphasizes that the use of a double mass curve as a convenient way to observe the consistency behavior of hydrological data records and it is one of the primary initial steps in the analysis of a longer data record. A double mass curves is a plot of cumulated figures of one hydrological variable against the cumulated figures of another such variable or the cumulated values of the same variable for a considered continuous data period. (Searchy and Hardison, 1960).Further, it says that to achieve more reliable results, the sum of one of the variables can be plotted against the sum of cumulations of a pattern composed of all kinds of similar records in a given spatial domain. (Merriam, 1937).The pattern, which is consists of the average of several records, is less affected by an inconsistent behavior in a record of any considered station.

Standing upon the above basis double mass curves for rainfall records were plotted and illustrated in Figure 4-3 for all six stations for the consistency checking of observed rainfall data series. Persistent breaks in the slopes cannot be observed in the graphs which indicates that the rainfall records are consistent over the period under consideration. DMC against Kuruvita and Wellandura shows small breaks but they are not persistent over the years and literature says to ignore breaks when they are not long-lasting for more than 5 years. (Searchy and Hardison, 1960).

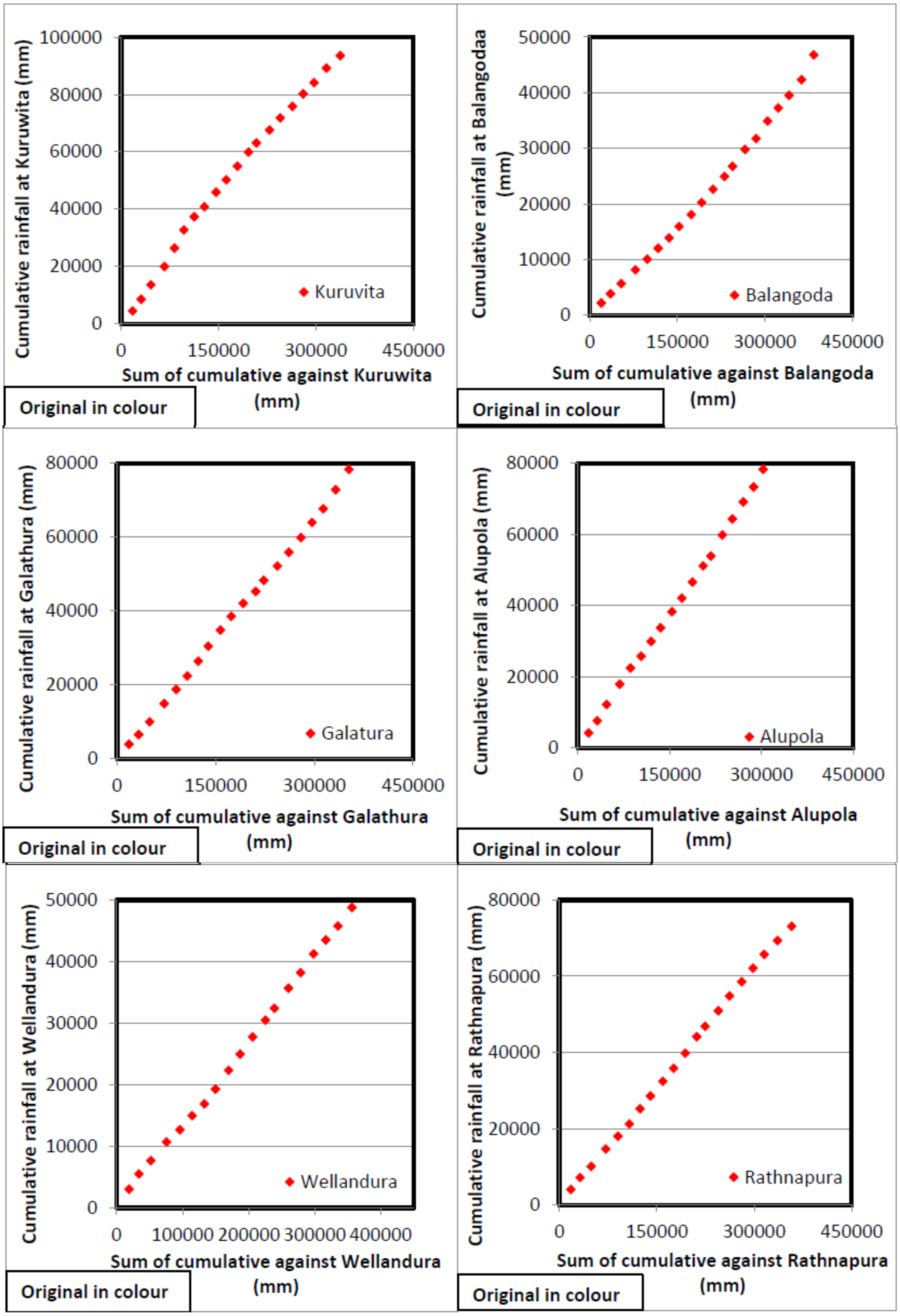


Figure 4-3: Double Mass Curves for Rainfall

4.1.2.3 Thiessen rainfall

To account for the spatial distribution of catchment rainfall it is required to use a well-developed spatial interpolation technique. Thiessen polygon method is the most common and well-practiced method to determine average rainfall over a considered spatial domain when there are several rain gauging stations are available. Under this Thiessen method, weight is given to each rainfall station by considering the area covered by the respective station. This method is more reliable when the catchment is more homogenous in everywhere based on its physical morphological features. Catchment heterogeneity will decrease the accuracy of this method. Therefore when selecting rainfall gauging stations to estimate spatially average rainfall it's a need to consider their placement within the catchment or outside the catchment.

Table 4-6: Thiessen weights for rainfall in Ellagawa and Rathnapura basins

Rainfall Station	**Ellagawa**		**Rathnapura**	
	Area (km2)	**Thiessen Weight**	**Area (km2)**	**Thiessen Weight**
Balangoda	80.3	0.06	80.1	0.13
Rathnapura	340.3	0.24	193.0	0.31
Wellandura	291.5	0.21	147.9	0.24
Alupola	203.6	0.15	206.6	0.33
Galatura	190.2	0.14		
Kuruwita	284.6	0.20		
Total	**1390.6**	**1.00**	**627.6**	**1.00**

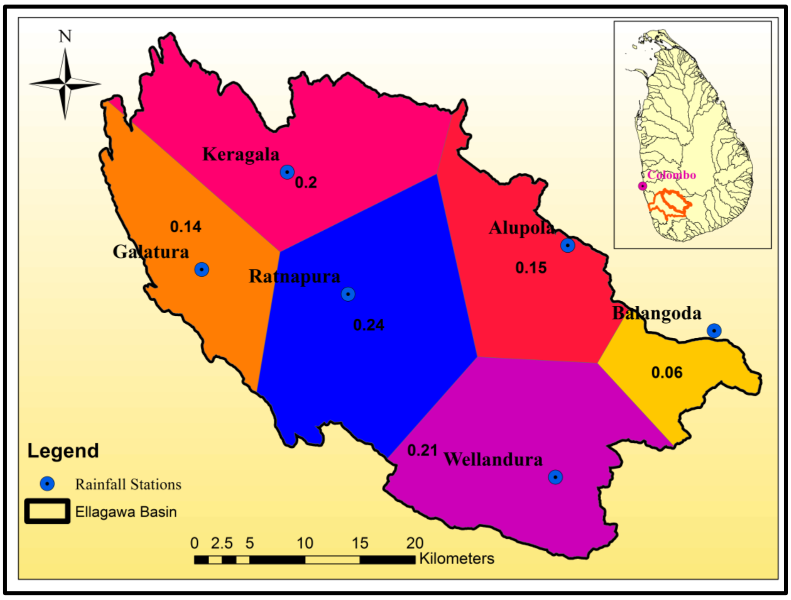


Figure 4-4: Thiessen Polygons for Rainfall - Ellagawa Basin

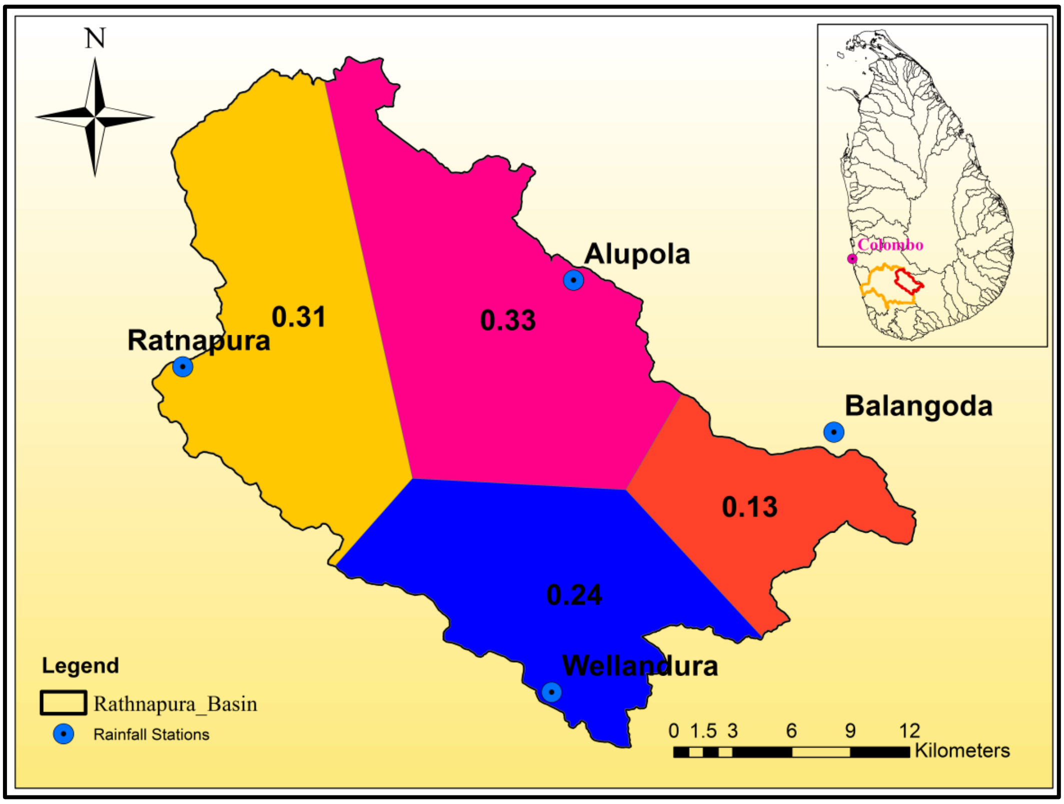


Figure 4-5: Thiessen Polygons for Rainfall- Rathnapura Basin

4.1.3 Streamflow

Under the present study, measured monthly streamflow data of Ellagawa and Rathnapura gauging stations were selected for model simulations.

Table 4-7: Annual Streamflow Conditions at Ellagawa and Rathnapura

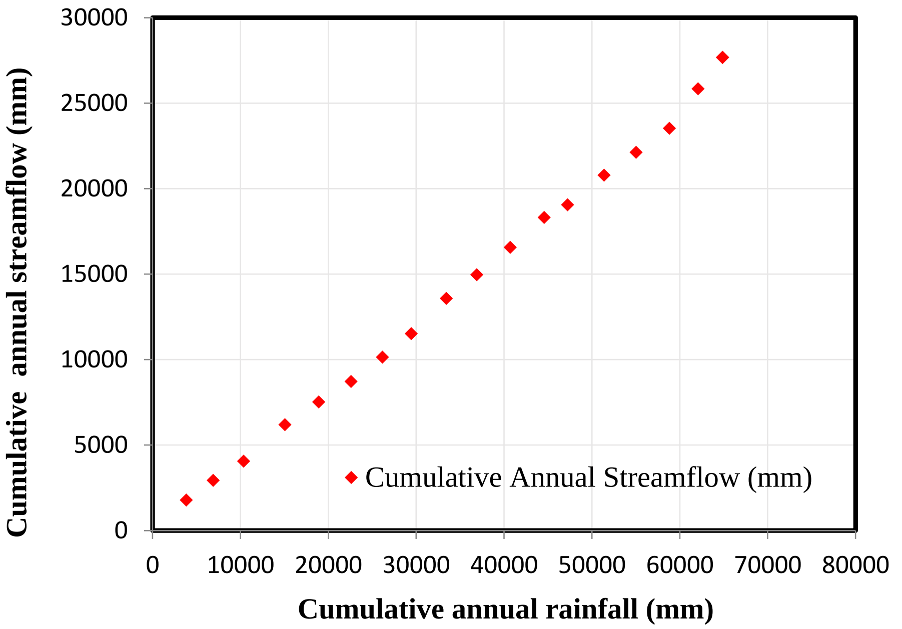
Station	Annual Maximum Streamflow (mm)	Annual Average Streamflow (mm)	Annual Minimum Streamflow (mm)
Ellagawa (1390km²)	2307	1537	739
Rathnapura (628 km²)	2040	1554	881

Before the application of streamflow data in model simulations, consistency checking has been carried out as previously done for the rainfall data by plotting a double mass curve. (Figure 4-6 & 4-7).For both stations, streamflow data from 1983 to 2019 were collected during data collection. Most of the previous literature stated that there exists an unrealistic behavior of streamflow data in the Kalu River. Therefore a detailed data checking was carried out initially and it is revealed that there exists an unrealistic behavior of streamflow data before the water year 1990/2000 for both stations. (Appendix B).With this result, for the present study, it is concluded to use 1999/2000 water year to 2018/2019 water year (20years) for the Ellagawa watershed since it shows realistic annual water balances and runoff coefficients, therefore, assuming it represents catchment hydrological behavior well. Since by the time the present study has carried out irrigation department has not published the data of water years 2018/2019. Therefore later the research has to be confined to a total of 19 years period (1999/2000 to 2017/2018).

Rathnapura streamflow data was not available for the period of 1999/2000 to 2005/2006 water year at its source. Therefore it is concluded to use 1989/1990 to 1995/1996 data along with the data from 2006/2007 to 2017/2018 water year. Altogether 19 years of data set was used for Rathnapura gauging station as same as Ellagawa. However, water years from 1989/1990 to 1995/1996 show higher runoff coefficients compared to water years after 2006/2007. This data period selection was done with the background support of reviewed literature (section 2.7, chapter2). For both stations streamflow shows consistent behavior throughout the selected 19 year period and illustrated in Figure 4-6& Figure 4-7.

Table 4-8: Selected data periods for the study

<table>
<tr><th>Basin</th><th>Streamflow</th><th colspan="2">Total Duration</th><th>Rainfall</th><th colspan="2">Total Duration</th></tr>
<tr><td>Ellagawa</td><td>1999/2000 to 2017/2018</td><td colspan="2">19 Years</td><td>1999/2000 to 2017/2018 (Balangoda, Kuruvita, Galathura, Wellndura, Alupola, Rathnapura)</td><td colspan="2">19 Years</td></tr>
<tr><td rowspan="2">Rathnapura</td><td>1989/1990 to 1995/1996</td><td>7 Years</td><td rowspan="2">19 Years</td><td>1989/1990 to 1995/1996 (Balangoda, Wellandura, Alupola, Rathnapura)</td><td>7 Years</td><td rowspan="2">20 Years</td></tr>
<tr><td>2006/2007 to 2017/2018</td><td>12Years</td><td>2006/2007 to 2017/2018 (Balangoda, Wellandura, Alupola, Rathnapura)</td><td>12 Years</td></tr>
</table>



Original in colour

Figure 4-6: Double Mass Curve of Annual Streamflow-Ellagawa

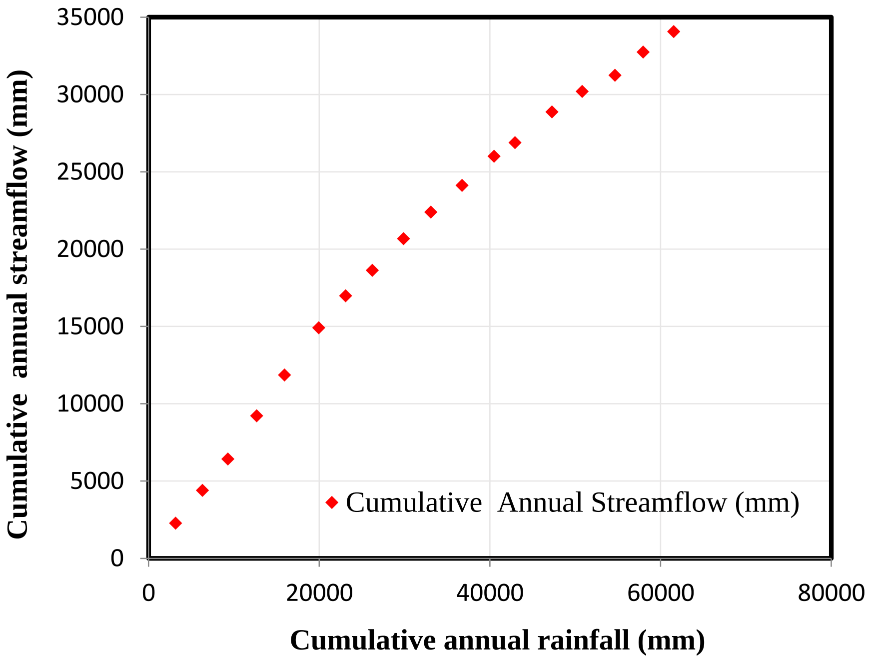


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Figure 4-7: Double Mass Curve of Annual Streamflow-Rathnapura

4.1.4 Evaporation

Measured Pan Evaporation data of the common gauging station of Rathnapura was collected for the modeling of both watersheds. Missing data sets were identified and gap filled considering the monthly averaged value of other water years. Consistency of the evaporation data set was assessed plotting a double mass curve and it shows a considerable level of consistency throughout the data period considered under the study.

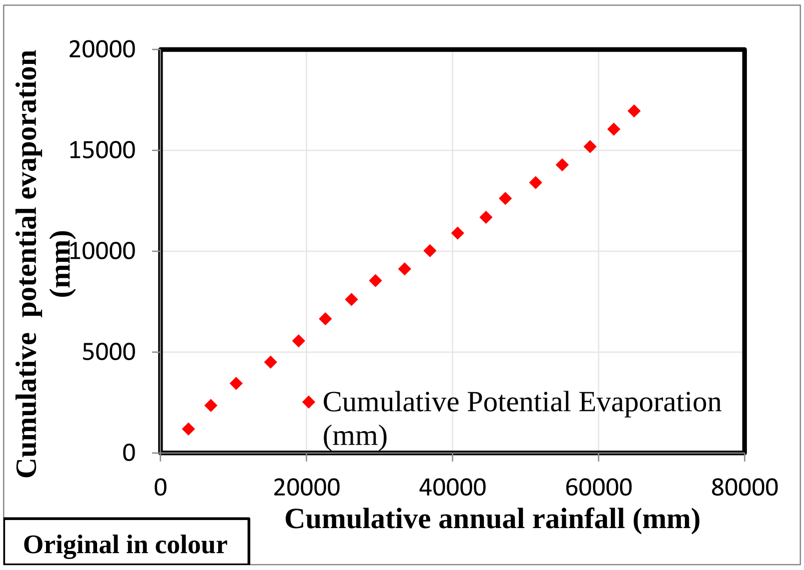

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Figure 4-8: Double Mass Curve of Annual Potential Evaporation-Rathnapura

4.1.5Annual water balance

The water balance was checked annually for two watersheds considered under the study the Ellagawa and Rathnapura since it gives a clear image of cyclic hydrological behavior of the watershed. (Table 4-9, 4-10 and Figure 4-9 & 4-10). The inputs to the catchment and the outputs from the catchment should approximately closer or should balance approximately unless if any permeant storages like reservoirs or any losses happen due to specific ground formations associated with the catchment which will not facilitate catchment modeling. For Ellagawa watershed average runoff coefficient remains 0.40 while it is 0.45 for Rathnapura. In literature, it is recorded that on average, the runoff coefficient for basin after the consideration of spatial variation as 0.49 for Kalu Ganga. (Wijesekara et al, 2016)

Table 4-9: Annual Water Balance of Ellagawa Watershed

Water Year	Annual Rainfall (mm)- (Thiessen)	Observed Annual Streamflow (mm)	Annual Water Balance (AWB) (mm)	Observed Pan Evaporation EP (mm)	ET/P	Runoff coefficient
1999/2000	3837.50	1786.56	2050.94	1186.61	0.31	0.47
2000/2001	3066.36	1149.05	1917.31	1165.20	0.38	0.37
2001/2002	3461.81	1125.15	2336.66	1090.86	0.32	0.33
2002/2003	4704.86	2133.80	2571.06	1054.20	0.22	0.45
2003/2004	3849.23	1322.89	2526.34	1058.56	0.28	0.34
2004/2005	3665.63	1204.56	2461.06	1087.77	0.30	0.33
2005/2006	3581.24	1419.21	2162.03	964.89	0.27	0.40
2006/2007	3275.67	1375.82	1899.85	929.53	0.28	0.42
2007/2008	4000.22	2061.42	1938.80	581.51	0.15	0.52
2008/2009	3463.89	1384.50	2079.39	902.41	0.26	0.40
2009/2010	3793.59	1600.17	2193.42	875.92	0.23	0.42
2010/2011	3873.62	1748.38	2125.24	784.17	0.20	0.45
2011/2012	2651.48	738.71	1912.77	934.97	0.35	0.28
2012/2013	4156.92	1738.13	2418.79	784.17	0.19	0.42
2013/2014	3648.71	1334.72	2313.99	874.42	0.24	0.37
2014/2015	3797.56	1407.51	2390.05	908.24	0.24	0.37
2015/2016	3545.33	2307.21	1238.11	864.84	0.24	0.65
2016/2017	3527.92	1837.34	1690.59	899.59	0.25	0.52
2017/2018	4081.03	2287.44	1793.59	863.72	0.21	0.56

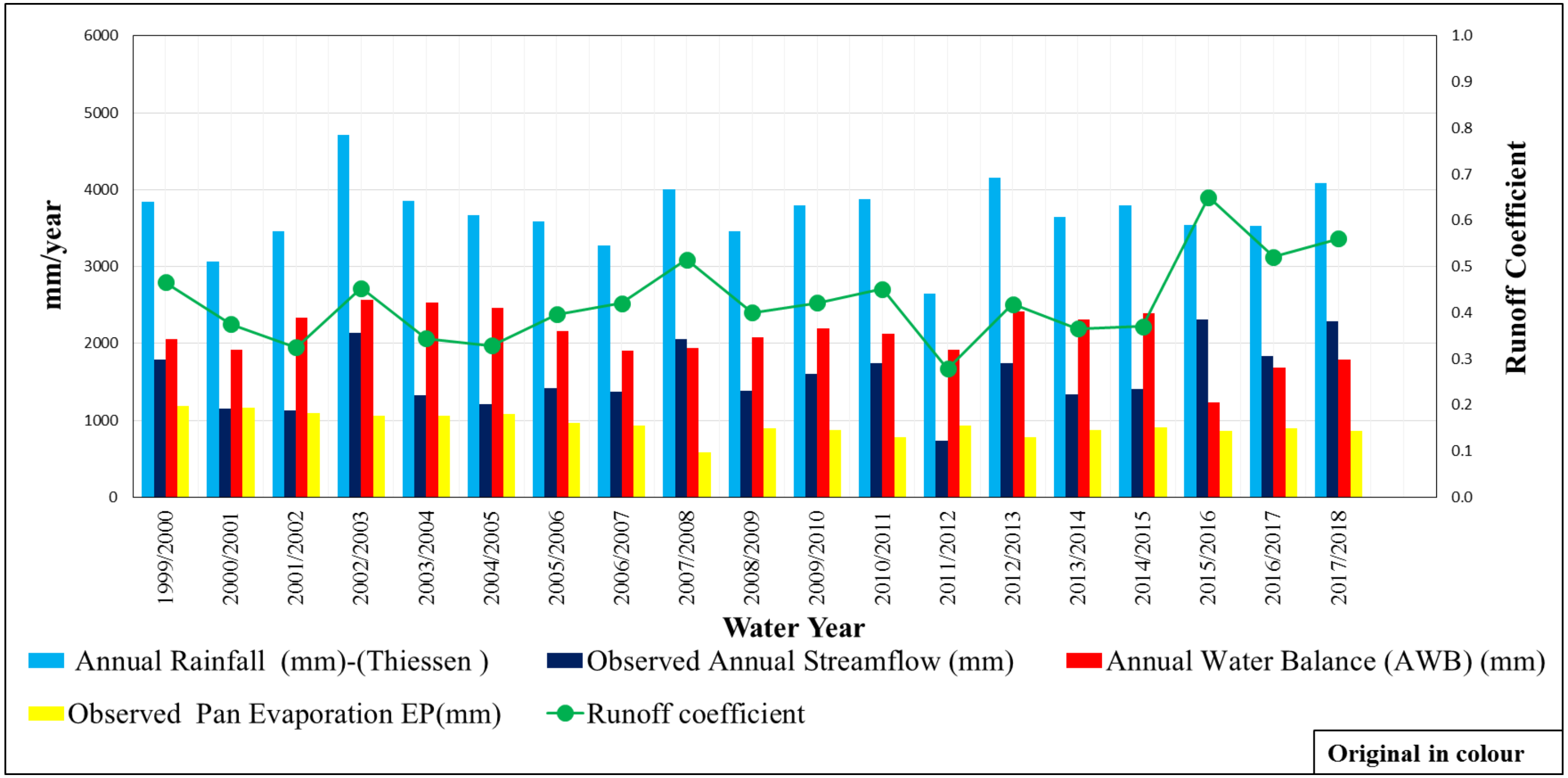


Figure 4-9: Annual Water Balance of Ellagawa Watershed

Table 4-10: Annual Water Balance of Rathnapura Watershed

Water Year	Annual Rainfall (mm)- (Thiessen)	Observed Annual Streamflow (mm)	Annual Water Balance (AWB) (mm)	Observed Pan Evaporation EP (mm)	ET/P	Runoff coefficient
1989/1990	3153.09	2276.89	876.20	1393.24	0.44	0.72
1990/1991	3156.19	2113.85	1042.34	1368.48	0.43	0.67
1991/1992	2975.77	2036.45	939.32	1377.94	0.46	0.68
1992/1993	3371.26	2790.30	580.96	1296.62	0.38	0.83
1993/1994	3260.14	2635.74	624.40	1218.11	0.37	0.81
1994/1995	4023.23	3055.01	968.22	1243.15	0.31	0.76
1995/1996	3146.70	2072.09	1074.60	1235.48	0.39	0.66
2006/2007	3121.24	1649.50	1471.74	929.53	0.30	0.53
2007/2008	3659.69	2040.32	1619.37	581.51	0.16	0.56
2008/2009	3202.07	1727.51	1474.56	902.41	0.28	0.54
2009/2010	3667.54	1728.92	1938.63	875.92	0.24	0.47
2010/2011	3748.73	1876.00	1872.73	784.17	0.21	0.50
2011/2012	2445.69	880.94	1564.75	934.97	0.38	0.36
2012/2013	4334.16	1987.02	2347.14	784.17	0.18	0.46
2013/2014	3544.85	1328.30	2216.55	874.42	0.25	0.37
2014/2015	3836.16	1047.32	2788.85	908.24	0.24	0.27
2015/2016	3304.99	1494.27	1810.72	864.84	0.26	0.45
2016/2017	3577.55	1332.48	2245.06	899.59	0.25	0.37
2017/2018	3661.50	1603.44	2058.05	863.72	0.24	0.44

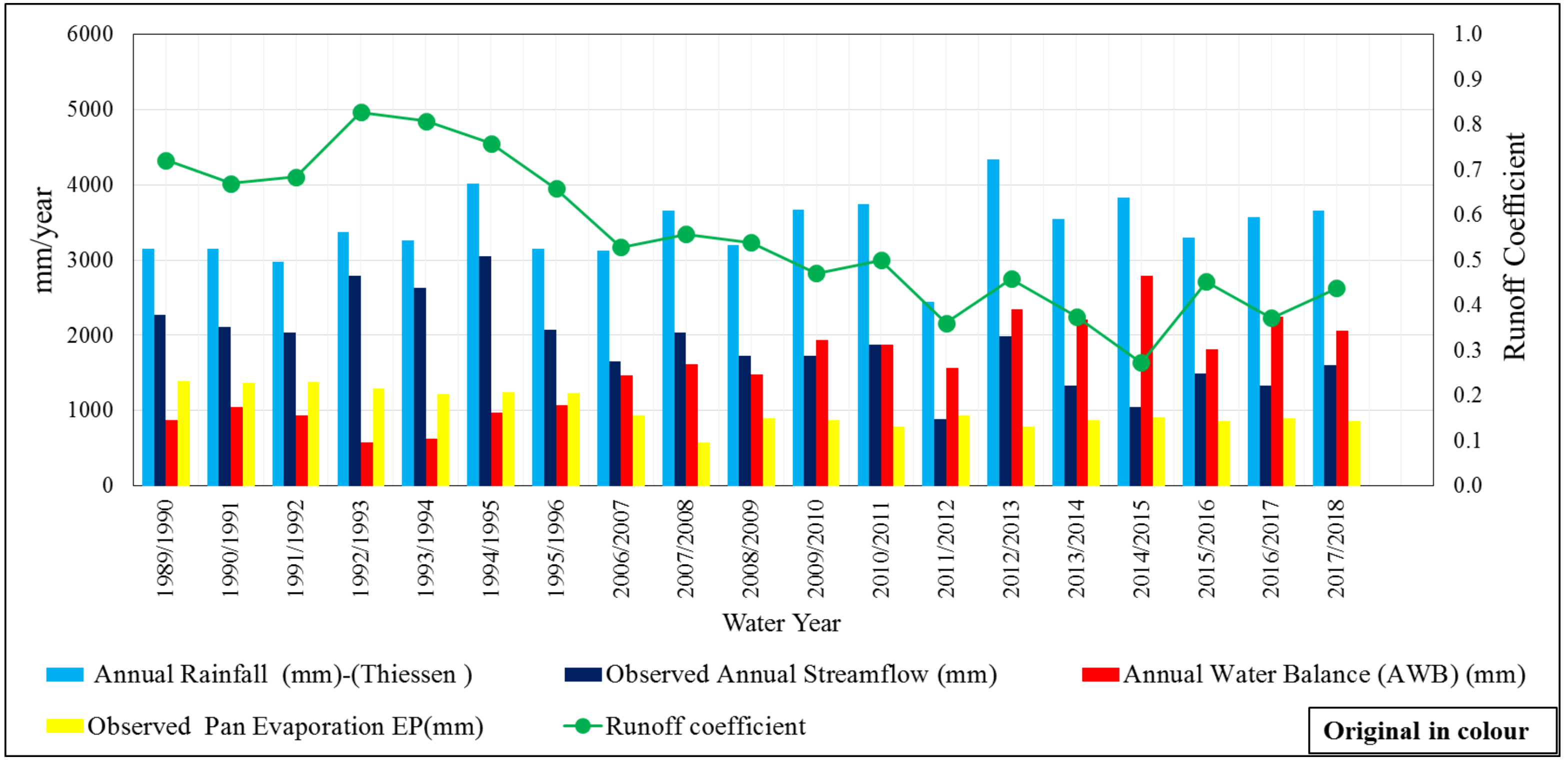


Figure 4-10: Annual Water Balance of Rathnapura Watershed

5 ANALYSIS OF RESULTS

5.1 State of the Art Evaluation

Under the comprehensive literature review, it has been identified that is a lack of availability of appropriate written material for the adequacy checking of parameter transferability for the streamflow estimations in ungauged catchments. Available documentation pointed to the major schemes of parameter transferability and supporting facilitates the making of valid decisions with a rational explanation. The following subsections discuss the reasons and facts for selection of each criterion and methods which facilitate to adequacy checking of parameter transferability options for streamflow estimations in ungauged watersheds.

5.1.1 Model complexity

Model complexity depends on the number of mathematical concepts and their advancements when they attempt to represent catchment behavior in hydrologically. When the model developer attempts to incorporate more physical processes observed in the real world, eventually the number of model parameters gets increased. A large number of model parameters create difficulties and require more time during the model parameter optimization procedure. It requires longer data sets for reliable results. Literature also emphasizes that the number of model parameters always does not decide the model accuracy. A model with a lesser number of model parameters can model catchment hydrology well when good representative data and methodologies are available. When the number of parameters increases, the parameter transferability also becomes more complex and requires longer datasets to achieve better results. The limited number of parameters reduce the complexity of both model and the methodologies and approaches follow during adequacy checking of transferability.

5.1.2 Data quality

Successful model simulation and reliable results always depend on the quality of input data to the model. Data should be a set of good representatives of the catchment hydrological behavior and also the data should be an output of quality measurements. When input data become a well representative of catchment hydrology, the model gets excited well. On the other hand, when the quality of measurements is high, it represents reality, and closer to the actual conditions prevails in the watershed. Missing data is the most common issue faced by modelers when doing water resources modeling. It is difficult to obtain common periods of data for rainfall, streamflow, and evaporation. When it is much easier to obtain a common data period. However, when the considered data duration for the study is longer, it is difficult to select a continuous common data period which was one of the challenges faced during the data selection of Rathnapura watershed. However, it was able to obtain a common data period of 12 years for both watersheds for the analysis under the present study.

When hydrological data represent hydrological behavior of the catchment well then it facilitates obtaining more reliable model parameters to transfer and it is observed that model parameters remain stable within a considered domain when there is well representative data available.

5.1.3 Time scale

The present study used the monthly time scale for model simulations. In practical, most commonly applicable temporal resolutions are found to be the monthly time scale especially when water resources planning and management are a major concern. Daily runoff hydrographs tend to display some irregular effects due to natural factors that prevail within shorter durations like few hours. Monthly runoff hydrograph smoothens out those effects. Very close inter-relation appears between runoff, rainfall, and evaporation on a monthly time scale. Compared to daily data, the availability of monthly data is higher and computation time is lower compared when the modeling with daily resolution.

5.2 Model Calibration and Validation

5.2.1 Data durations for calibration and verification

Under the literature review, it has been identified, it requires a minimum of 10 years of continuous data period for better calibration. If it is more than 10 years then results will become more reliable and smooth. (Annex A, Table A-1).More weight is required to be given for calibrations data set than the verification data set. Calibration data periods have to be consists of both wet and dry periods. Standing upon this bases, calibration and verification data durations were selected for the calibration and verification during the present modeling exercise. Following table given the calibration and verification data durations for both watersheds. For Ellagawa watershed, 19 years of continuous data set was used and it split into two as 12 years for calibration and 7 years for validation. In the case of Rathnapura watershed continuous 19 years period couldn't be collected due to the unavailability of the data in the irrigation department because of the malfunctioning of the gauging station for 1996/1997 to 2005/2006 period. Therefore, for calibration, 12 years was used after the water year 2006/2007 and for validation, 7 years were used before the water year 1996/1997.

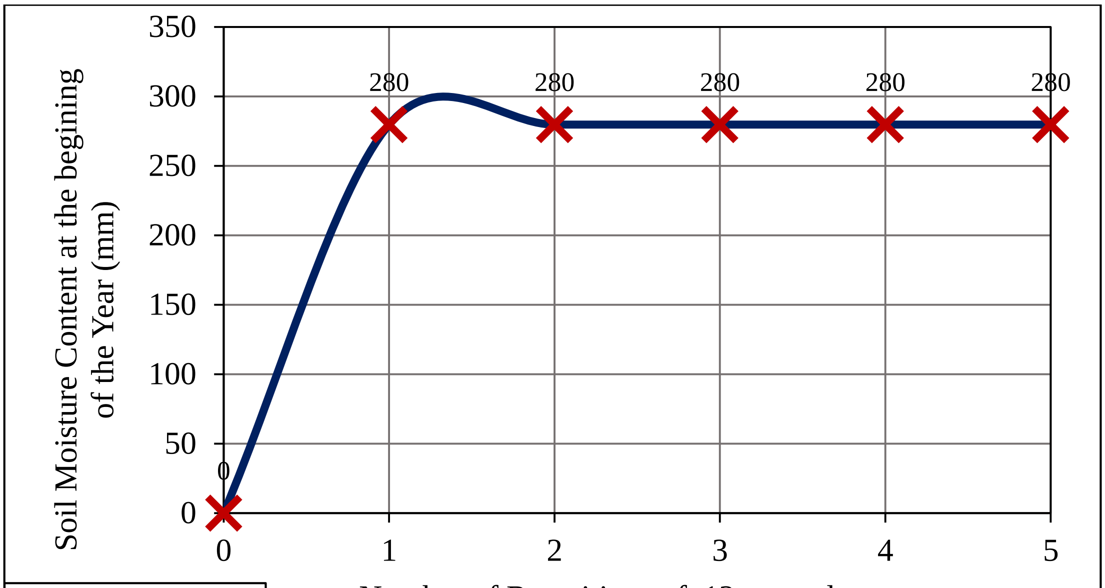
Table 5-1: Calibration and Validation Data Durations

Watershed	Cali/Vali	Data Duration	No of Years	Description
Ellagawa	Calibration	2006/2007 to 2017/2018	12 Years	Includes three flood/peak flow events Includes three drought years
	Verification	1999/2000 to 2005/2006	7Years	Includes two peak flow events Includes four drought years
Rathnapura	Calibration	2006/2007 to 2017/2018	12 Years	Includes three flood/Peak flow event Includes four drought year
	Verification	1989/1990 to 1995/1996	7 Years	Includes three peak flow events Includes two drought years

5.2.2 Model Optimization

5.2.2.1 Warmup period

In the 2P model initial soil water content *S (t-1)* make influences on computed runoff in the first few months in the model simulation period. Under this exercise, initial soil moisture content was determined by running five consecutive model runs of calibration data duration and obtain the stabilized value. This repetition of five cycles of the same data sets known as the warm-up period and the constant value obtain at the end of this scenario is then used as the initial soil water content for the model calibration. For the model verification similar method followed for the determination of the initial value of soil moisture content. The soil moisture stabilization during the warmup period is given in Figure 5-1 and Figure 5-2 for Ellagawa and Rathnapura watersheds respectively.



Original in Color

Figure 5-1: Initial Soil Moisture Content Variation in Warm-up Period – Ellagawa Watershed

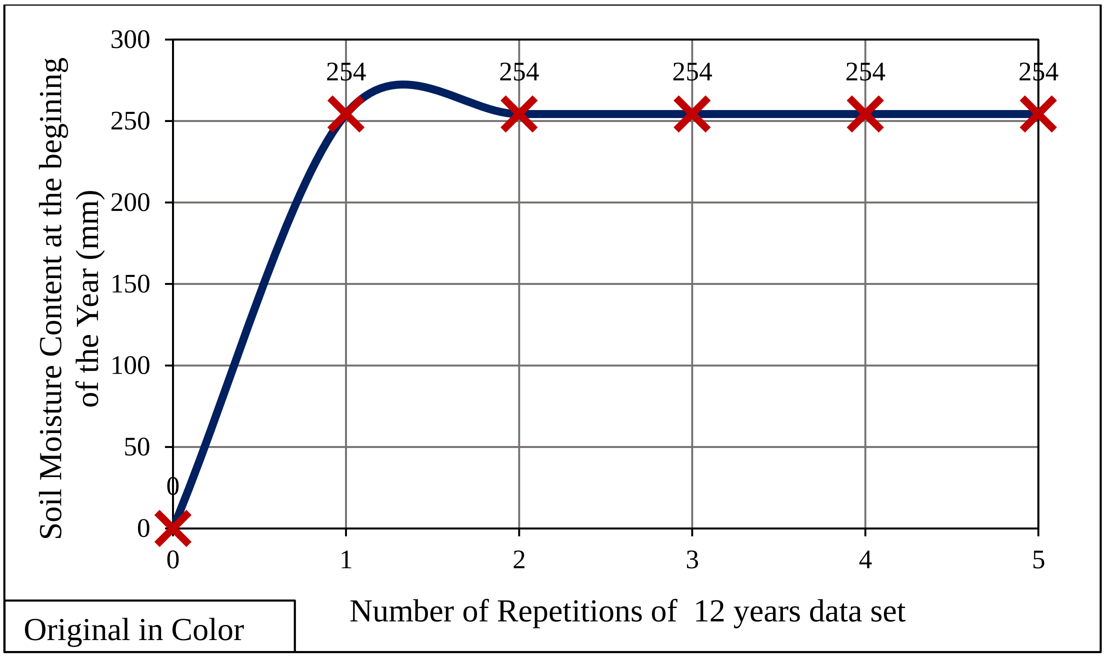


Figure 5-2: Initial Soil Moisture Content Variation in Warm-up Period – Rathnapura Watershed

5.2.2.2 Global minimum optimization

The 2P model considered under the study is developed in the MS excel environment and for the parameter optimization the “Solver” tool used which comes as a built-in tool in excel itself. Initial values of model parameters were changed systematically to reach the global minimum while avoiding local minimums. A coarse range of c and Sc were experienced initially and scanned the parameter values to identify when the model is hitting local minimums. Then systematical move towards a finer range of model parameters and concluded the final values of model parameters which set the global minimum of MRAE values for the considered data domain. Figure 6-1 shows how to reach the global minimum during model calibration of Ellagawa watershed. The same procedure was followed for Rathnapura watershed.

5.2.3 Model calibration and validation

For both watersheds, 12 years of data set were used to model calibration as described in Table 5-1. Five repetitions of the 12-year data set were used as a warmup period to obtain initial soil moisture content of the calibration period for model calibration of both watersheds. Similarly, 7 years of data set were used to model verification for both watersheds as described in Table 5-1. Two major criteria have used for the model performance evaluation as described under section 2.8. Under the graphical evaluation total streamflow hydrographs in monthly time scale, sorted and unsorted flow duration curves, soil moisture variations, and simulated and observed annual water balance differences were represented graphically for the visual observations and comparisons. MRAE values have obtained and summarized as the main numerical evaluation criteria for the model performance. Table 5.2 & Table 5-5 summarized the results of model calibration and verification for both Ellagawa and Rathnapura watersheds.

Table 5-2: Model Calibration and Validation Results Summary for Ellagawa Watershed

Model Performance	Ellagawa Watershed	
	Calibration	Validation
Data period	12 Years	7 Years
C	2.38	2.38
SC	1461	1461
MRAE - Overall Hydrograph	0.38	0.36
NASH- Overall Hydrograph	0.66	0.47
Soil moisture content-Beginning of the period	280	258
Soil moisture content- End of the period	280	258
Maximum soil moisture content (mm)	407	403
Minimum soil moisture content (mm)	43	25
Average Annual Water Balance Difference (mm)	(203)	(198)
Maximum Flow (mm/month)	599	424
FDC - MRAE - Overall flow	0.38	0.36
FDC - MRAE - High flow	0.28	0.40
FDC - MRAE - Intermediate	0.43	0.41
FDC - MRAE - Low flow	0.37	0.48
Pan coefficient	0.99	1.00
Observed Runoff coefficient	0.45	0.38
Simulated Runoff coefficient	0.50	0.33
Data period	2006/2007 - 2017/2018	1999/2000 - 2005/2006

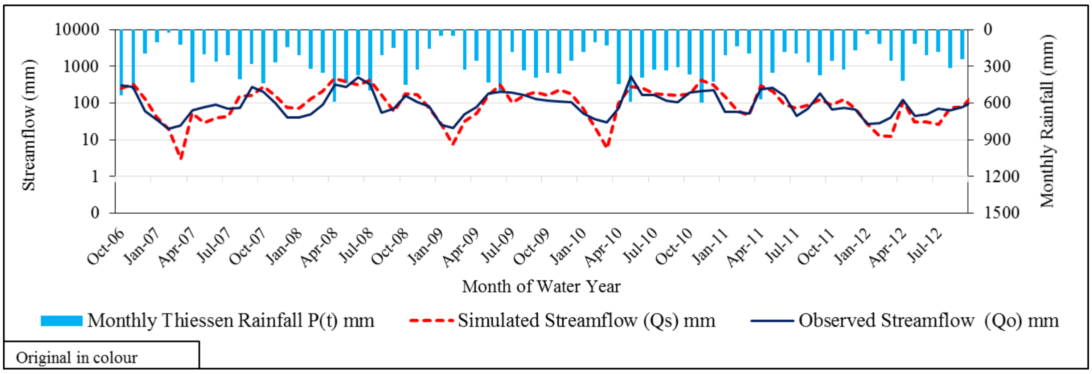


Figure 5-5: Total Hydrograph for Ellagawa Calibration (2006/07-2011/12)

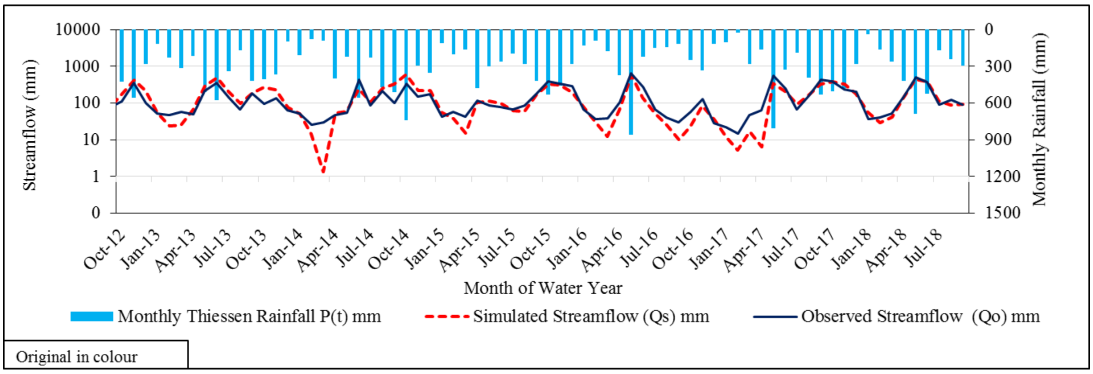


Figure 5-4: Total Hydrograph for Ellagawa Calibration (2012/13-2017/18)

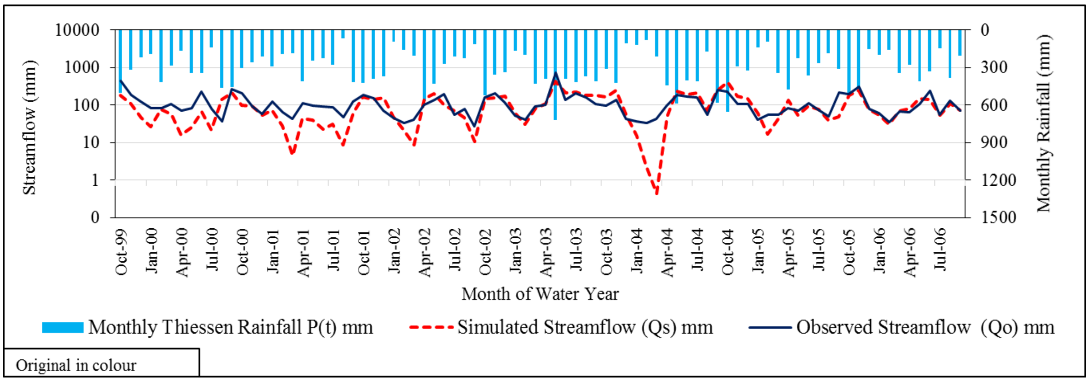


Figure 5-3: Total hydrograph for Ellagawa Validation (1999/00-2005/06)

Annual water balances during model calibration of Ellagawa watershed are given by following Tables 5-3 & Figure 5-6.

Table 5-3: Annual Water Balance of 12 Years Calibration Data Set

Water Year	Annual Thiessen Rainfall (mm)	Qo Observed Flow (mm)	Qs Simulated Flow (mm)	Annual Water Balance Observed (mm)	Annual Water Balance Simulated (mm)	Error % in Annual Water Balance
2006/2007	3276	1376	1240	1900	2036	7%
2007/2008	4000	2061	2725	1939	1276	34%
2008/2009	3464	1384	1463	2079	2000	4%
2009/2010	3794	1600	1807	2193	1987	9%
2010/2011	3874	1748	2047	2125	1826	14%
2011/2012	2651	739	682	1913	1969	3%
2012/2013	4157	1738	2264	2419	1893	22%
2013/2014	3649	1335	1691	2314	1957	15%
2014/2015	3798	1408	1747	2390	2051	14%
2015/2016	3545	2307	1793	1238	1752	42%
2016/2017	3528	1837	2532	1691	996	41%
2017/2018	4081	2287	2264	1794	1817	1%
Average	**3651**	**1652**	**1855**	**2000**	**1797**	**17%**

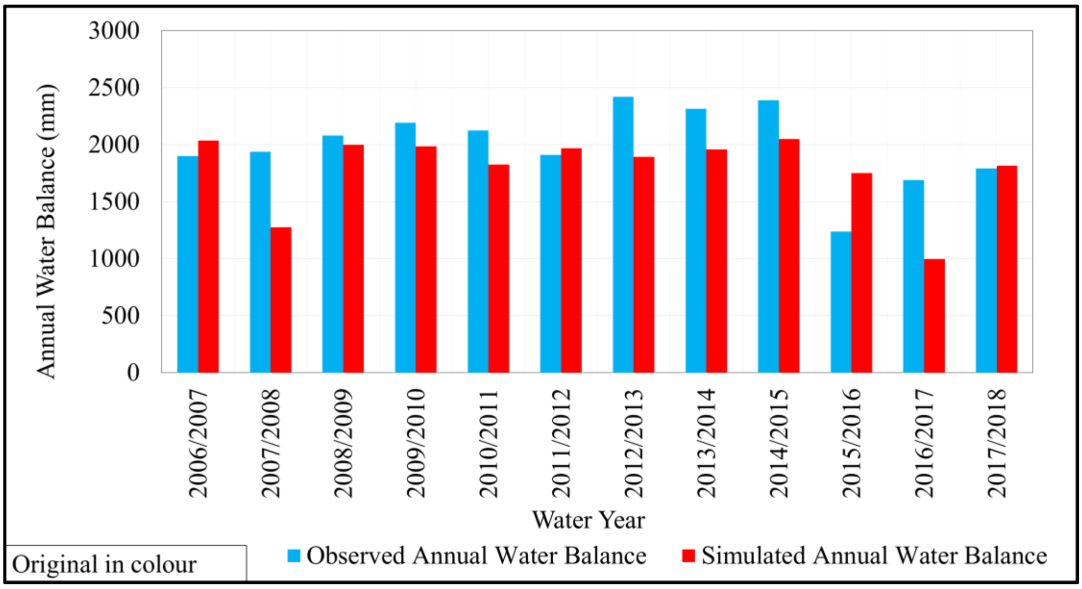
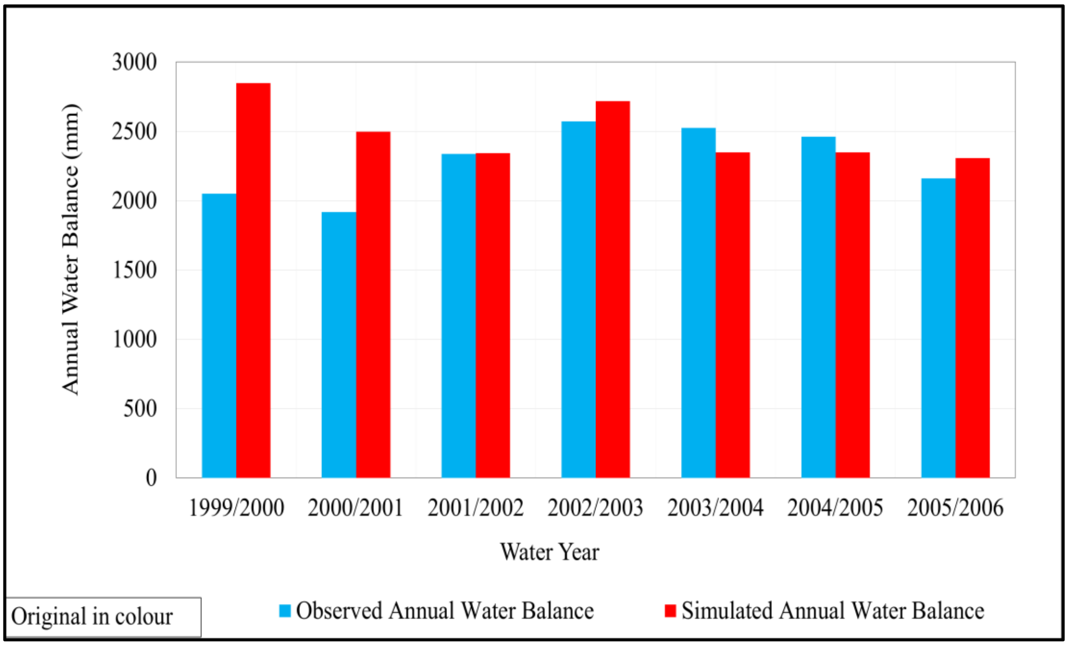


Figure 5-6: Annual Water Balance Comparison for Ellagawa Calibration

Annual water balances during model verification of Ellagawa watershed are given by the following Table 5-4 & Figure 5-7.

Table 5-4: Annual Water Balance of 7 Years Validation Data Set

Water Year	Annual Thiessen Rainfall (mm)	Qo Observed Flow (mm)	Qs Simulated Flow (mm)	Annual Water Balance Observed (mm)	Annual Water Balance Simulated (mm)	Error % in Annual Water Balance
1999/2000	3837	1787	990	2051	2847	39%
2000/2001	3066	1149	568	1917	2499	30%
2001/2002	3462	1125	1118	2337	2344	0%
2002/2003	4705	2134	1985	2571	2719	6%
2003/2004	3849	1323	1500	2526	2349	7%
2004/2005	3666	1205	1318	2461	2347	5%
2005/2006	3581	1419	1275	2162	2306	7%
Average	**3738**	**1449**	**1251**	**2289**	**2487**	**13%**



Original in colour

Figure 5-7: Annual Water Balance Comparison for Ellagawa Verification

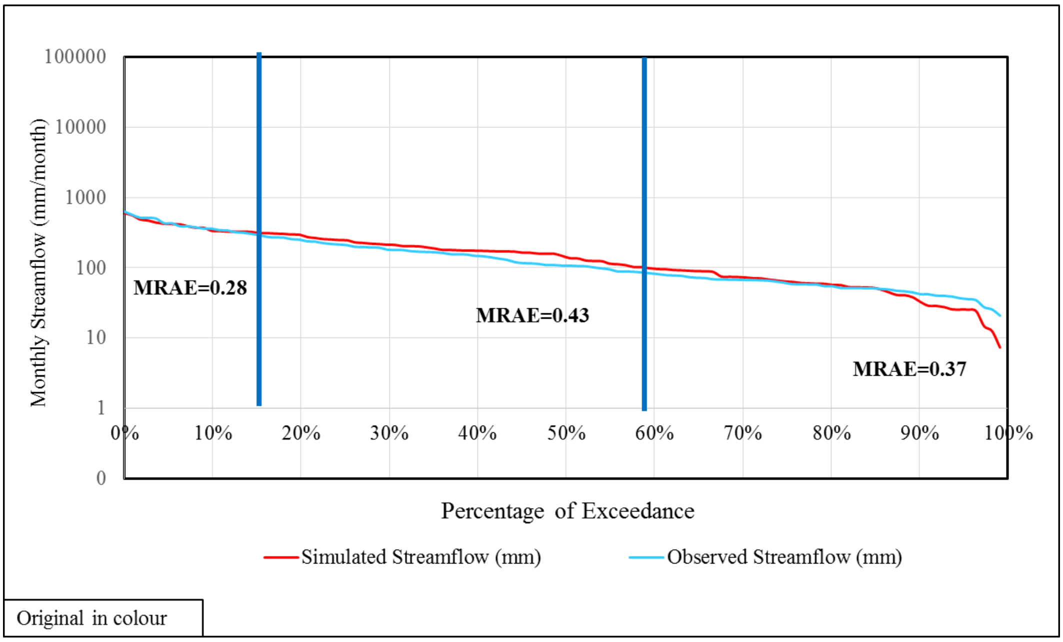


Figure 5-9: Flow Duration Curve for Ellagawa Calibration

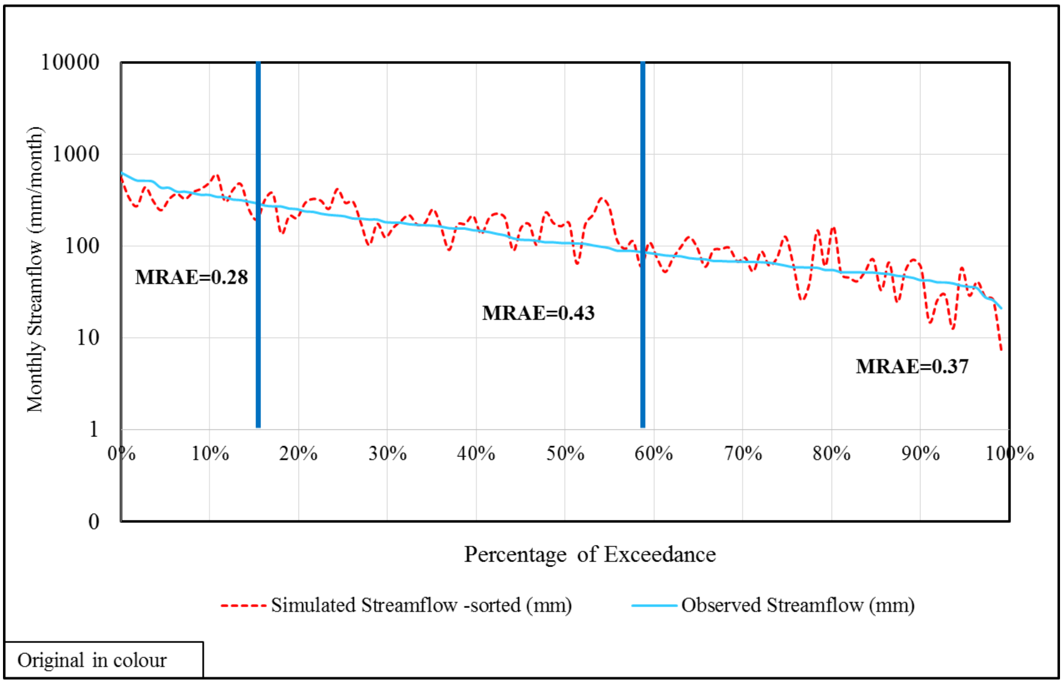


Figure 5-8 : Flow Duration Curve for Ellagawa Calibration (Sorted Simulated Flow)

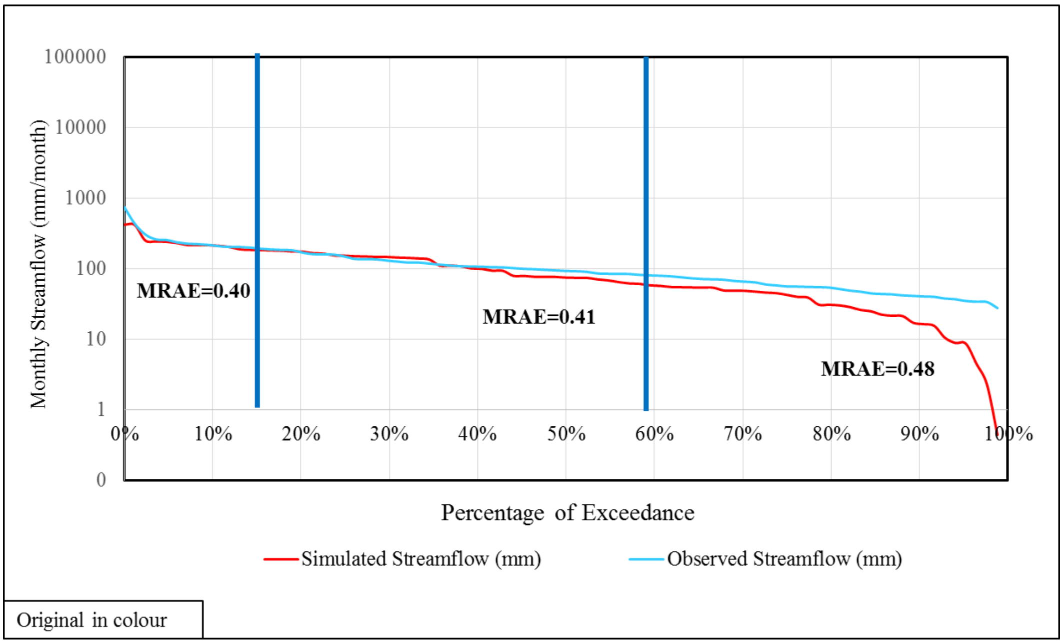


Figure 5-11: Flow Duration Curve for Ellagawa Verification

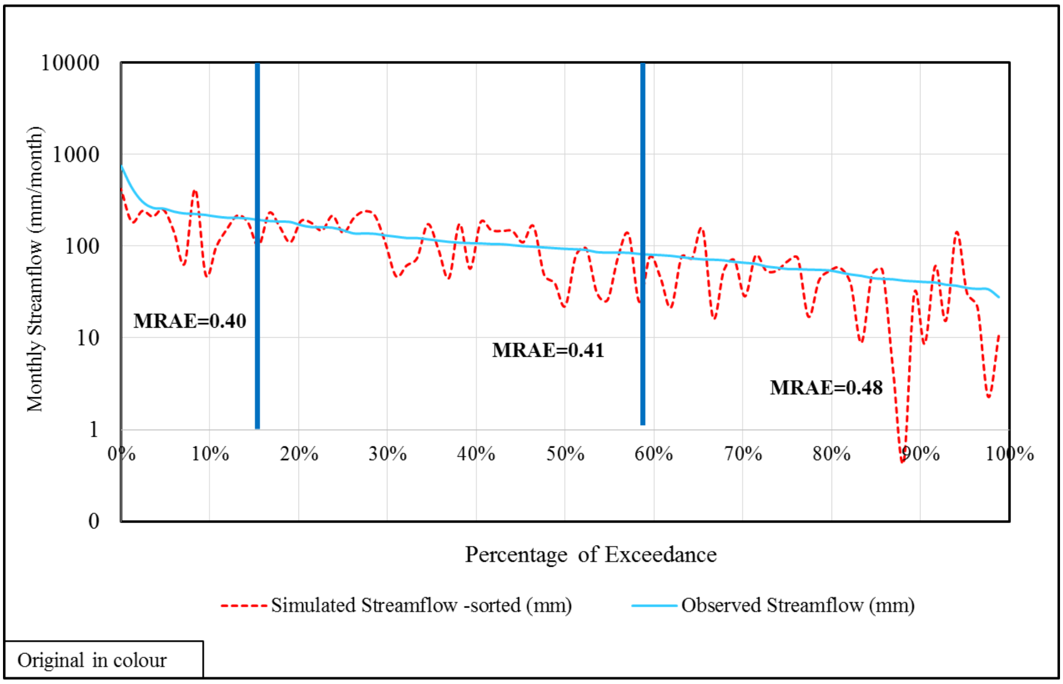


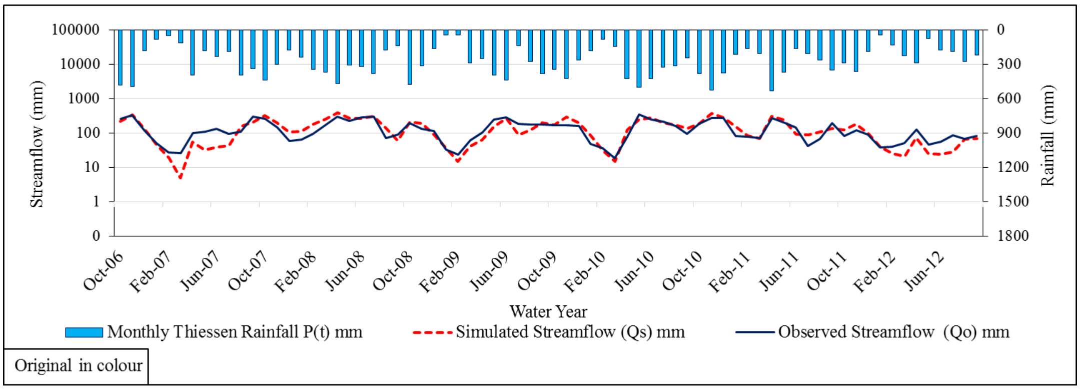
Figure 5-10: Flow Duration Curve for Ellagawa Verification (Sorted Simulated Flow)

Table 5-5: Model Calibration and Validation Results Summary for Rathnapura Watershed

Model Performance	Rathnapura Watershed	
	Calibration	Validation
Data period	12 Years	7 Years
C	2.09	2.09
SC	1420	1420
MRAE - Overall Hydrograph	0.36	0.32
NASH- Overall Hydrograph	0.54	0.8
Soil moisture content-Beginning of the period	254	389
Soil moisture content- End of the period	254	389
Maximum soil moisture content (mm)	395	395
Minimum soil moisture content (mm)	79	132
Average Annual Water Balance Difference (mm)	(289)	(389)
Maximum Flow (mm/month)	588	477
FDC - MRAE - Overall flow	0.36	0.32
FDC - MRAE - High flow	0.32	0.21
FDC - MRAE - Intermediate	0.39	0.23
FDC - MRAE - Low flow	0.36	0.38
Pan coefficient	0.99	0.97
Observed Runoff coefficient	0.44	0.73
Simulated Runoff coefficient	0.52	0.61
Data period	2006/2007-2017/2018	1989/1990-1995/1996

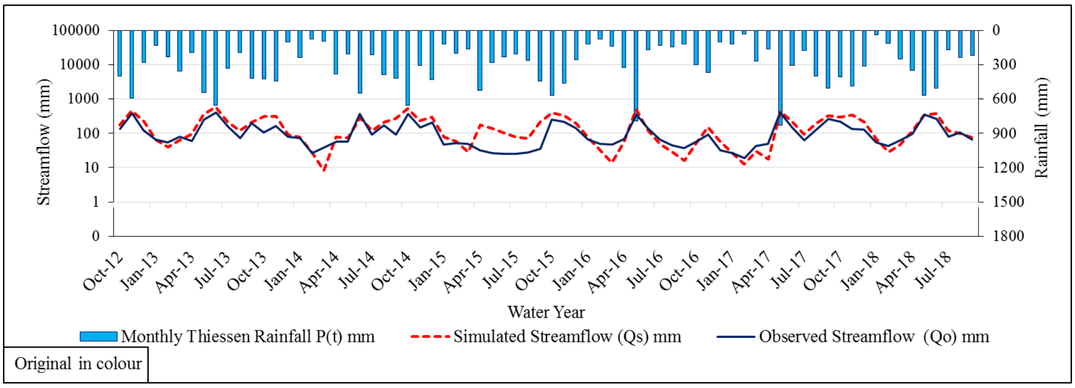
Figure 5.14 shows the total hydrograph for Rathnapura validation results. Compared to Figure 5.12 & and Figure 5.13, which are showing total hydrographs for calibration, figure 5.14 shows that model has performed well in validation compared to the calibration period. Sorted and unsorted flow duration curves also illustrate this under figures 5.19 and 5.20. During the data checking (Figure 4.10, and in Appendix Figure B-4 and B-5), it is identified that from water year 1989/1990 to water year 1995/1996, observed runoff coefficients are higher and they are off from the reality. For the same annual rainfalls, considerably higher streamflow values are observed which is illustrates in Figure 4-10. However with this constraint of observed data during this period, still good MRAE values are observed during the validation period, that is because MRAE values indicate differences between observed and simulated flows and MRAE has no direct relationship with the runoff coefficient. Simply, for the calibrated

parameters, the model has a response to given rainfall and simulated the flows which are closer to observed flows giving low MRAE values compared to the calibration period. However, though it gives low MRAE values in this period, as table 5.7 shows, the unrealistic behavior of observed streamflows with the rainfall and higher runoff coefficients in these years, caused high water balance errors during validation.



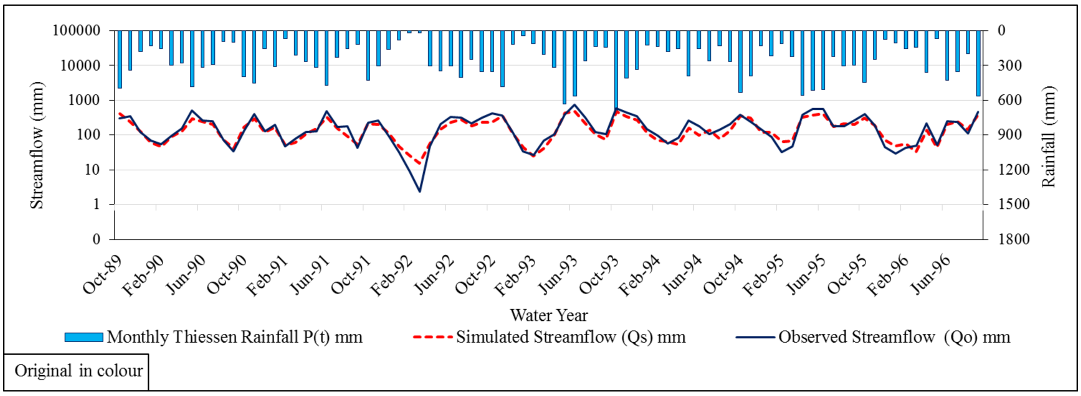
Original in colour

Figure 5-12: Total Hydrograph for Rathnapura Calibration - (2006/07 - 2011/2012)



Original in colour

Figure 5-13: Total Hydrograph for Rathnapura Calibration - (2006/07 - 2011/2012)



Original in colour

Figure 5-14: Total Hydrograph for Rathnapura Validation - (1989/90 - 1995/1996)

Annual water balances during model calibration of Rathnapura watershed are given by following Tables 5-6 & Figure 5-15.

Table 5-6: Annual Water Balance of 12 Years Calibration Data Set

Water Year	Annual Thiessen Rainfall (mm)	Qo Observed Flow (mm)	Qs Simulated Flow (mm)	Annual Water Balance Observed (mm)	Annual Water Balance Simulated (mm)	Error % in Annual Water Balance
2006/2007	3121	1650	1276	1472	1846	25%
2007/2008	3660	2040	2575	1619	1085	33%
2008/2009	3202	1728	1469	1475	1733	18%
2009/2010	3668	1729	1952	1939	1716	12%
2010/2011	3749	1876	2117	1873	1631	13%
2011/2012	2446	881	769	1565	1677	7%
2012/2013	4334	1987	2627	2347	1707	27%
2013/2014	3545	1328	1844	2217	1700	23%
2014/2015	3836	1047	1997	2789	1839	34%
2015/2016	3305	1494	1812	1811	1493	18%
2016/2017	3578	1332	1607	2245	1970	12%
2017/2018	3661	1603	2116	2058	1546	25%
Average	**3509**	**1558**	**1847**	**1951**	**1662**	**21%**

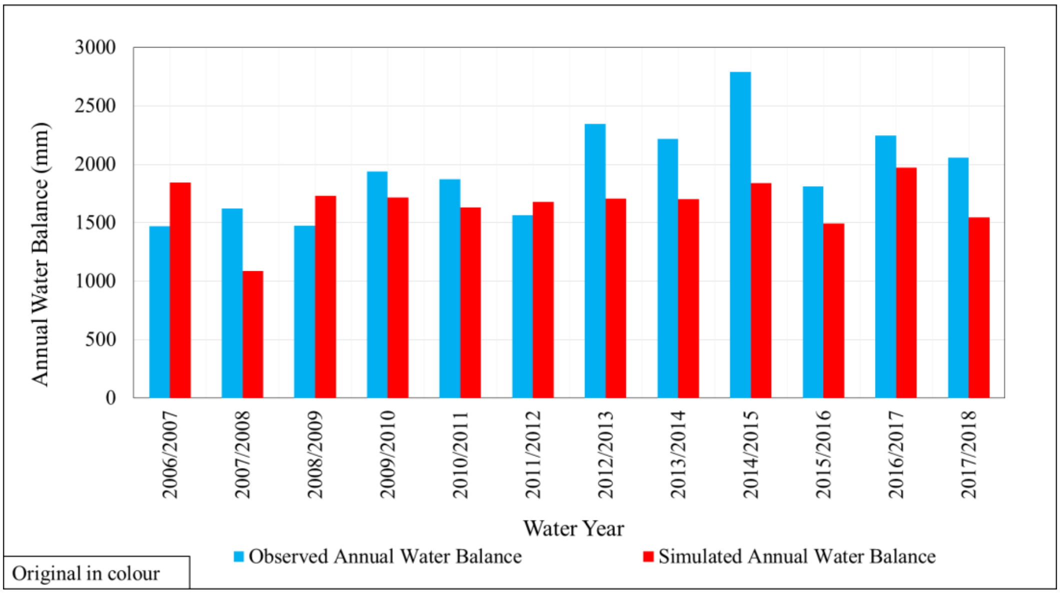


Figure 5-15: Annual Water Balance Comparison of Calibration

Annual water balances during model Verification of Rathnapura watershed are given by following Tables 5-7 & Figure 5-16.

Table 5-7: Annual Water Balance of 7 Years Validation Data Set

Water Year	Annual Thiessen Rainfall (mm)	Qo Observed Flow (mm)	Qs Simulated Flow (mm)	Annual Water Balance Observed (mm)	Annual Water Balance Simulated (mm)	Error % in Annual Water Balance
1989/1990	3153	2277	1948	876	1205	38%
1990/1991	3156	2114	1764	1042	1392	34%
1991/1992	2976	2036	1738	939	1238	32%
1992/1993	3371	2790	2211	581	1160	100%
1993/1994	3260	2636	1988	624	1272	104%
1994/1995	4023	3055	2744	968	1280	32%
1995/1996	3147	2072	1868	1075	1279	19%
Average	**3298**	**2426**	**2037**	**872**	**1261**	**51%**

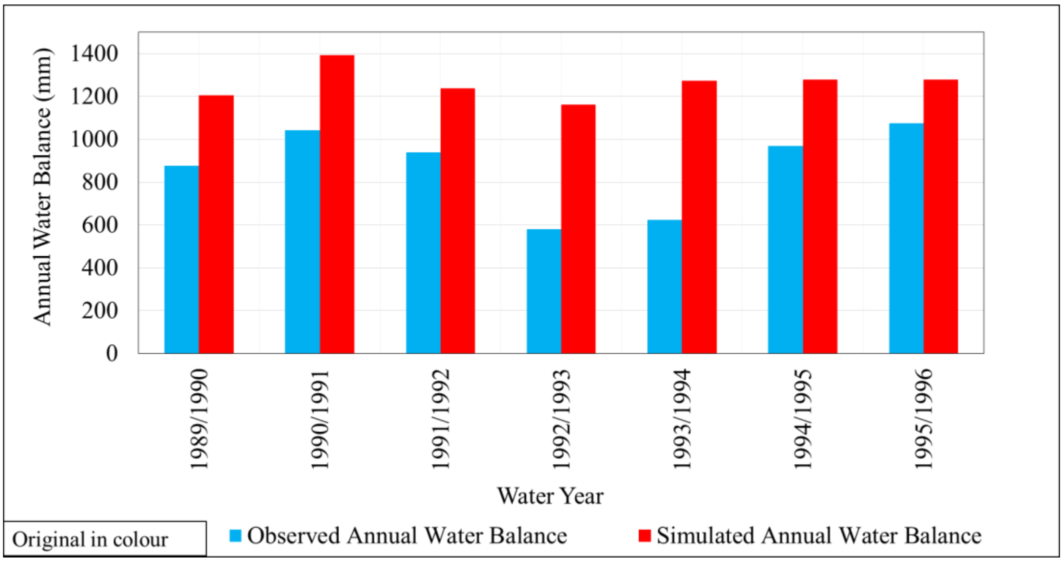


Figure 5-16: Annual Water Balance Comparison of Verification

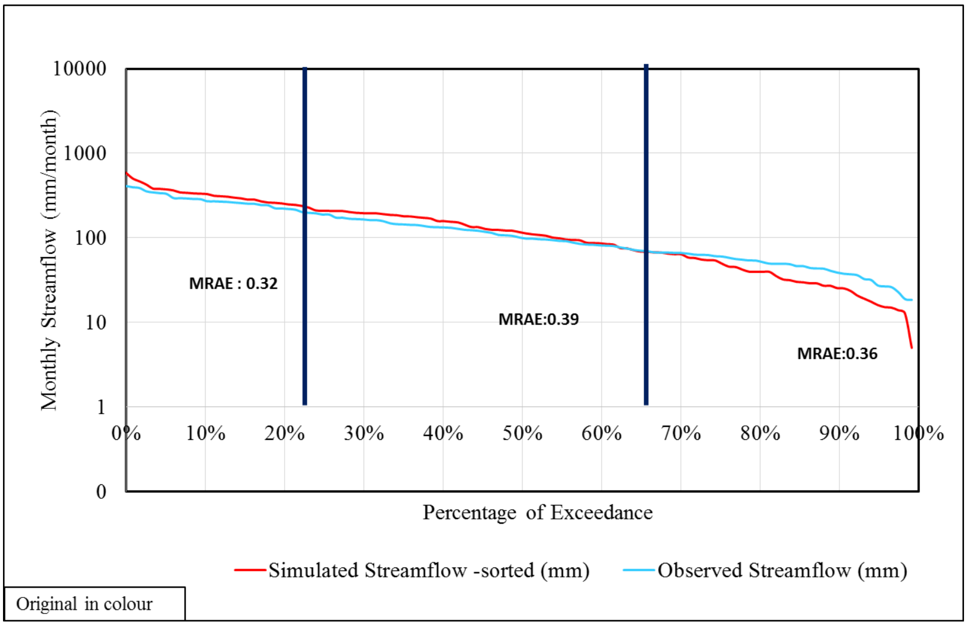


Figure 5-17: Flow Duration Curve for Rathnapura Calibration

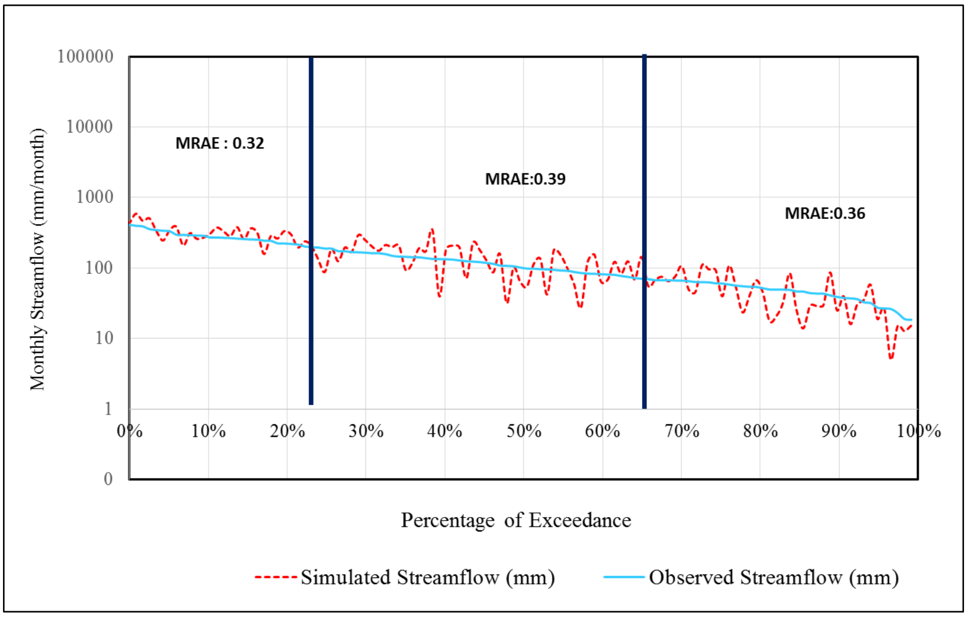
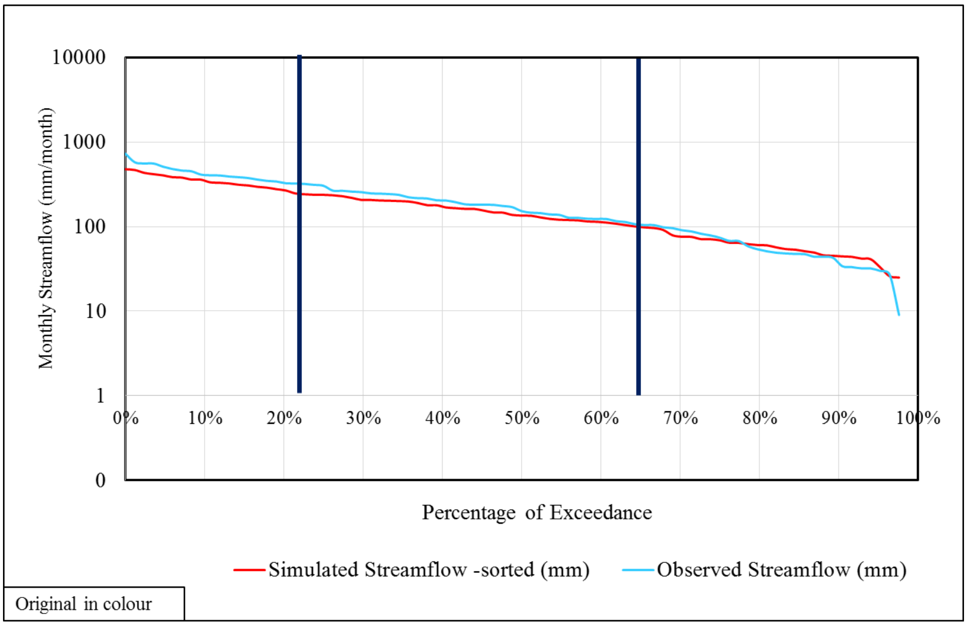


Figure 5-18: Flow Duration Curve for Rathnapura Calibration (Sorted Streamflow)



Original in colour

Figure 5-19: Flow Duration Curve for Rathnapura Verification

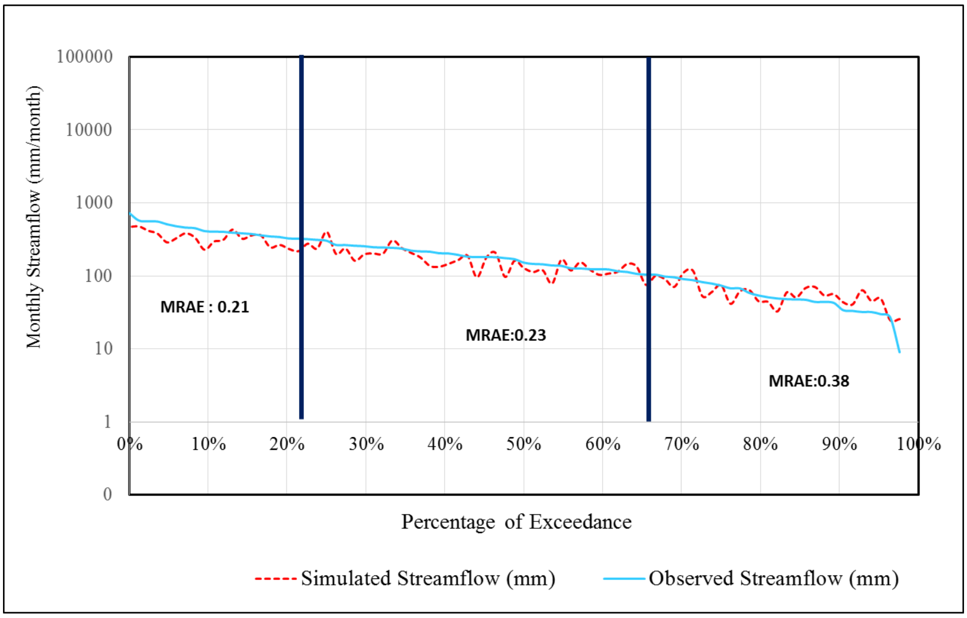


Figure 5-20: Flow Duration Curve for Rathnapura Verification (Sorted Streamflow)

5.3 Model Parameter Transferability

5.3.1 Transferability options

Under the comprehensive literature review, it is revealed that over the years, researches have taken immense efforts to transfer model parameters from gauged to ungauged catchments by experiencing various methodologies and approaches to predict and forecast streamflow at ungauged catchments. For streamflow forecasting, researches have transferred model parameters in time while transferring model parameters in space for streamflow predictions or in both space and time for furcating and estimation. Under the present study, three model parameter transferability options have been executed and results were finalized. Followings are the three considered options

Option 1: Temporal transfer

For the same catchment, model parameters from calibration period 1 are transferred to calibration period 2, and vice versa.

Option 2: Spatial transfer

Model parameters of a catchment are obtained from its nearest neighbor catchment over the same period.

Option 3: Spatiotemporal transfer

Model parameters of a catchment are obtained from its nearest neighbor catchment across different periods

As described in section 5.2 model calibration data duration were 12 years for both watersheds and the number of validation years was 7 years for both. It is considered as the transferability option one since it transfers model parameters temporally from one time period to a different period within the same watershed. Table 5-8 describes the durations and tasks carried out in each transferability option.

Table 5-8: Transferability Options and Description

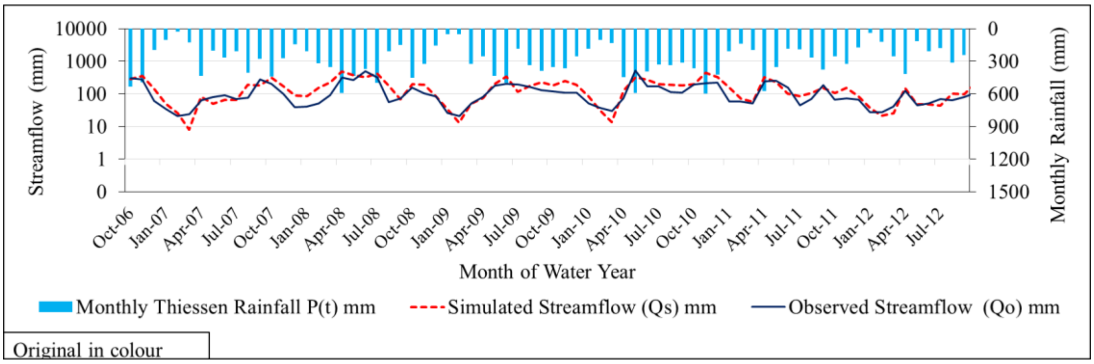
Transferability option	**Task carried out under the option**
Option 1: Temporal transfer scheme	Calibration and verification (section 5.2)
Option2: Spatial transfer scheme	• Calibrated and Validated parameters of Ellagawa watershed were transferred to Rathnapura watershed • Calibrated and Validated parameters of Rathnapura watershed were transferred to Ellagawa watershed • Considered common data period of 12 years (2006/2007 – 2017/2018)
Option3: Spatiotemporal transfer scheme	• Calibrated and Validated parameters of Ellagawa watershed were transferred to Rathnapura watershed for whole 19 years period • Calibrated and Validated parameters of Rathnapura watershed were transferred to Ellagawa watershed for whole 19 years period • Considered data period of 19 years Ellagawa–(1999/2000 – 2017/2018) – • Rathnapura - (1989/1990 – 1995/1996 and 2006/2007 to 2071/2018) – • This option consists of both overlapping and non-overlapping years. Therefore this option is considered to be a form of spatiotemporal transferability with a little deviation from its original definition described in the literature.

5.3.2 Model parameter transferability – Ellagawa watershed

Calibrated and verified model parameters for Rathnapura watershed were transferred to the Ellagawa watershed under the above three schemes and resulted in total hydrographs, flow duration curves, and annual water balances were obtained. Calibrated C value and Sc value for Rathnapura were 2.09 and 1420 respectively. Transferring these two parameter values to Ellagawa for the common data period of 12 years and the period of the whole 19 years, the simulated flows were compared with the observed flows. Following Table 5-9 gives the summary of model parameter transferability for the Ellagawa watershed.

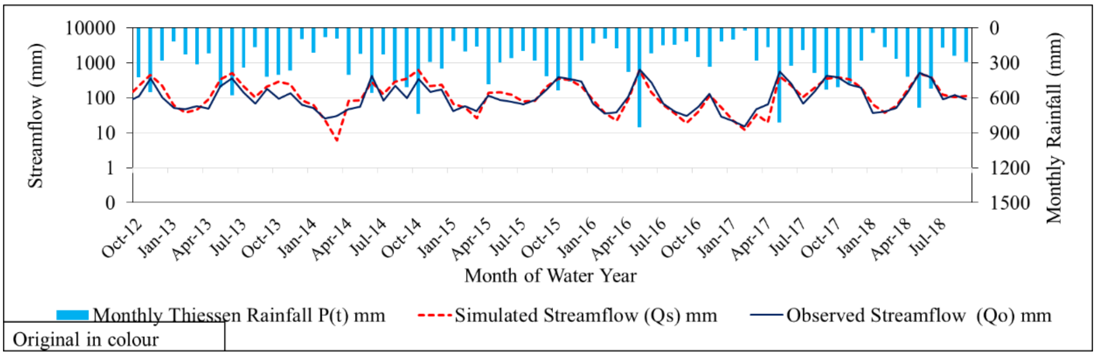
Table 5-9: Summary of Model Performance for Transferability Options - Ellagawa

Model Performance	Transformation of Model Parameters **Option 3**	Transformation of Model Parameters **Option 2**
Data period	19 Years	12 Years
C	2.09	2.09
SC	1420	1420
MRAE - Overall Hydrograph	0.38	0.45
Soil moisture content-Beginning of the period	293	293
Soil moisture content- End of the period	293	293
Maximum soil moisture content (mm)	395	395
Minimum soil moisture content (mm)	87	87
Average Annual Water Balance Difference (mm)	(248)	(436)
Maximum Flow (mm/month)	622	622
FDC - MRAE - Overall flow	0.38	0.45
FDC - MRAE - High flow	0.24	0.25
FDC - MRAE - Intermediate	0.43	0.52
FDC - MRAE - Low flow	0.39	0.45
Pan coefficient	1.00	0.99
Observed Runoff coefficient	0.42	0.45
Simulated Runoff coefficient	0.49	0.56
Data period	1999/2000-2017/2018	2006/2007-2017/2018



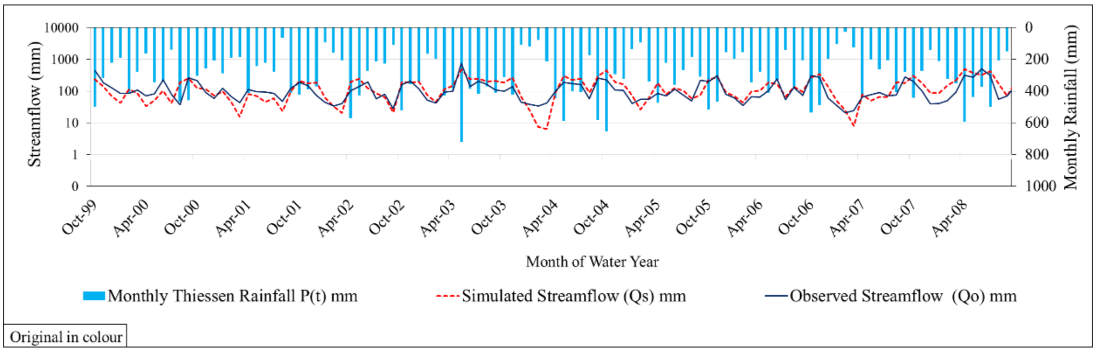
Original in colour

Figure 5-21: Total Hydrograph for Ellagawa Option 2- (2006/2007 - 2011/2012)



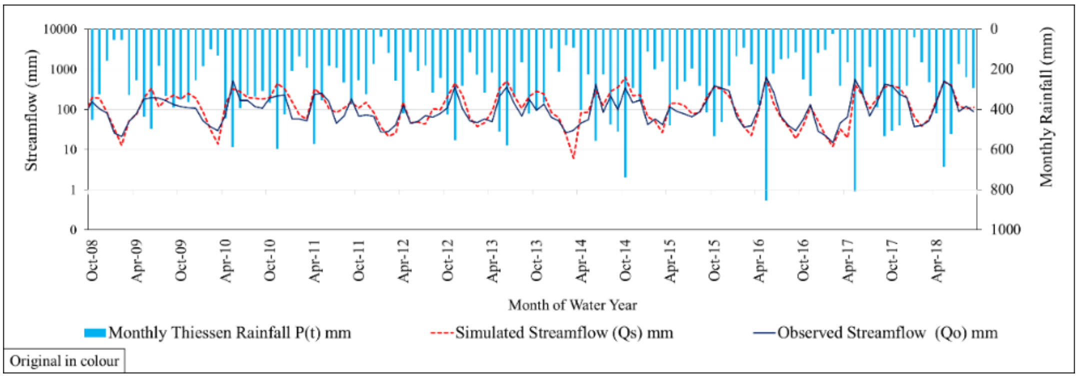
Original in colour

Figure 5-22: Total Hydrograph for Ellagawa Option 2- (2012/2013 - 2017/2018)



Original in colour

Figure 5-23: Total Hydrograph for Ellagawa Option 3- (1999/2000 - 2007/2008)



Original in colour

Figure 5-24: Total Hydrograph for Ellagawa Option 3- (2008/2009 - 2017/2018)

The following tables give the annual water balance conditions during transferability options for Ellagawa watershed.

Table 5-10: Annual Water Balance for Option 2 - Ellagawa

Water Year	Annual Thiessen Rainfall (mm)	Qo Observed Flow (mm)	Qs Simulated Flow (mm)	Annual Water Balance Observed (mm)	Annual Water Balance Simulated (mm)	Error % in Annual Water Balance
2006/2007	3276	1376	1488	1900	1788	6%
2007/2008	4000	2061	2886	1939	1114	43%
2008/2009	3464	1384	1700	2079	1764	15%
2009/2010	3794	1600	2048	2193	1745	20%
2010/2011	3874	1748	2262	2125	1612	24%
2011/2012	2651	739	917	1913	1735	9%
2012/2013	4157	1738	2502	2419	1655	32%
2013/2014	3649	1335	1932	2314	1717	26%
2014/2015	3798	1408	1987	2390	1811	24%
2015/2016	3545	2307	2008	1238	1538	24%
2016/2017	3528	1837	2845	1691	683	60%
2017/2018	4081	2287	2479	1794	1602	11%
Average	**3651**	**1652**	**2088**	**2000**	**1564**	**24%**

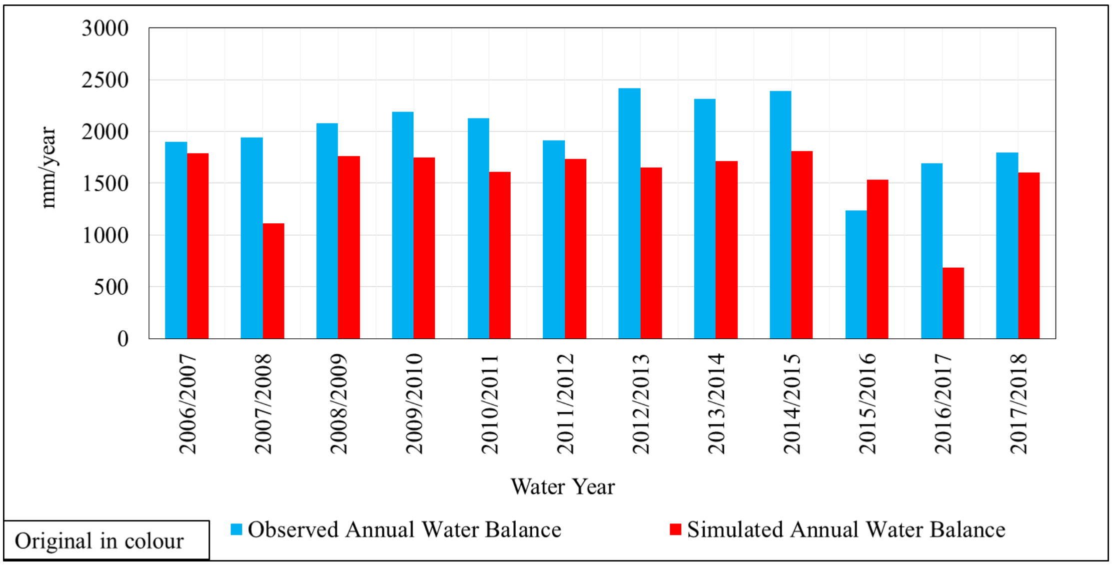


Figure 5-25: Annual Water Balance Comparison for Ellagawa Option 2

Table 5-11: Annual Water Balance for Option 3 - Ellagawa

Water Year	Annual Thiessen Rainfall (mm)	Qo Observed Flow (mm)	Qs Simulated Flow (mm)	Annual Water Balance Observed (mm)	Annual Water Balance Simulated (mm)	Error % in Annual Water Balance
1999/2000	3837	1787	1354	2051	2484	21%
2000/2001	3066	1149	852	1917	2215	16%
2001/2002	3462	1125	1420	2337	2042	13%
2002/2003	4705	2134	2323	2571	2382	7%
2003/2004	3849	1323	1786	2526	2063	18%
2004/2005	3666	1205	1591	2461	2075	16%
2005/2006	3581	1419	1568	2162	2013	7%
2006/2007	3276	1376	1470	1900	1806	5%
2007/2008	4000	2061	2886	1939	1114	43%
2008/2009	3464	1384	1700	2079	1764	15%
2009/2010	3794	1600	2048	2193	1745	20%
2010/2011	3874	1748	2262	2125	1612	24%
2011/2012	2651	739	917	1913	1735	9%
2012/2013	4157	1738	2502	2419	1655	32%
2013/2014	3649	1335	1932	2314	1717	26%
2014/2015	3798	1408	1987	2390	1811	24%
2015/2016	3545	2307	2008	1238	1538	24%
2016/2017	3528	1837	1585	1691	1943	15%
2017/2018	4081	2287	2479	1794	1602	11%
Average	**3683**	**1577**	**1825**	**2106**	**1859**	**18%**

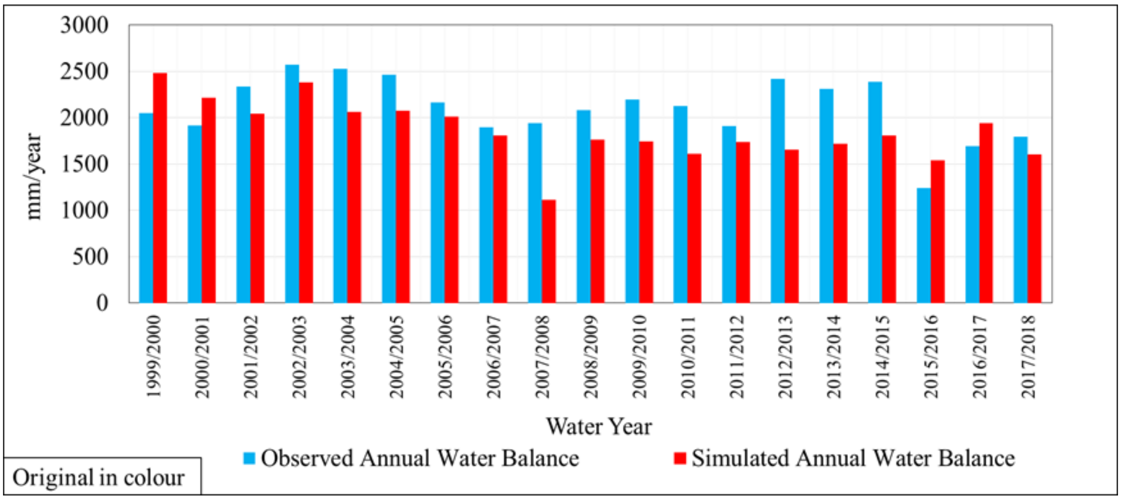


Figure 5-26: Annual Water Balance Comparison for Ellagawa Option 2

Flow duration curves observed during transferability options for Ellagawa watershed are given in the following figures.

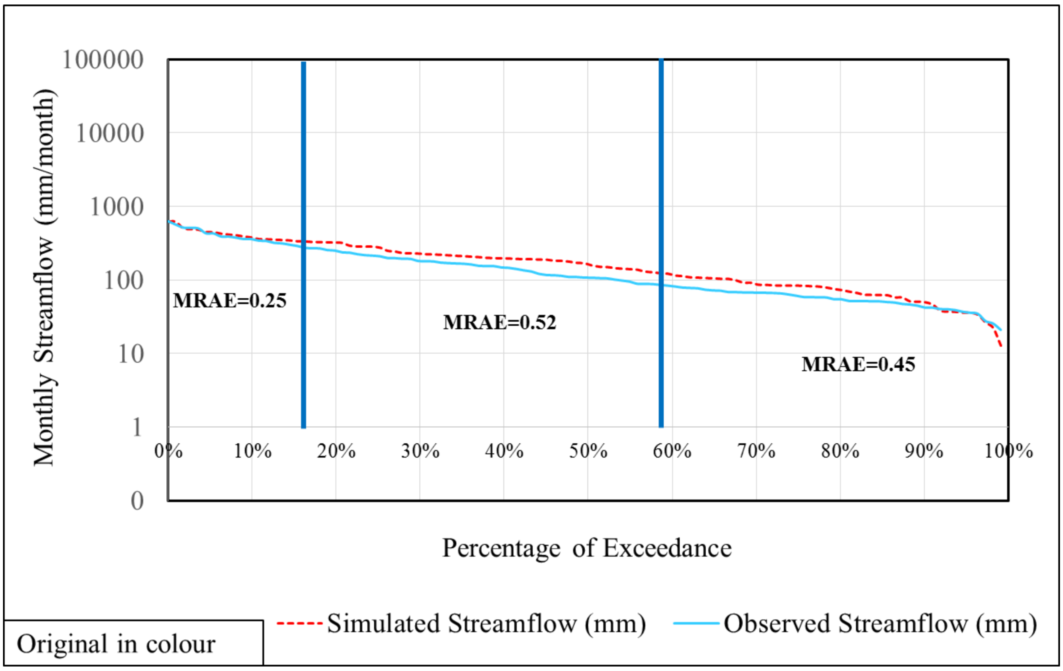


Figure 5-27: Flow Duration Curve for Ellagawa - Option 2

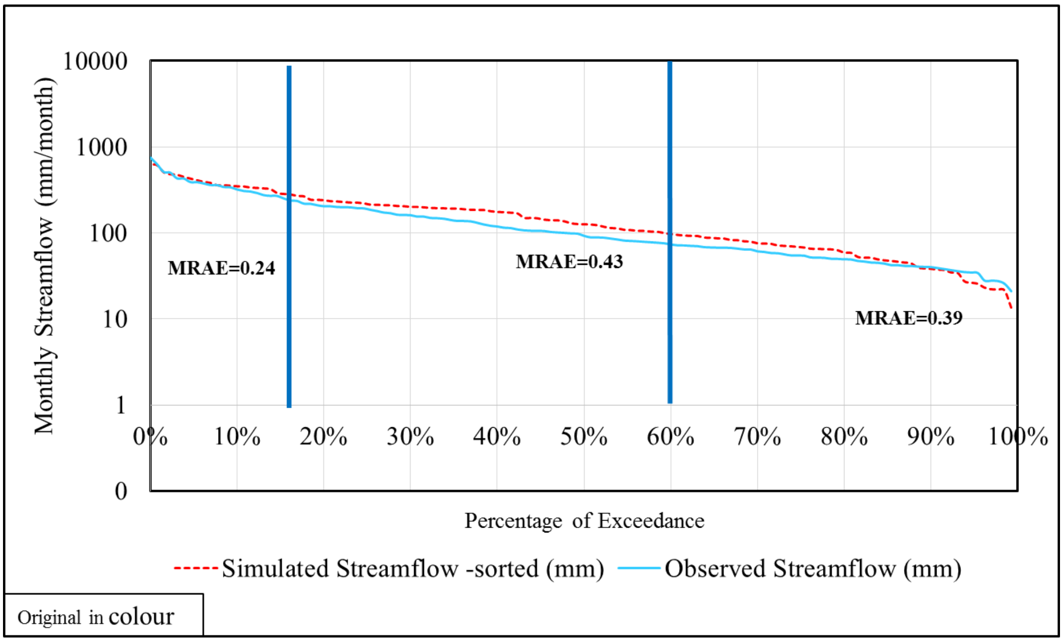
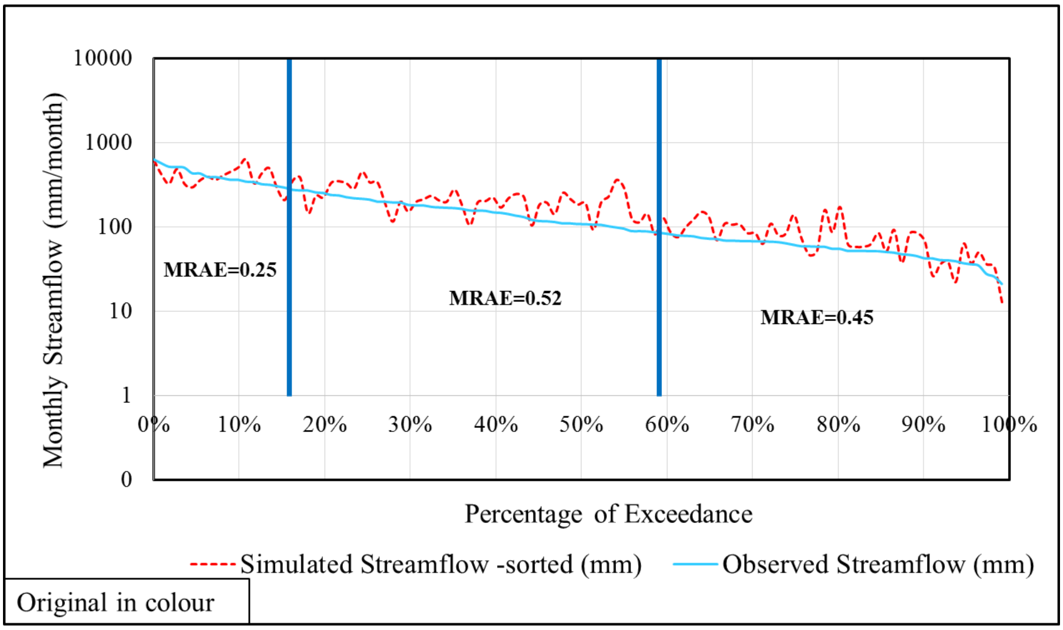
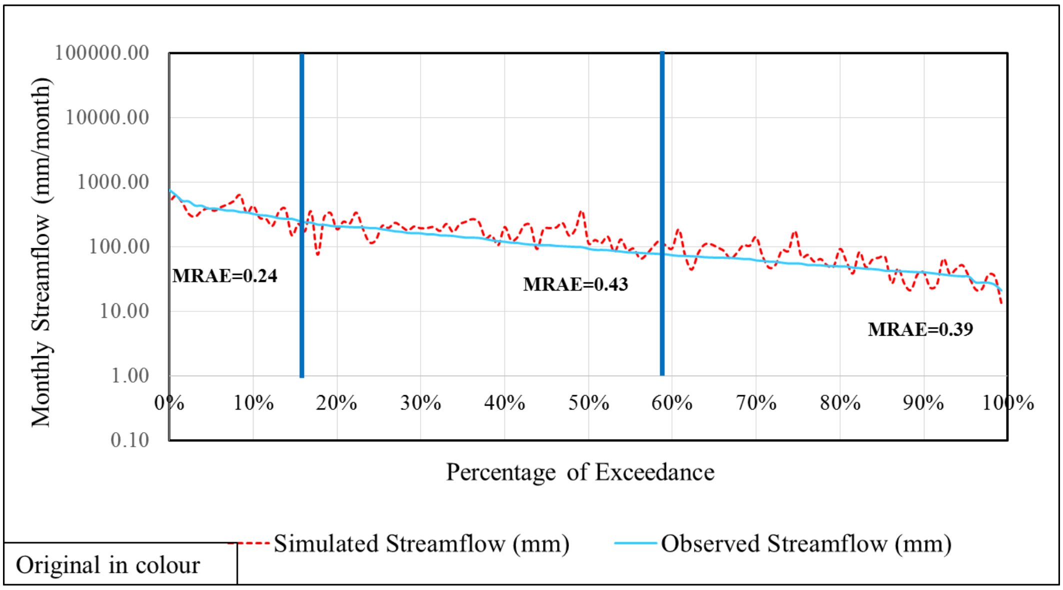


Figure 5-28: Flow Duration Curve for Ellagawa - Option 2



Original in colour

Figure 5-29: Flow Duration Curve for Ellagawa (Sorted Streamflow) - Option 2



Original in colour

Figure 5-30: Flow Duration Curve for Ellagawa (Sorted Streamflow) - Option 3

5.3.3 Model parameter transferability – Rathnapura watershed

Calibrated and verified model parameters for Ellagawa watershed were transferred to the Rathnapura watershed under the above three schemes and resulted in total hydrographs, flow duration curves, and annual water balances were obtained. Calibrated C value and Sc value for Ellagawa watershed were 2.38 and 1461 respectively. Transferring these two parameter values to Rathnapura for the common data period of 12 years and the period of the whole 19 years, the simulated flows were compared with the observed flows. Following Table 5-12 gives the summary of model parameter transferability for the Rathnapura watershed.

Table 5-12: Summary of Model Performance for Transferability Options - Rathnapura

Model Performance	Transformation of Model Parameters- **Option 3**	Transformation of Model Parameters **Option 2**
Data period	19 Years	12 Years
C	2.38	2.38
SC	1461	1461
MRAE - Overall Hydrograph	0.32	0.39
Soil moisture content-Beginning of the period	237	237
Soil moisture content- End of the period	237	237
Maximum soil moisture content (mm)	406	406
Minimum soil moisture content (mm)	40	32
Average Annual Water Balance Difference (mm)	(107)	(59)
Maximum Flow (mm/month)	571	571
FDC - MRAE - Overall flow	0.32	0.39
FDC - MRAE - High flow	0.29	0.28
FDC - MRAE - Intermediate	0.28	0.29
FDC - MRAE - Low flow	0.31	0.58
Pan coefficient	0.99	0.99
Observed Runoff coefficient	0.55	0.44
Simulated Runoff coefficient	0.51	0.45
Data period	1989/1990-1995/1996 2006/2007-2017/2019	2006/2007-2017/2018

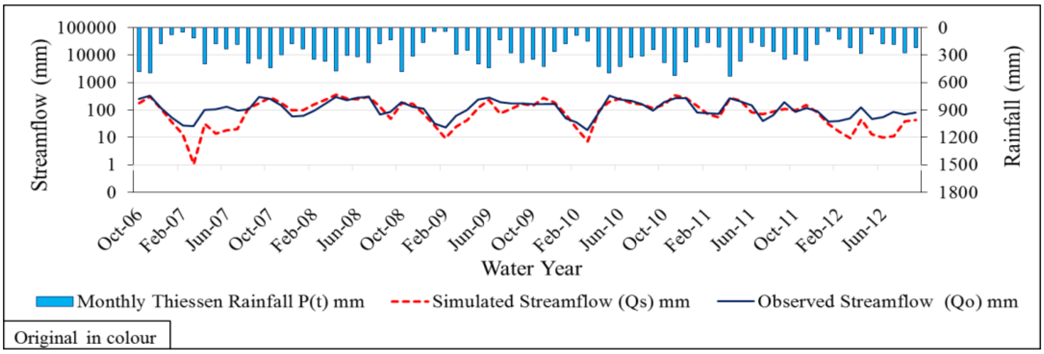


Figure 5-31: Total Hydrograph for Rathnapura Option 2- (2006/2007 - 2011/2012)

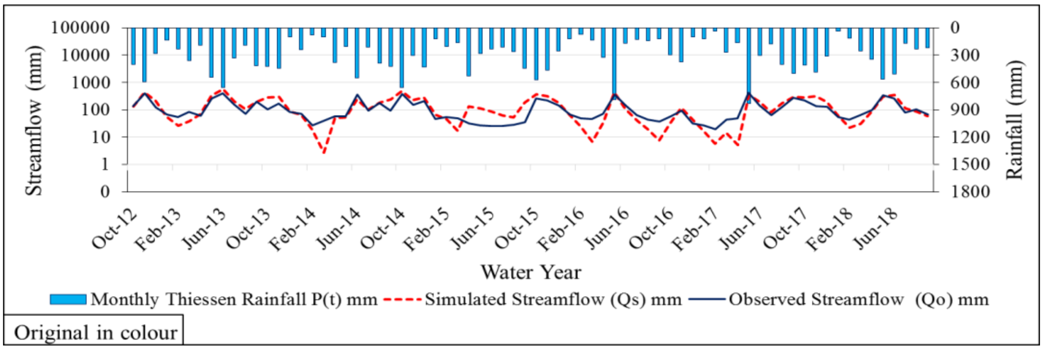


Figure 5-32: Total Hydrograph for Rathnapura Option 2- (2012/2013 - 2017/2018)

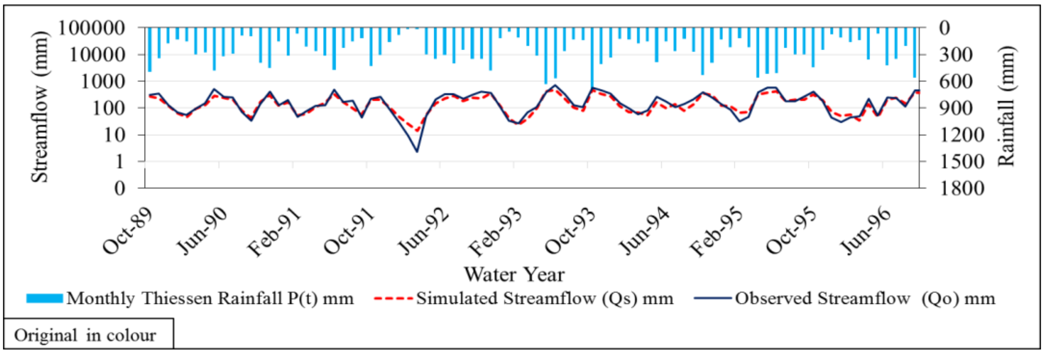


Figure 5-33: Total Hydrograph for Rathnapura Option 3- (1989/1990 - 1995/1996)

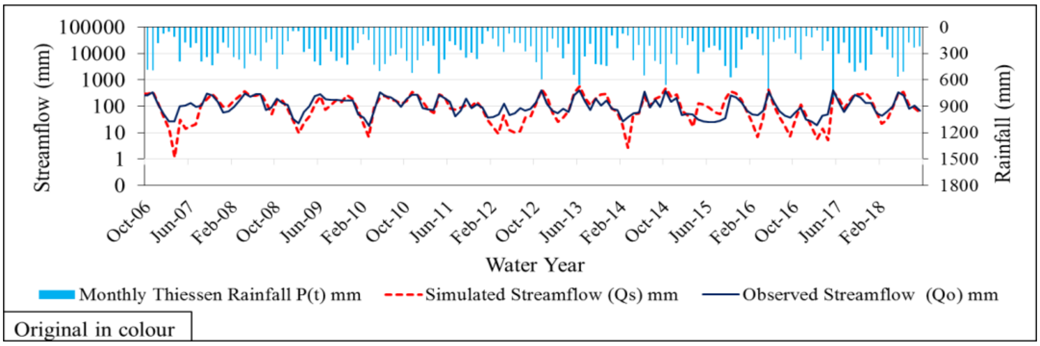


Figure 5-34: Total Hydrograph for Rathnapura Option 3- (2006/2007 - 2017/2018)

The following tables give the annual water balance conditions during transferability options for Rathnapura watershed.

Table 5-13: Annual Water Balance for Option 2 - Rathnapura

Water Year	Annual Thiessen Rainfall (mm)	Qo Observed Flow (mm)	Qs Simulated Flow (mm)	Annual Water Balance Observed (mm)	Annual Water Balance Simulated (mm)	Error % in Annual Water Balance
2006/2007	3121	1650	1023	1472	2098	43%
2007/2008	3660	2040	2413	1619	1247	23%
2008/2009	3202	1728	1238	1475	1964	33%
2009/2010	3668	1729	1711	1939	1956	1%
2010/2011	3749	1876	1900	1873	1849	1%
2011/2012	2446	881	552	1565	1894	21%
2012/2013	4334	1987	2370	2347	1964	16%
2013/2014	3545	1328	1608	2217	1937	13%
2014/2015	3836	1047	1750	2789	2087	25%
2015/2016	3305	1494	1605	1811	1700	6%
2016/2017	3578	1332	1327	2245	2251	0%
2017/2018	3661	1603	1906	2058	1756	15%
Average	3509	1558	1617	1951	1892	16%

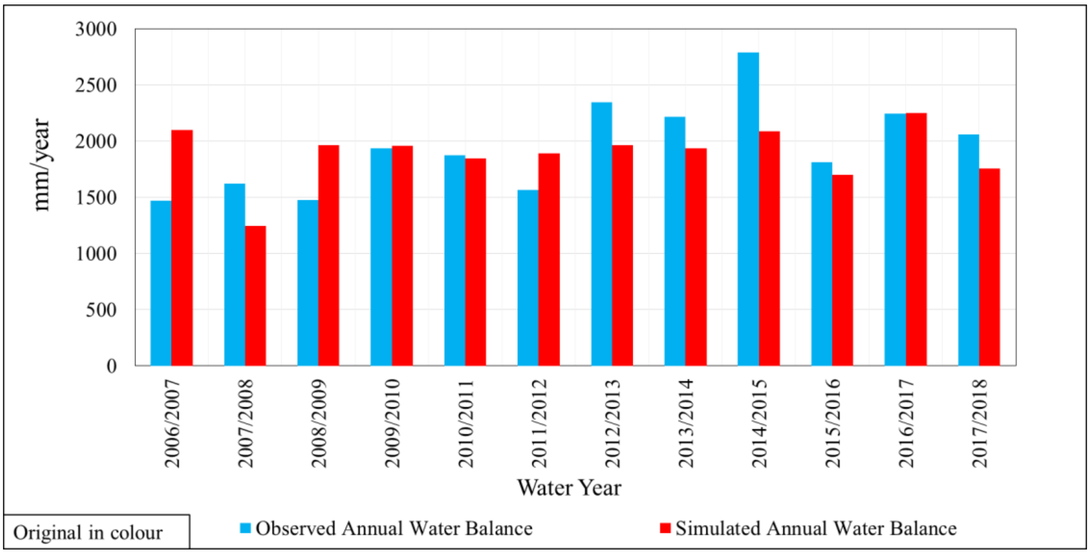


Figure 5-35: Annual Water Balance Comparison for Rathnapura Option 2

Table 5-14: Annual Water Balance for Option 3 - Rathnapura

Water Year	Annual Thiessen Rainfall (mm)	Qo Observed Flow (mm)	Qs Simulated Flow (mm)	Annual Water Balance Observed (mm)	Annual Water Balance Simulated (mm)	Error % in Annual Water Balance
1989/1990	3153	2277	1790	876	1363	56%
1990/1991	3156	2114	1764	1042	1392	34%
1991/1992	2976	2036	1726	939	1250	33%
1992/1993	3371	2790	2201	581	1171	102%
1993/1994	3260	2636	1988	624	1272	104%
1994/1995	4023	3055	2742	968	1281	32%
1995/1996	3147	2072	1866	1075	1281	19%
2006/2007	3121	1650	1186	1472	1936	32%
2007/2008	3660	2040	2413	1619	1247	23%
20008/2009	3202	1728	1238	1475	1964	33%
2009/2010	3668	1729	1711	1939	1956	1%
2010/2011	3749	1876	1900	1873	1849	1%
2011/2012	2446	881	552	1565	1894	21%
2012/2013	4334	1987	2370	2347	1964	16%
2013/2014	3545	1328	1608	2217	1937	13%
2014/2015	3836	1047	1750	2789	2087	25%
2015/2016	3305	1494	1605	1811	1700	6%
2016/2017	3578	1332	1327	2245	2251	0%
2017/2018	3661	1603	1906	2058	1756	15%
Average	3431	1878	1771	1553	1660	16%

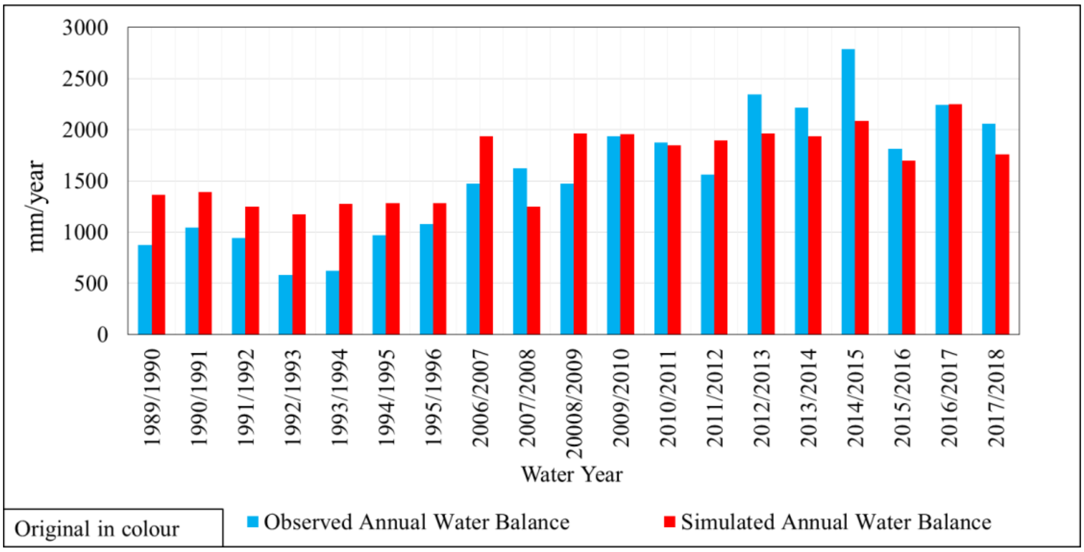
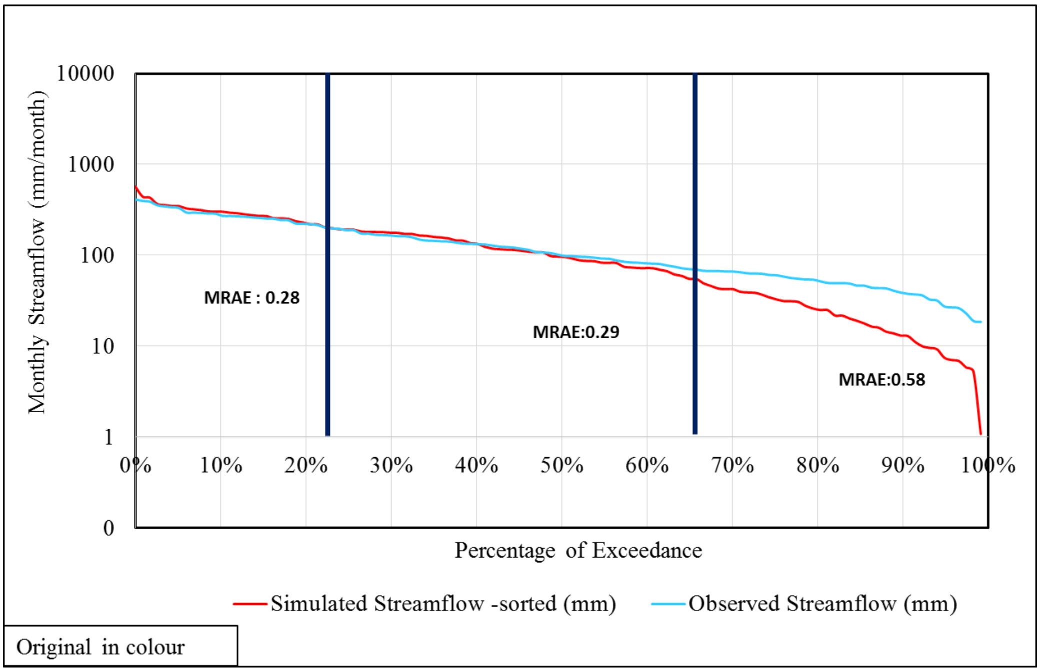


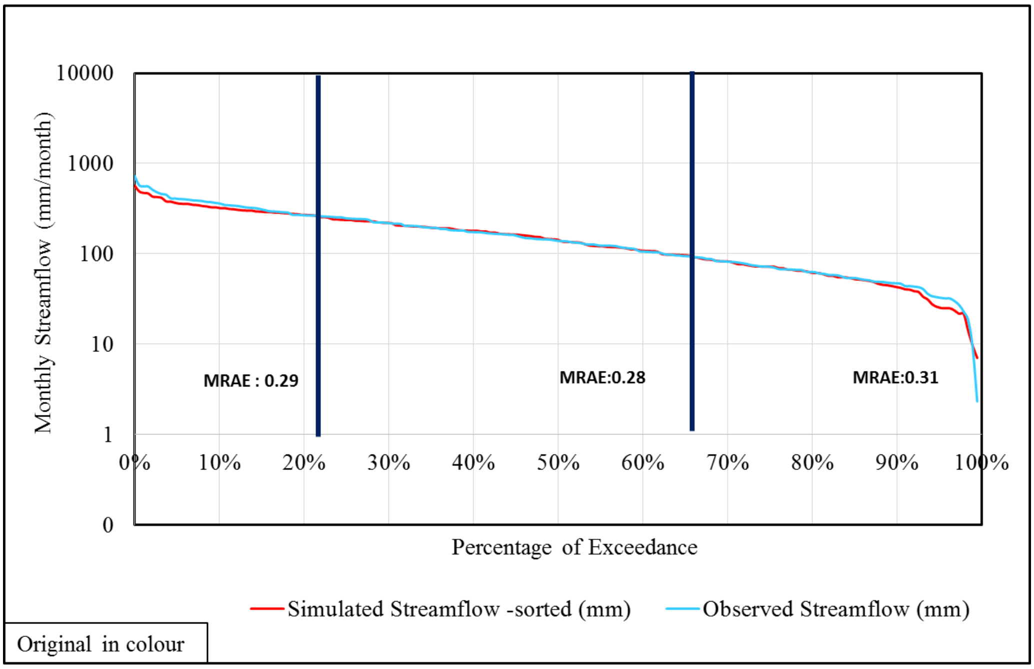
Figure 5-36: Annual Water Balance Comparison for Rathnapura Option 3

Flow duration curves observed during transferability options for Rathnapura watershed are given in the following figures.



Original in colour

Figure 5-37: Flow Duration Curve for Ellagawa - Option 2



Original in colour

Figure 5-38: Flow Duration Curve for Ellagawa - Option 2

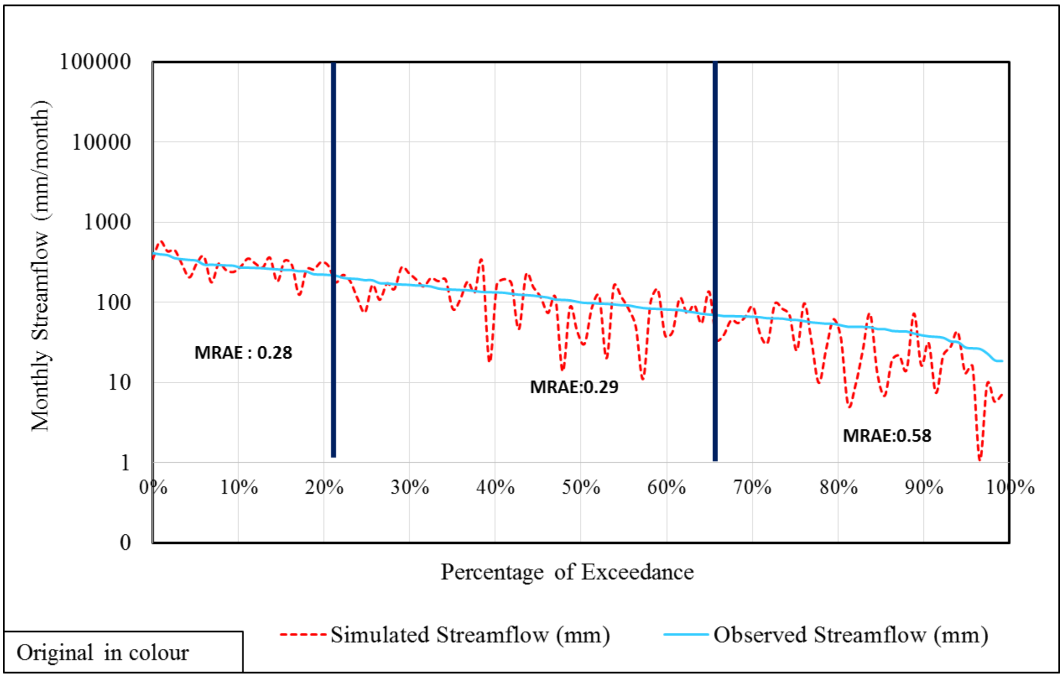


Figure 5-39: Flow Duration Curve for Ellagawa (Sorted Streamflow) - Option 2

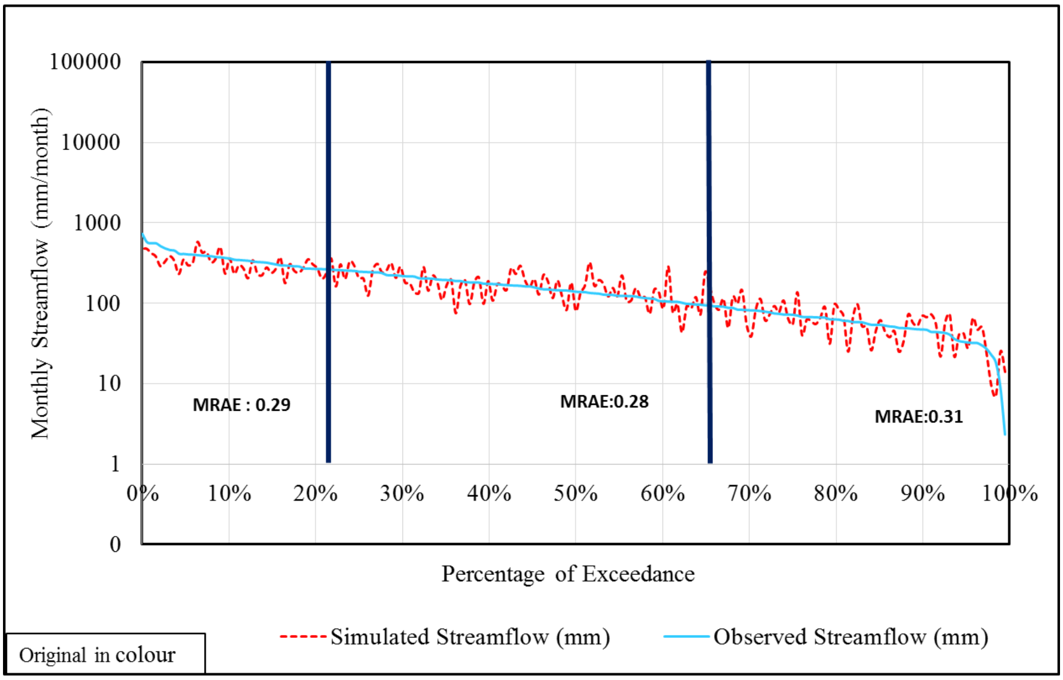


Figure 5-40: Flow Duration Curve for Ellagawa (Sorted Streamflow) - Option 2

6 DISCUSSION

6.1 Data and Data Periods

The two watersheds covered under the present study occupied three major hydrological data on a monthly time scale. They are streamflow, rainfall, and evaporation. At the initial stage of the study above three types of data were collected covering the data period from 1984 to 2017. It is more than 30 years. However, before the water year 1999/2000, There exists a considerable reduction in streamflow for both Ellagawa and Rathnapura while rainfall remaining in the same magnitude as other water years after the water year1999/2000.The double mass curve analysis also shows the inconsistency behavior of streamflow before the above-mentioned water year. Therefore, a consistent and continuous 19 years of data set was used for Ellagawa from 1999/2000 to 2017/2018. For the Rathnapura watershed, this same 19 years couldn't be collected due to the unavailability of data in the irrigation department for the Rathnapura streamflow gauge from 1995/1996 to 2005/2006 due to malfunction of the gauging station. However, it was able to continue with 19 years of data set for Rathnapura but not a continuous set since the above limitation. It is 7 years from 1989/1990 to 1995/1996 and 12 years from 2006/2007 to 2017/2018. For the transferability checking whole 19y years of data set was used under option 3 while option 2 used only a common data period of 12 years.

1. Results analysis shows annual water balance errors are high in some water years (2006/2007, 2007/2008, 2008/2009 for Rathnapura 2007/2008, 2016/2017 for Ellagawa) due to lesser values of observed rainfall caused by the rainfall averaging and station configurations.
2. Other than above, in some years during Rathnapura verification, before the water year 1995/1996, annual water balance errors are high (Table 5-13, 5-14) due to higher observed flow values. For the same annual average rainfalls, the given observed streamflow values are higher compared to water years after 2006/2007. The observed runoff coefficient is sometimes doubled as land use

runoff coefficient. This happens due to the unrealistic behavior of observed data in Rathnapura before the water year 1995/1996. (Appendix – Figure B-4)

Apart from above, most of the years for both watersheds simulated runoffs found to be larger than the respectively observed runoffs and the original paper of the 2P model concludes that this bias is attributed to the model structure.

6.2 Flow Regime Separation

Under the literature review, it is revealed that the probability of exceedance threshold for the low flow in Ellagawa catchment as 0.20. The high flow thresholds in Ellagawa were captured as 0.60. (Wijesekera, 2018). This literature clearly stated that the conventional flow duration curve plots do not reveal identifiable boundaries to distinguish flow thresholds. Instead, an order of magnitude flow duration curves and the corresponding slopes were suggested which provides easy capturing of different flow types. It is further stated that the monthly flow duration curves demonstrated an easiness to capture streamflow thresholds when compared with the identifications based only on the daily flow duration curves. Therefore under the present study order of magnitude flow durations curves were plotted for both Ellagawa and Rathnapura watersheds following the methodology described under the respective literature. Figure C-1 and Figure C-2 in Appendix C illustrates the order of magnitude flow duration curves for Ellagawa and Rathnapura watersheds separately. Figure C-1 indicates that the probability of an exceedance threshold for the low flow in Ellagawa catchment as 0.15 and the high flows it is 0.59. Figure C-2 indicates that the probability of an exceedance threshold for the low flow in Rathnapura catchment as 0.23 and the high flows it is 0.66. It reveals that these values are in greater accordance with the values given in the literature and the observed slight variations are particularly due to the changes is considered data periods and length of the data durations. Under this study, monthly streamflow data of 20 years were used to plot the order of magnitude flow duration curves. The resulted threshold values were used to discriminate separate flow regimes under the following sections during the parameter transferability checking.

6.3 Objective Function and Criteria Selection

Several objective functions were screened under the literature review and their applicability of various studies was checked. (Table A-3).Prioritize the objective functions and evaluate their performance in different flow regimes with the aid of literature and MRAE found to be the best objective function for both intermediate and overall flow matching. Under the scope of the research major concerns are given for the intermediate and overall flows. That is because, in water resources planning activities, intermediate flows are the major concern since water uses throughout the year for productive activities are almost associated with the intermediate flow. Therefore present study concentrates on the MRAE which performs best with the intermediate flow. It is observed during model simulations, the model performance is high when it captures intermediate flows and high flows. Other than this numerical model evaluation criteria, the graphical evaluation by using flow durations curves and total hydrographs were carried out and presented in the analysis of the results chapter. The flow duration curves clearly show how the model behaves under three major flow regimes.

Table 6-1: Summary of Objective Function Variation within Considered Model Simulations

MRAE Value	**Ellagawa**	**Rathnapura**
Calibration	Overall=0.38 High=0.28 Intermediate=0.43 Low=0.37	Overall=0.36 High=0.32 Intermediate=0.39 Low=0.36
Validation	Overall=0.36 High=0.40 Intermediate=0.41 Low=0.48	Overall=0.32 High=0.21 Intermediate=0.23 Low=0.38
Transferability Option 2	Overall=0.45 High=0.25 Intermediate=0.52 Low=0.45	Overall=0.39 High=0.28 Intermediate=0.29 Low=0.58
Transferability Option 3	Overall=0.38 High=0.24 Intermediate=0.43 Low=0.39	Overall=0.32 High=0.29 Intermediate=0.28 Low=0.31

According to the above summary table

1. The model is capable of predicting high flows quite well in all considered options (calibration, validation, transferability). Since compared to the other two flow regimes lowest MRAE values are obtained for high flows.
2. When compared MRAE values for three flow regimes, it is clear that MRAEs for Low flows are much higher than the other two (Table 6-1). In FDCs also it is clear that the low flow regime is less performed compared to other flow regimes. (Figure 5-8, 5-17, 5-27, and 5-28).

6.4 Soil Moisture Variation and Warmup Period

Developers of the model themselves say initial soil moisture contents S (0) at the beginning of the model simulations have the potential to take effect on model performance and optimal parameter determination. When the considered model data period is no longer enough this effect would be high. In the present case, the behavior of the soil moisture content is assumed to be a cyclic one within one year. This yearly cyclic behavior is a common feature of most of the hydrological variables. Therefore in similar months of the years, the soil water content cannot vary considerably in its magnitude. Therefore soil moisture content at the beginning of the year shall not differ significantly that of the end of the year due to its annual cyclic behavior. Standing upon this basis until it gets becomes stabilize cycles of the same data set were repetitively used and initial soil moisture contents were obtained throughout the model simulation exercise.(Figure 5-1 & 5-2).Soil moisture variation along with the rainfall was observed during model calibration, model validation, and parameter transferability options. It’s observed that it follows the same pattern as the rainfall for calibration and verification periods and during all other model simulation options. It is noted as a good indication of the smooth performance of the model.

6.5 Model Parameter Comparison in Catchments.

Efficiency and the stability of the models are indicated by their associated model parameters. The presented 2P water balance model consists of two parameters denoted by C and Sc. Parameter C accounts for the change of time scale from year to month while Sc is used to represent the field capacity of catchments. Model parameter optimization is done both manually and automatically. A matrix of two model parameters was given into model and MRAE is recorded for each combination in the matrix (Figure 6-1) and find a finer range for the two model parameters and then used excel inbuilt solver tool to optimize the parameters within a finer range. During the optimization procedure, it is found that the optimum value of the parameter Sc is very robust and insensitive to the initial values of the parameters. During model calibration and validation, C is 2.09 for Rathnapura Watershed and it is 2.38 for Ellagawa watershed. When the watersheds are nearby, then parameter c does not vary from each other considerably. It is a 13 % difference from each other. Parameter Sc for Rathnapura was 1420 whereas it is 1461 for Ellagawa. It is a 3% difference from each other. The second model parameter doesn’t show considerable variation within nearby watersheds. From that observation, it is revealed that model parameters do not vary considerably over the catchments within Kalu river basin (C = 2.38,1461 for Ellagawa and C=2.09, 1420 for Rathnapura).

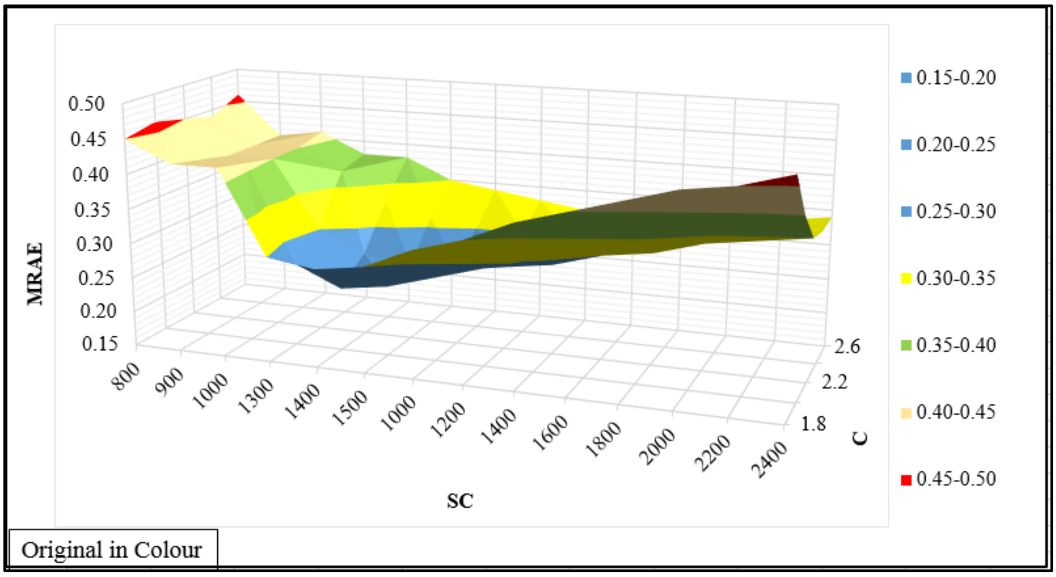


Figure 6-1: Model Parameter Matrix for the Optimization – Ellagawa

6.6 Transferability Options

Table 6-1 shows the MRAE values obtained for separate transferability options. Flow duration curves for respective options can be found under the Figures 5-27,5-29,5-37 and Figure 5-38.

6.6.1 Temporal transfer scheme

In the temporal transfer scheme, average MRAE value for overall flows found to be as 0.34. For high flows, it is 0.30 and for low flows, it is 0.39. For the intermediate flows average MRAE value is 0.36. For overall flows minimum, the MRAE value is 0.32 while its maximum is 0.38. For high flows minimum, the MRAE value is 0.21 while its maximum is 0.40. In this temporal transfer scheme for low flows, maximum MRAE is found to be as 0.48 while the minimum is 0.36. It is clear that with the lowest average MRAE value of 0.30, the temporal transfer scheme is to perform better for high flows compared to other flow conditions.

6.6.2 Spatial transfer scheme

In the spatial transfer scheme, average MRAE value for overall flows found to be as 0.42. For high flows, it is 0.26 and for low flows, it is 0.51. For the intermediate flows, the average MRAE value is found to be as 0.40. For overall flows, the minimum MRAE value is 0.39 while its maximum is 0.45. For high flows, the minimum MRAE value is 0.25 while its maximum is 0.28. In this spatial transfer scheme, for low flows, maximum MRAE is found to be as 0.58 while the minimum is 0.45. It reveals that with the lowest average MRAE value of 0.26, the spatial transfer scheme performs better for high flows compared to the other two flow conditions which are similar to the temporal transfer scheme.

6.6.3 Spatiotemporal transfer scheme

In the spatiotemporal transfer scheme, the average MRAE value for overall flows found to be 0.35. For high flows, it is 0.26 and for low flows, it is 0.35. For the intermediate flows average MRAE value is found to be as 0.35. For overall flows minimum, the MRAE value is 0.32 while its maximum is 0.38. For high flows minimum, the MRAE value is 0.24 while its maximum is 0.29. In this spatiotemporal transfer scheme, for low flows, maximum MRAE is found to be as 0.39 while the minimum is 0.31. It reveals that with the lowest average MRAE value of 0.26, the spatiotemporal transfer scheme performs better for high flows compared to other flow conditions which are similar to both temporal and spatial transfer schemes.

1. These research findings show that no systematic differences in considered three transferability options. The spatiotemporal model transfer scheme gives the lowest MRAE values among the three considered transferability options.
2. Whether it is temporal, spatial, or spatiotemporal, when the data period is getting longer the model transferability results get closer to observed values. Lowest MRAE values get under the transferability option 3 which considered 19 years of data set which is the longest duration considered under the parameter transferability checking.

6.6 Variations in Flow Magnitudes.

For the temporal transfer scheme, monthly and annual flow magnitude variation is given in table 5-4 and 5-7 separately for Ellagawa and Rathnapura watersheds. For the spatial transfer scheme, monthly and annual flow magnitude variation is given in table 5-10 and 5-13 separately for Ellagawa and Rathnapura watersheds. For the spatiotemporal scheme, monthly and annual flow magnitude variation is given in table 5-11 and 5-14 separately for Ellagawa and Rathnapura watersheds. Under the spatial transfer scheme, in the water 2006/2007, annual water balance error is 43 %. It is 23% and 33% for the water years 2007/2008 and 2008/2009 respectively. However average water balance error is 16% for Rathnapura watershed under the spatial transfer scheme while it is 24% for Ellagawa watershed. In the spatiotemporal scheme average water balance error is 16% for Rathnapura watershed whereas it is 18% for Ellagawa watershed. In the 2012/2013 water year, annual water balance error is found to be 32

% for Ellagawa watershed under the spatial transfer scheme while it is 43 for 2007/2008 water year.

The reasons identified for these variations can be summarized as follows.

1. Above mentioned tables show that annual water balance errors are high in some water years (2006/2007, 2007/2008, 2008/2009 for Rathnapura 2007/2008, 2016/2017 for Ellagawa) due to lesser values of observed rainfall caused by the rainfall averaging and station configurations.
2. Other than above, in some years of Rathnapura watershed (Table 5-13, 5-14) annual water balance errors are high due to low observed flow values. These may be due to data errors and due to unrealistic observed streamflow values in Rathnapura watershed.

Errors in monthly and seasonal flow magnitudes are given under Table C 1 to Table C 8 in Appendix C. The results show that three model transfer schemes perform unevenly in each season and each monthly. There is no uniform behavior of schemes concerning error percentages in flow magnitudes. Under the spatiotemporal transfer scheme, in Ellagawa watershed, the lowest average error in water quantity is found to be in February which is 14.95mm in the model and is equal to 240.37 m3/s in quantity. The highest average error is found to be in October which is 84.51mm in the model and is equal to 1360.17m3/s in quantity. For the Rathnapura watershed, the lowest average error in water quantity is found to be in January and February which is 18mm in the model and is equal to 130.00 m3/s in quantity. The highest average error is found to be in June which is 87.66mm in the model and is equal to 636.7m3/s in quantity.

When considering the seasonal flows, the highest average error percentage is given under transferability option two in the Maha season and is equal to 54%. Lowest average error percentage comes under the spatial transfer scheme in Maha Season and is equal to 13%. Table C-2, Table C-4, Table C-6, and Table C-8 gives error percentages in seasonal flows separately in detail.

7 CONCLUSIONS

1. The transferability of model parameters within Kalu River basin showed that the temporal transfer scheme has the highest capability of predicting overall flows with the average MRAE values of o.34 while it is 0.42 and 0.35 in spatial and spatiotemporal transfer schemes respectively.
2. Spatial and spatiotemporal transfer schemes perform at the same accuracy level for predicting high flows with an average MRAE value of 0.27 while it is 0.30 in temporal transfer scheme. The temporal transfer scheme has the highest capability to predict intermediate flows with an average MRAE value of 0.32 while it is 0.41 and 0.36 in spatial and spatiotemporal schemes respectively.
3. Spatiotemporal transfer scheme performs best for low flows with an average MRAE value of 0.35 while it is 0.43 and 0.52 in temporal and spatial transfer schemes respectively, reveals that compared to MRAE values for high flows and intermediate flows, low flows have given highest average MRAE values in all three considered transfer schemes.
4. Transferability option 3, which used 19 years total data has the high capability to predict streamflows with a high accuracy level by giving MRAE values 0.35, 0.27, 0.36 and 0.35 for overall, high, intermediate and low flows respectively compared to transferability option 2 which used 12 years of common data period giving MRAE values 0.42, 0.27, 0.41 and 0.52 for overall, high, intermediate and low flows respectively.
5. Model parameters C is 2.09 for Rathnapura watershed and it is 2.38 for Ellagawa which is having a 13% difference in each other.SC is 1420 for Rathnapura and 1461 for Ellagawa having a 3% difference from each other, indicating that model parameters do not vary across the catchments in Kalu River Basin and they are stable in a spatial domain.
6. The spatiotemporal scheme has the highest capability to predict Yala seasonal streamflows by giving 13% of error percentage while for Ellagawa watershed and Spatial transfer scheme has the highest capability to predict Maha seasonal flow with the average error percentage of 13.29%.

8 RECOMMENDATIONS

1 Water resources engineers and modelers can select, temporal, spatial, Spatio-temporal transferability of model parameters to predict streamflows in Kalu river basin depending on the accuracy levels expect to be achieved and the type of the study they targeted to do.

2 Model parameter transferability options can be expanded and further studied for variable data durations, and more gauged watersheds within the basin and can obtain and transferable model parameters for the whole basin.

3 Rainfall averaging methods and different stations and station configurations can be recommended for further advancements of annual water balances for more accurate results from model transferability.

4 Further research is recommended to carry out for the low flow predictions and the use of parameter transferability for studies related to low flow analyzes.

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APPENDIX A - Analysis of Literature

Table A-1: Summary of Water Resources Modeling Studies with the Selected Data Durations

Research	Summary Description	Time scale	Recommended duration - Years
(Xu and Vandewiele, 1994)	Worked on 91 catchments in Belgium and China having extents between 16 km² to 3626 km², and using 2, 5, 10, 15, 20 years long **monthly** data from a 158 year data series, concluded that a **10 year** data period is necessary for an adequate model calibration.	Monthly	10
Michaud and Sorooshian, (1994)	Selecting 6 events for calibration and 24 events for validation of simple and complex runoff 13 models in semi-arid watersheds **-** concluded that a minimum data length of **15 years** is required for calibration.	Monthly	15
GÖrgens (1983)	Gorgens (1983) in a research on two hydrologic models for a **semi-arid 73.1 km²** catchment with monthly datasets of 3, 6, 10, 15 and 20 years, also concluded that **15 years of monthly** data is required for a reliable model optimization.	Monthly	15
Haans, (1972)	After a modelling study of 7 catchments in USA, Haans, (1972) stated that at least one and preferably **2 or 3 years** of observed **monthly** flows are required for acceptable parameter estimation.	Monthly	2 or 3
Guideline issued by Department of Water Resources in Rajasthan, India,	states that a minimum of **25** years of monthly rainfall data and runoff data of maximum available period is required for yield studies.	Monthly	25
Kherde (2016)	recommend a one year dataset for the warm-up period, a **10** year data set for calibration and a minimum of 2 years data for validation	Monthly	10
(Keshtegar et al., 2016)	A monthly dataset of 60 years enabling 30 years each for model calibration and verification has been recommended as the best modelling option for Nile River	Monthly	30

Table A-2: Summary of Water Resources Modeling Studies on the Kalu River basin with the Selected Data Durations

Author & Year	Name of the study	Streamflow Gauging station	Data duration	Data resolution	Data duration for calibartion	Data duratioj for verification	No of Rainfall stations	Basin area	Source
Ariyasena ,2019	Identification of Minimum data duration for Monthly water balance model Calibration	Ellagwa	Streamflow - (42 Years) (1976-2017)	Monthly	1983/1984 to 2012/2017 (35 Years)	1976/1977 to 1982/1983 (7 years)	5	1394 Km²	Digital library UOM
			Rainfall (42 years) (1976-2017)	Monthly					
			Evaporation-Rathnapura 30 years (1976-2017)	Monthly					
Gunasekara,2018	Application of 'abcd' monthly water balance model for Kalu ganga and Gin ganga basins and its application potential for	Ellagwa	Rainfall - 20years (1980-2000)	Monthly	4	5	12	1383 Km²	Digital library UOM
			Streamflow data -20 years (1980-2000)	Monthly					
			Evaporation-Rathnapura 30 years (1980-2000)	Monthly					
Kodippili, 2019	Influence of station density And interpolation methods on Spatial averaging of rainfall for Water resources management	Ellagwa	Rainfall - 8 years (2006-2014)	Daily	6 years	-	5	1395 Km²	Digital library UOM
			Streamflow data -8 years (2006-2014)	Daily					
			Evaporation-Rathnapura 8 years (2006-2014)	Daily					
Dissanayake, 2017	Applicability of a two parameter water balance model to simulate daily rainfall runoff – case study of Kalu and Gin river	Ellagawa	Rainfall - 8 years (2006-2014)	Daily	2006 to 2010	2010 to 2014.	5	1372 Km²	Digital library UOM
			Streamflow data -8 years (2006-2014)	Daily					
			Evaporation-Rathnapura (2006-2014)	Daily					
Schulz and Kingston	GCM-related uncertainty in river flow projections at the threshold for "dangerous" climate change: the Kalu Ganga river, Sri	Putupaula	Rainfall - 31 years (1980-2011)	Daily	1989-1993	1980-1983 1983-1987	1	2765 Km²	Hydrological Sciences Journal
			Streamflow data -31 years (1980-2011)	Daily					
			Evaporation-Rathnapura -31 years (1980-2011)	Daily					
Jayadeera , 2016	Development of a rainfall runoff model for Kalu ganga basin of Sri Lanka using HEC-HMS model	Ellagwa	Evaporation-8 years (2006-2014)	Daily	2006 to 2010	2010 to 2014.	5	1358 Km²	Digital library UOM
			Streamflow data -8 years (2006-2014)	Daily					
			Evaporation-Rathnapura -8 years (2006-2014)	Monthly					
Jayadeera , 2016	Development of a rainfall runoff model for Kalu ganga basin of Sri Lanka using HEC-HMS model	Rathnapura	Rainfall - 8 years (2006-2014)	Daily	2007 to 2010	2011 to 2014.	4	635 Km²	Digital library UOM
			Streamflow data -8 years (2006-2014)	Daily					
			Evaporation-Rathnapura -8 years (2006-2014)	Monthly					
Wijesekera & Musiake,	Streamflow modelling of Sri Lankan Catchments - Kalu river catchment at Putupaula	Putupaula	Rainfall (1972-1979)	Daily	1972-1975	1976-1979	6	2598Km²	Tokyo university Reposito
			Streamflow (1972-1979)	Daily					
			Evaporation (1972-1979)	Daily					

Table A-3: Evaluation of Objective Functions

Objective Function	**Equation**	**Peak Flow Matching**	**Intermediate Flow Matching**	**Low Flow Matching**	**Overall Flow Matching**	**Reference Literature**	**Overall Objective Function Suitability**
MRAE	$MRAE = \frac{1}{n}[\sum \frac{\lvert Yobs - Ycal \rvert}{Yobs}$	Medium	Very Good	Medium	Very Good	Perera & Wijesekera, 2010; Wijesekera, 2000, Wanniarachchi, 2013,	Very Good
Nash Sutcliffe Coefficient (NSE)	$E = 1 - \frac{\sum_{i=1}^{n}(X_{obs,i} - X_{model})^2}{\sum_{i=1}^{n}(X_{obs,i} - \overline{X_{obs}})^2}$	Very Good	Very Good	Medium	Medium	Xiong & Guo, (1999), Guo et al., (2002), Chen et al., 2007; Fish, (2011), Krause et al., (2005), Zhang & Savenije, (2005)	Very Good
RAEM	$A = \frac{\sum \lvert y_c - y_o \rvert}{n\overline{y_o}}$	Poor	Medium	Medium	Medium	Recommended by WMO	Medium
RE	$RE = \frac{\sum(Qi - Qi')}{\sum Qi} \times 100\%$	Poor	Medium	Medium	Medium	Xiong & Guo, (1999) and Guo et al., (2002)	Medium
RMSE	$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(Xobs,i - Xmodel,i)^2}{n}}$	Medium	Medium	Poor	Medium	Moreda, (1999)	Medium

APPENDIX B - Data

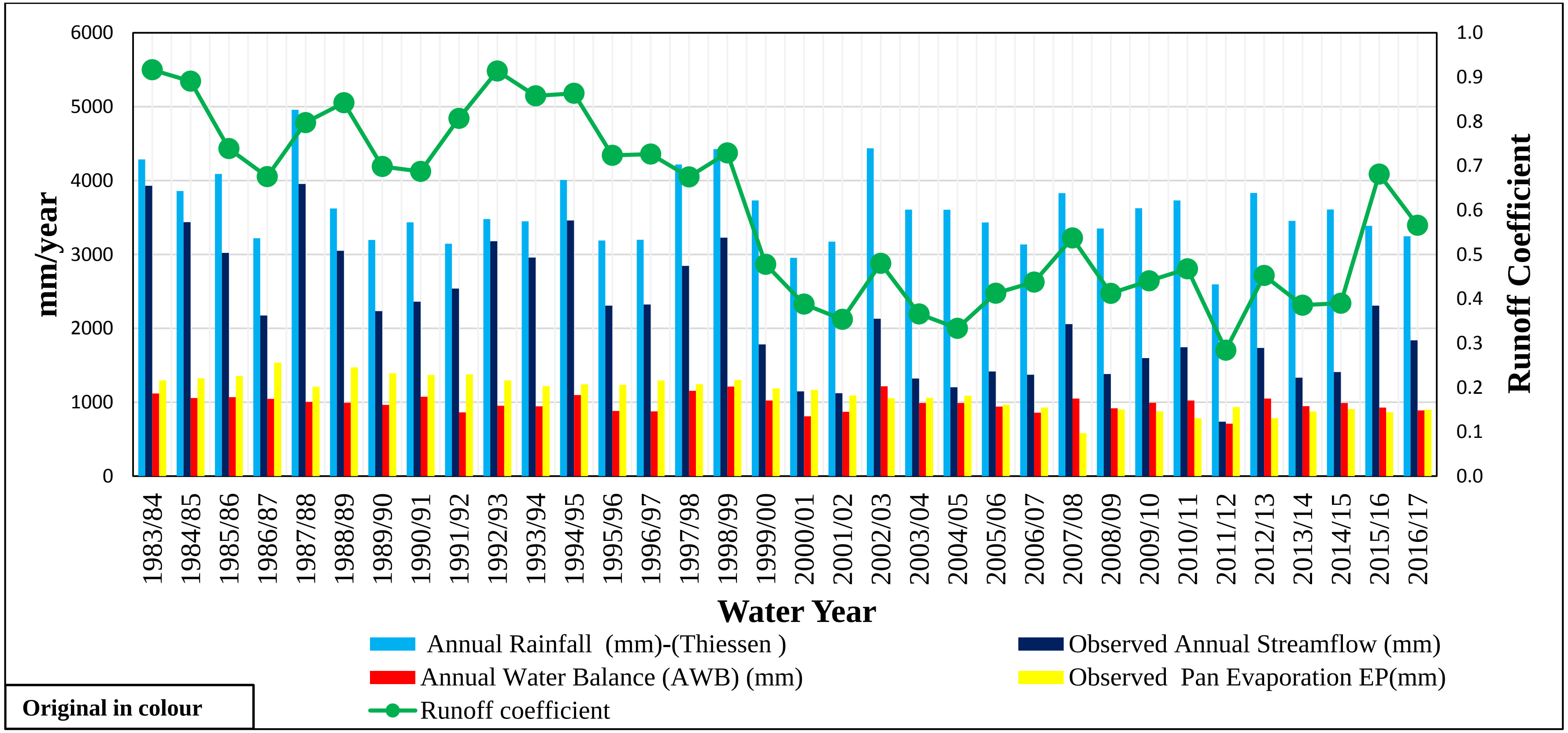


Figure B 1: Annual Water Balance and Runoff Coefficients for Ellagawa Watershed - (1983-2017)

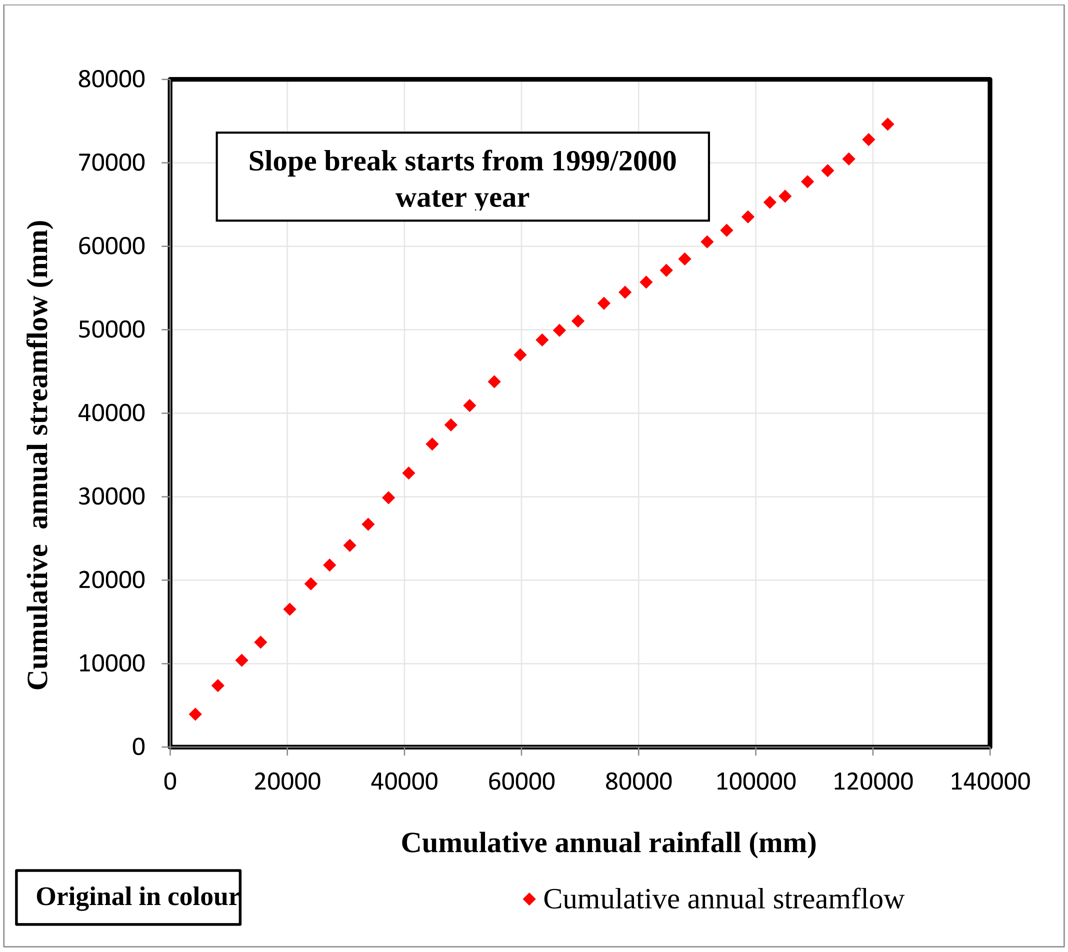
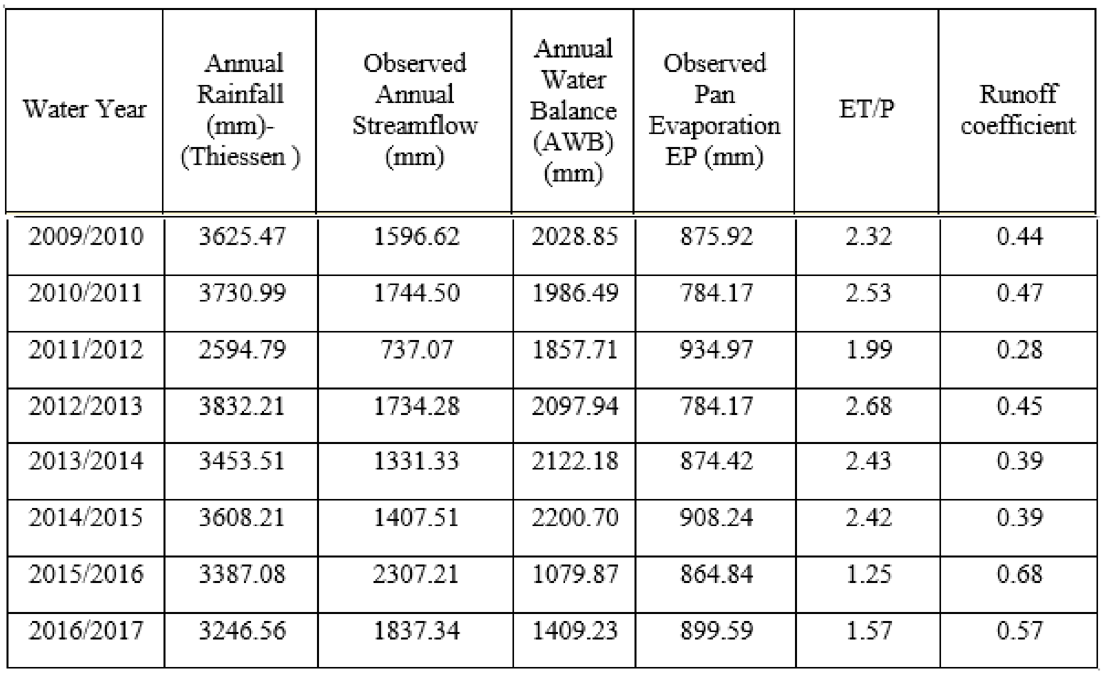


Figure B 2: Double Mass Curve for Ellagawa Watershed-(1983-2017)

Table B-1: Annual Water Balance-Ellagawa Watershed - (1983-2017)

Water Year	Annual Rainfall (mm)-(Thiessen)	Observed Annual Streamflow (mm)	Annual Water Balance (AWB) (mm)	Observed Pan Evaporation EP (mm)	ET/P	Runoff coefficient
1983/1984	4286.62	3928.72	357.91	1295.17	0.28	0.92
1984/1985	3857.82	3436.29	421.53	1324.98	0.32	0.89
1985/1986	4090.04	3021.54	1068.50	1354.35	0.79	0.74
1986/1987	3219.57	2174.60	1044.97	1536.65	0.68	0.68
1987/1988	4957.27	3953.14	1004.13	1210.42	0.83	0.80
1988/1989	3621.82	3050.13	571.70	1472.07	0.39	0.84
1989/1990	3197.08	2232.49	964.59	1393.24	0.69	0.70
1990/1991	3434.14	2360.05	1074.09	1368.48	0.78	0.69
1991/1992	3145.51	2538.23	607.28	1377.94	0.44	0.81
1992/1993	3479.12	3179.50	299.62	1296.62	0.23	0.91
1993/1994	3448.13	2957.30	490.83	1218.11	0.40	0.86
1994/1995	4007.92	3460.55	547.37	1243.15	0.44	0.86
1995/1996	3188.56	2306.81	881.75	1235.48	0.71	0.72
1996/1997	3198.59	2323.31	875.27	1294.88	0.68	0.73
1997/1998	4217.05	2846.29	1370.76	1244.13	1.10	0.67
1998/1999	4425.82	3226.61	1199.20	1301.87	0.92	0.73
1999/2000	3730.46	1782.59	1947.86	1186.61	1.64	0.48
2000/2001	2954.61	1146.50	1808.11	1165.20	1.55	0.39
2001/2002	3174.50	1122.65	2051.85	1090.86	1.88	0.35
2002/2003	4437.45	2129.06	2308.39	1054.20	2.19	0.48
2003/2004	3607.66	1319.96	2287.71	1058.56	2.16	0.37
2004/2005	3604.74	1201.89	2402.85	1087.77	2.21	0.33
2005/2006	3433.22	1416.06	2017.16	964.89	2.09	0.41
2006/2007	3135.80	1372.77	1763.03	929.53	1.90	0.44
2007/2008	3829.26	2056.84	1772.42	581.51	3.05	0.54
2008/2009	3350.61	1381.43	1969.18	902.41	2.18	0.41



Water Year	Annual Rainfall (mm)-(Thiessen)	Observed Annual Streamflow (mm)	Annual Water Balance (AWB) (mm)	Observed Pan Evaporation EP (mm)	ET/P	Runoff coefficient
2009/2010	3625.47	1596.62	2028.85	875.92	2.32	0.44
2010/2011	3730.99	1744.50	1986.49	784.17	2.53	0.47
2011/2012	2594.79	737.07	1857.71	934.97	1.99	0.28
2012/2013	3832.21	1734.28	2097.94	784.17	2.68	0.45
2013/2014	3453.51	1331.33	2122.18	874.42	2.43	0.39
2014/2015	3608.21	1407.51	2200.70	908.24	2.42	0.39
2015/2016	3387.08	2307.21	1079.87	864.84	1.25	0.68
2016/2017	3246.56	1837.34	1409.23	899.59	1.57	0.57

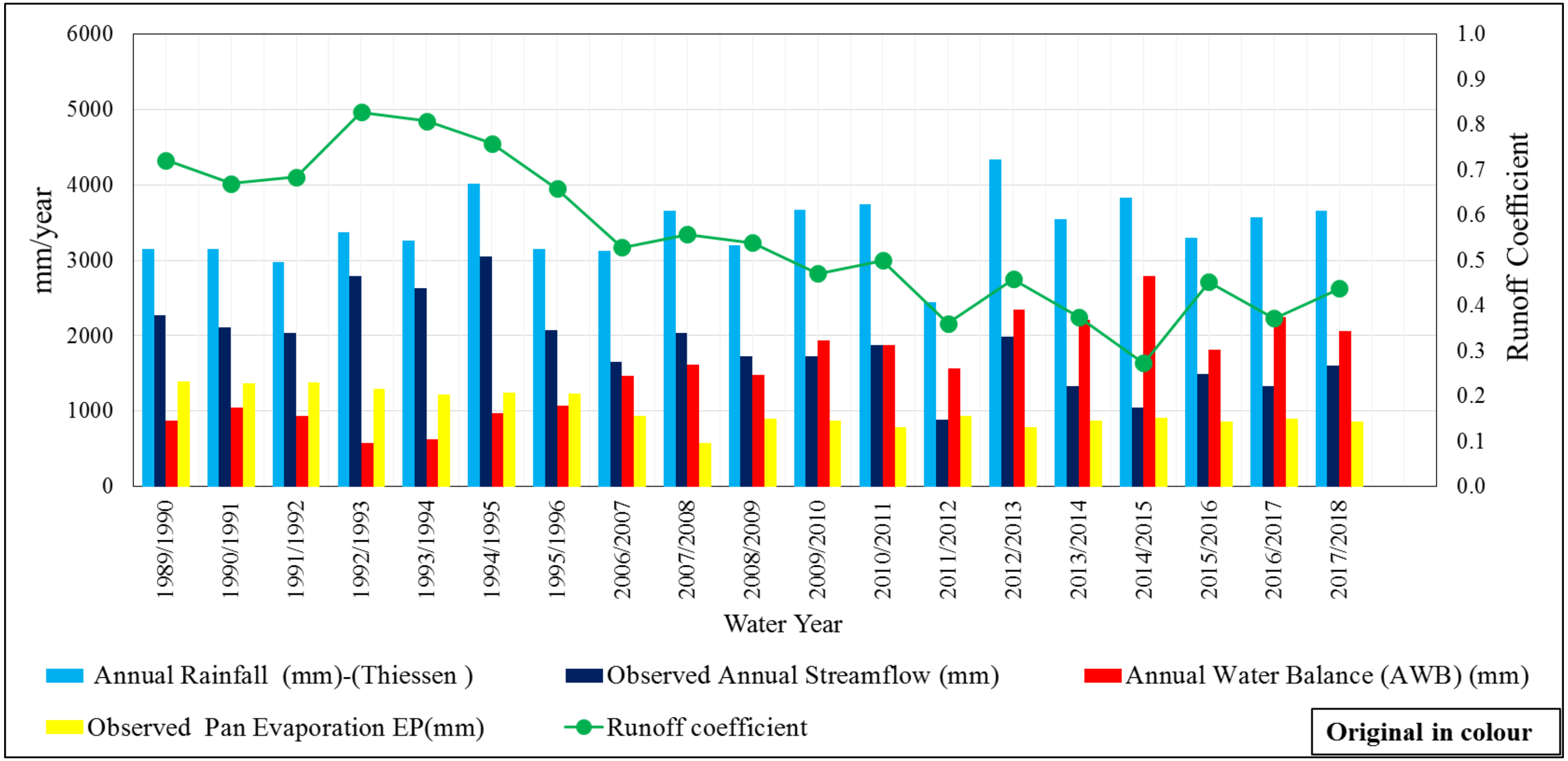


Figure B-3: Annual Water Balance and Runoff Coefficients for Rathnapura Watershed - (1989-2018)

Table B-2: Annual Water Balance-Rathnapura Watershed - (1989-2018)

Water Year	Annual Rainfall (mm)-(Thiessen)	Observed Annual Streamflow (mm)	Annual Water Balance (AWB) (mm)	Observed Pan Evaporation EP(mm)	ET/P	Runoff coefficient
1989/1990	3153.09	2276.89	876.20	1393.24	0.44	0.72
1990/1991	3156.19	2113.85	1042.34	1368.48	0.43	0.67
1991/1992	2975.77	2036.45	939.32	1377.94	0.46	0.68
1992/1993	3371.26	2790.30	580.96	1296.62	0.38	0.83
1993/1994	3260.14	2635.74	624.40	1218.11	0.37	0.81
1994/1995	4023.23	3055.01	968.22	1243.15	0.31	0.76
1995/1996	3146.70	2072.09	1074.60	1235.48	0.39	0.66
2006/2007	3121.24	1649.50	1471.74	929.53	0.30	0.53
2007/2008	3659.69	2040.32	1619.37	581.51	0.16	0.56
2008/2009	3202.07	1727.51	1474.56	902.41	0.28	0.54
2009/2010	3667.54	1728.92	1938.63	875.92	0.24	0.47
2010/2011	3748.73	1876.00	1872.73	784.17	0.21	0.50
2011/2012	2445.69	880.94	1564.75	934.97	0.38	0.36
2012/2013	4334.16	1987.02	2347.14	784.17	0.18	0.46
2013/2014	3544.85	1328.30	2216.55	874.42	0.25	0.37
2014/2015	3836.16	1047.32	2788.85	908.24	0.24	0.27
2015/2016	3304.99	1494.27	1810.72	864.84	0.26	0.45
2016/2017	3577.55	1332.48	2245.06	899.59	0.25	0.37
2017/2018	3661.50	1603.44	2058.05	863.72	0.24	0.44

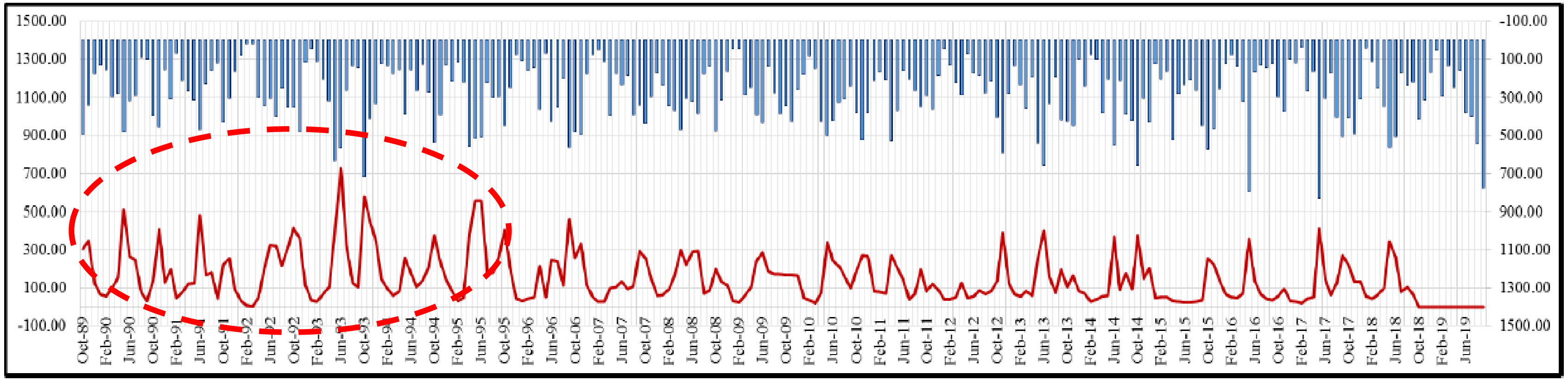


Figure B-4: Streamflow variation with rainfall of Rathnapura Watershed - (1989-2018)

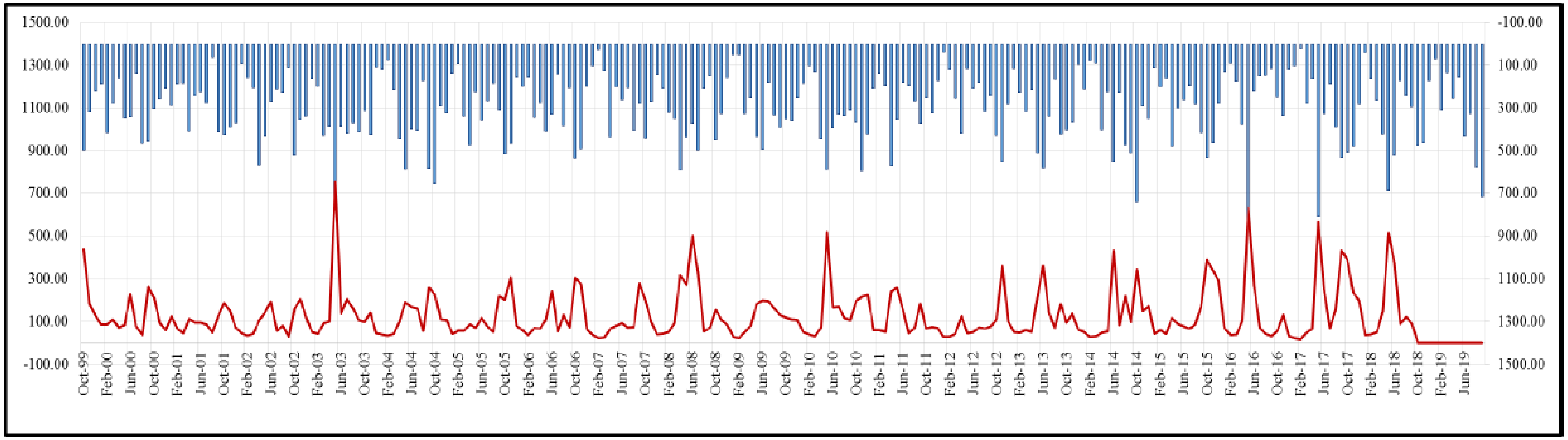


Figure B-5: Streamflow variation with rainfall - Ellagawa Watershed - (1999-2018)

APPENDIX C – ANALYSIS & RESULTS

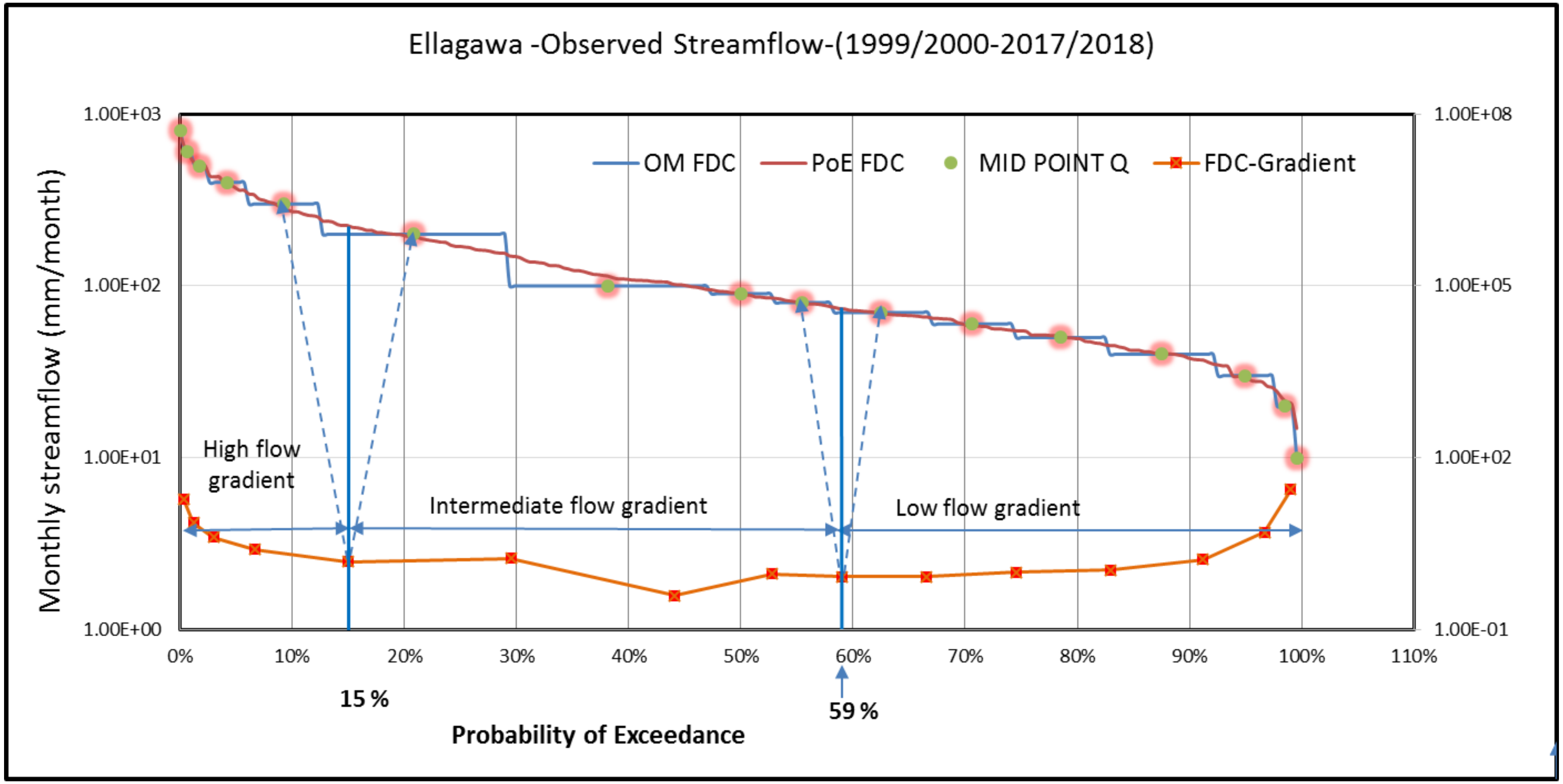


Figure C-1: Threshold values Determinations for Different Flow Regimes using order of magnitude FDC - Ellagawa Watershed

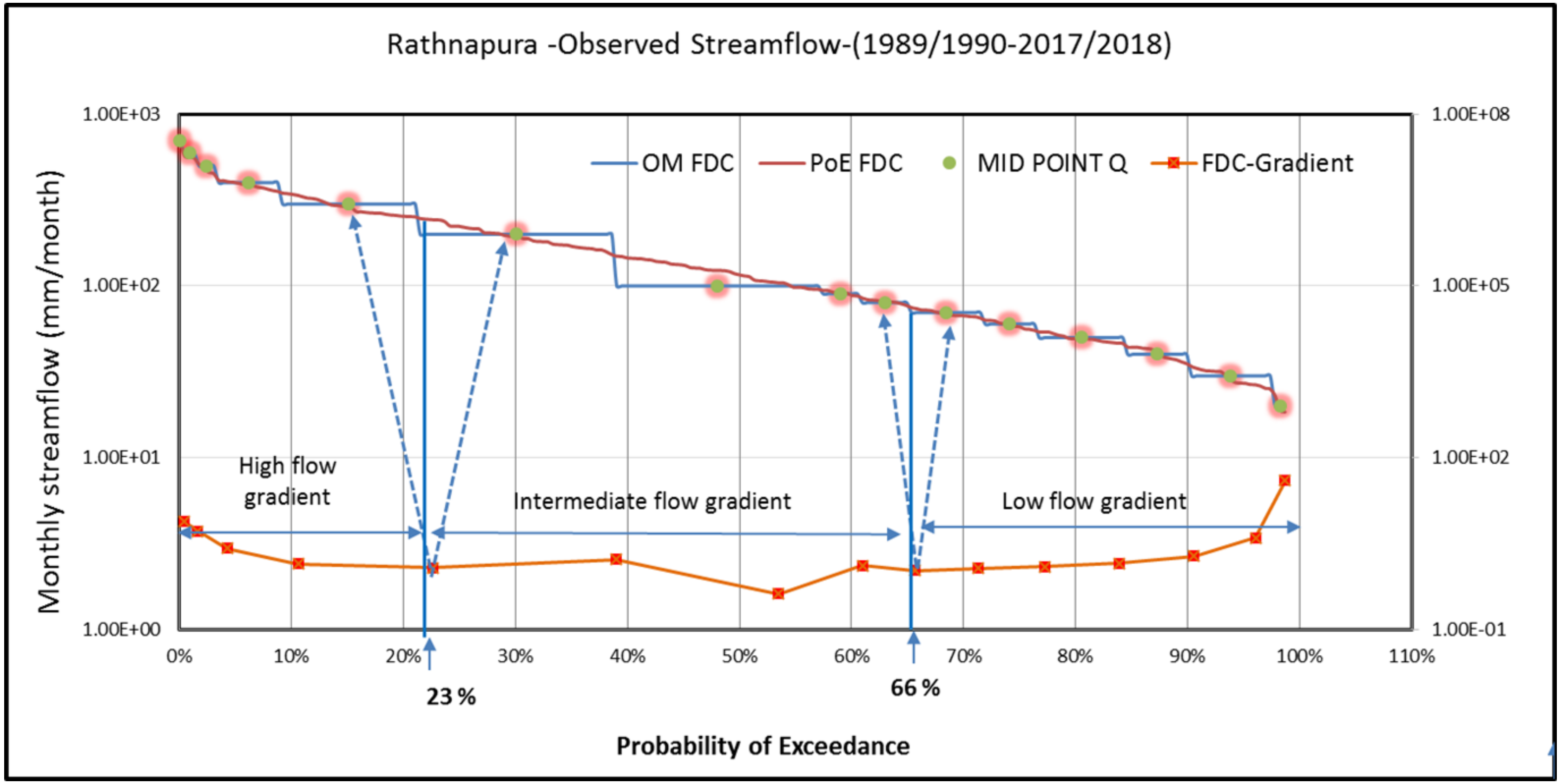


Figure C-2: Threshold values Determinations for Different Flow Regimes using order of magnitude FDC - Rathnapura Watershed

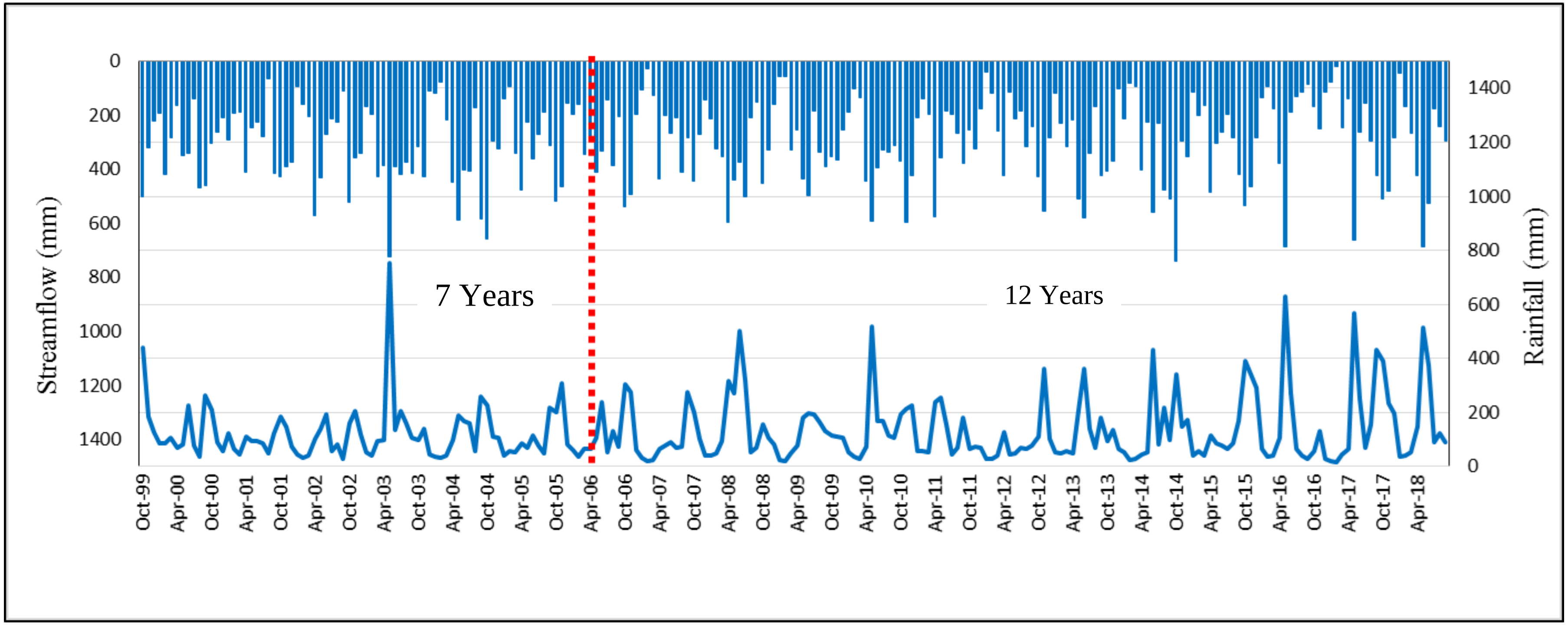


Figure C-3: Calibration (7 Years) and Validation (12 Years) Data Duration - Ellagawa Watershed

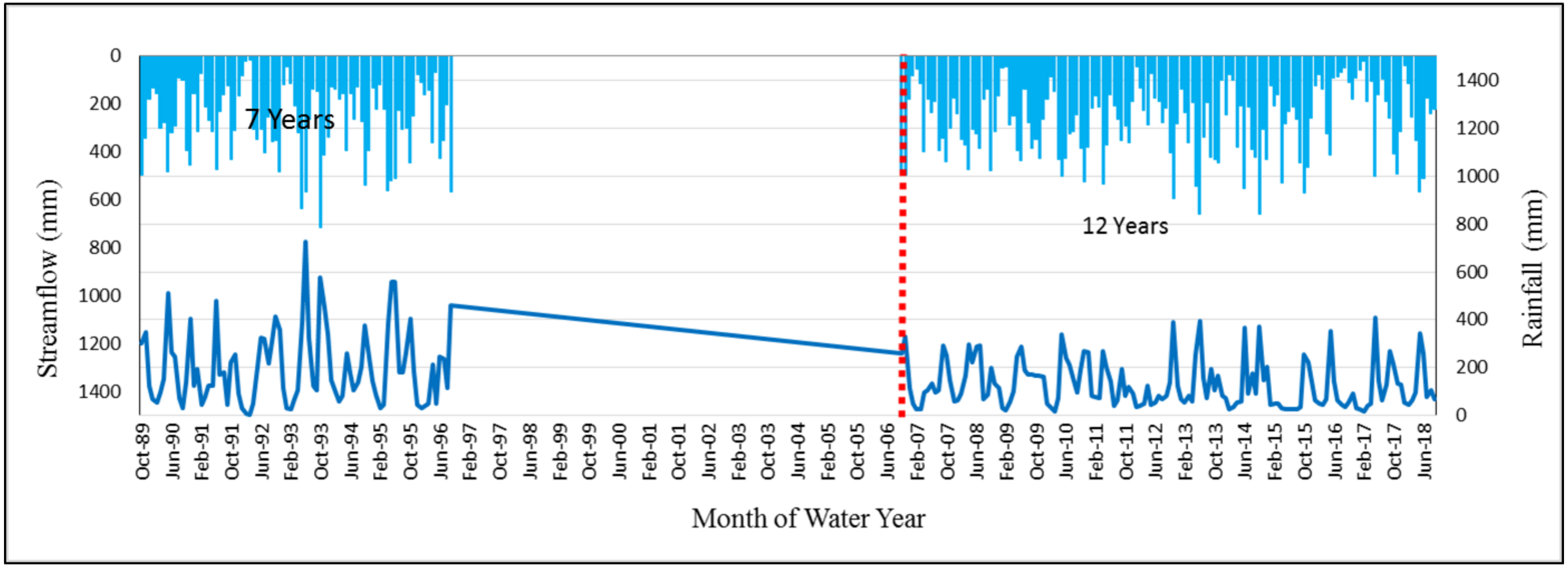


Figure C-4: Calibration (7 Years) and Validation (12 Years) Data Duration – Rathnapura Watershed

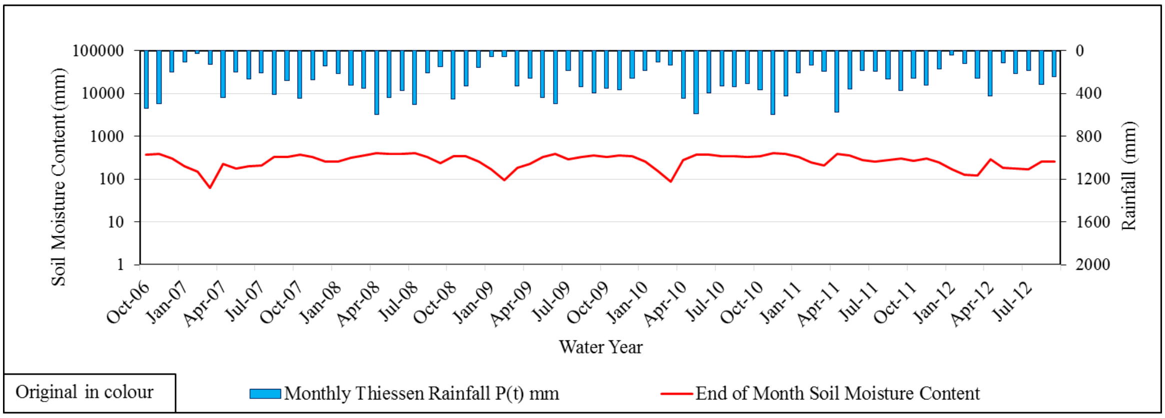


Figure C-5: Soil Moisture Variation during Calibration – Ellagawa Watershed (2006/2007 – 2011/2012)

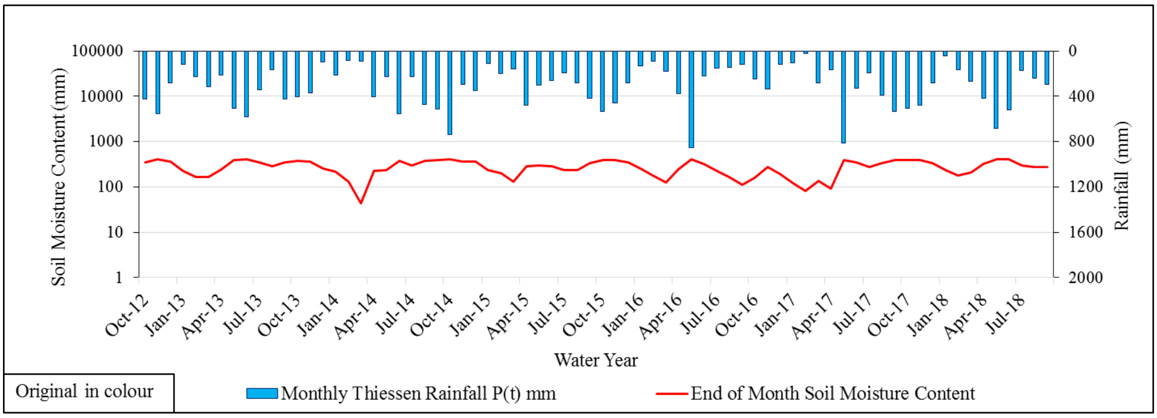


Figure C-6: Soil Moisture Variation during Calibration – Ellagawa Watershed (2011/2012 – 2017/2018)

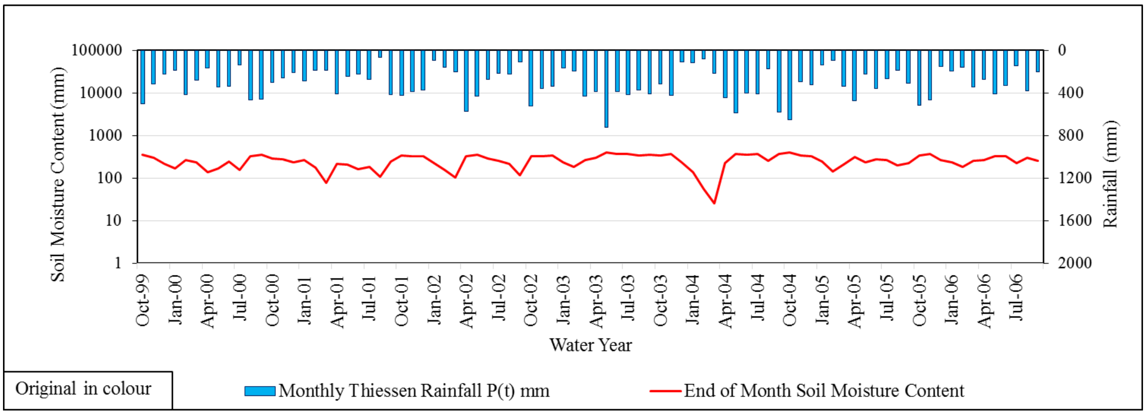


Figure C-7: Soil Moisture Variation during Verification – Ellagawa Watershed (1999/2000 – 2005/2006)

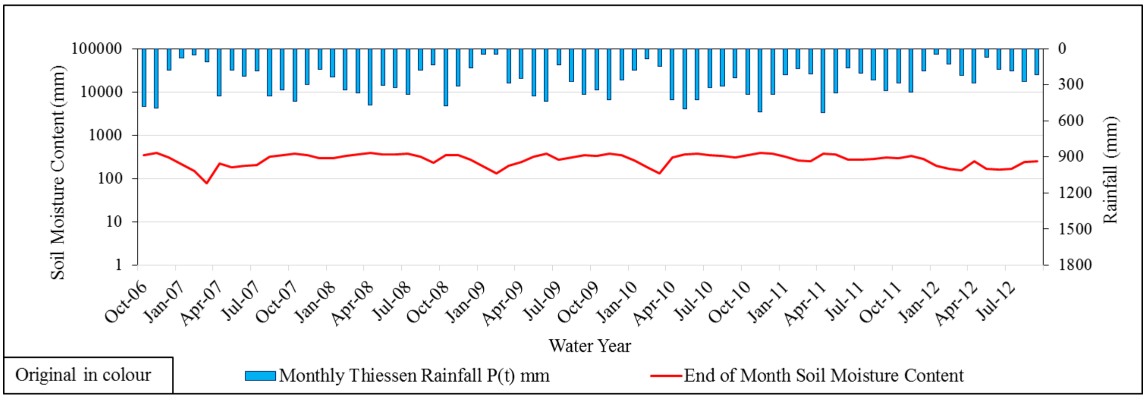


Figure C-8: Soil Moisture Variation during Calibration– Rathnapura Watershed (2006/2007 – 2011/2012**)**

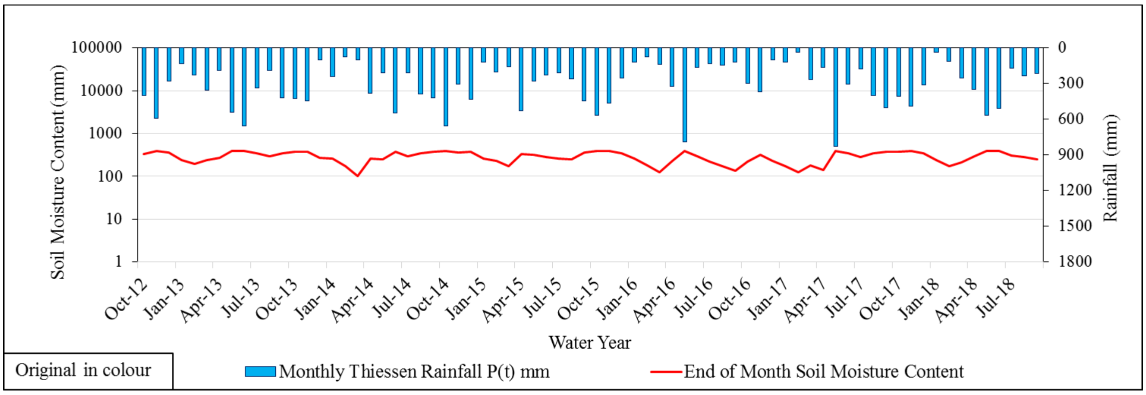


Figure C-9: Soil Moisture Variation during Calibration– Rathnapura Watershed (2011/2012 – 2017/2018)

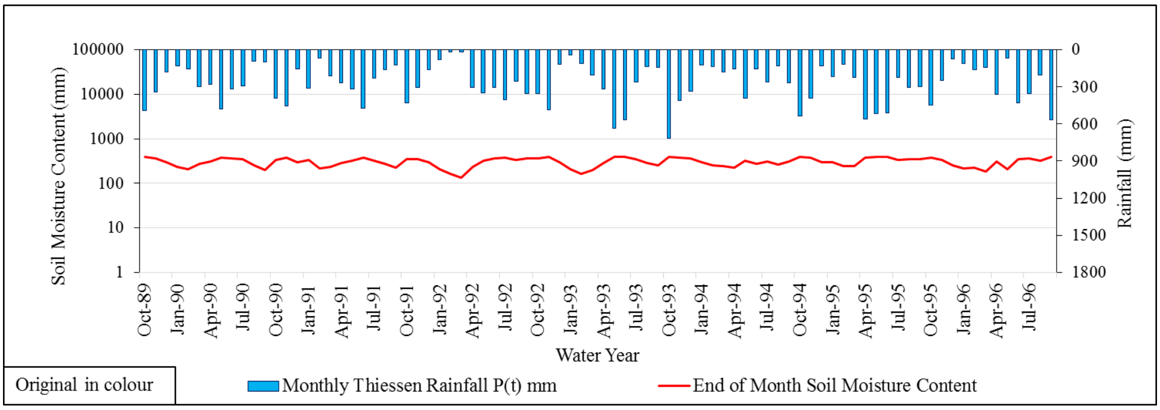


Figure C-10: Soil Moisture Variation during Calibration– Rathnapura Watershed (2011/2012 – 2017/2018)

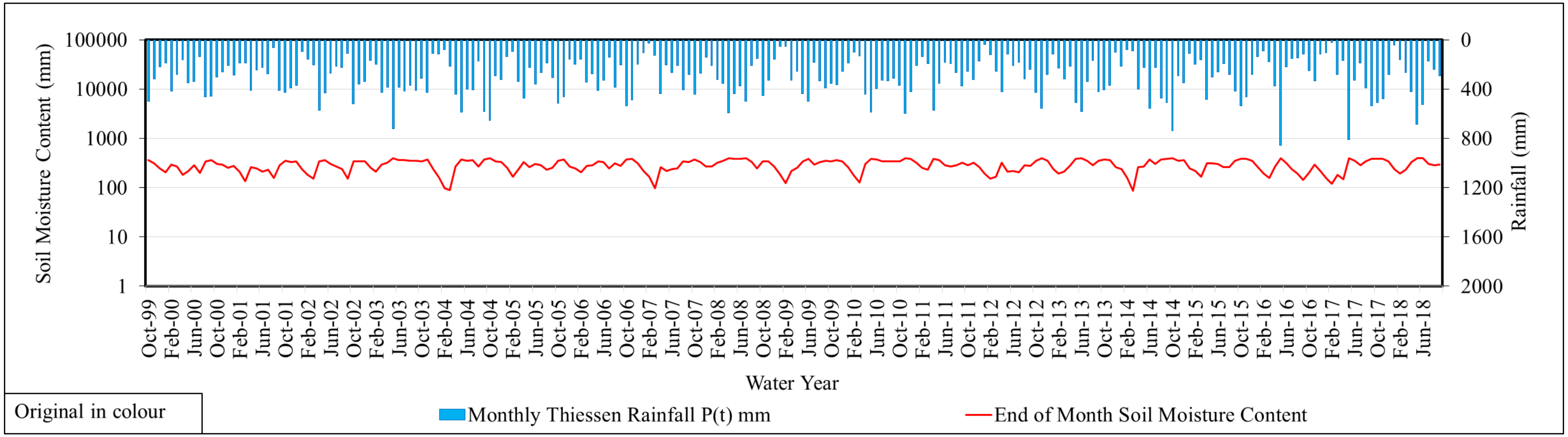


Figure C-11: Soil Moisture Variation during Transferability Option 3 - Ellagawa Watershed

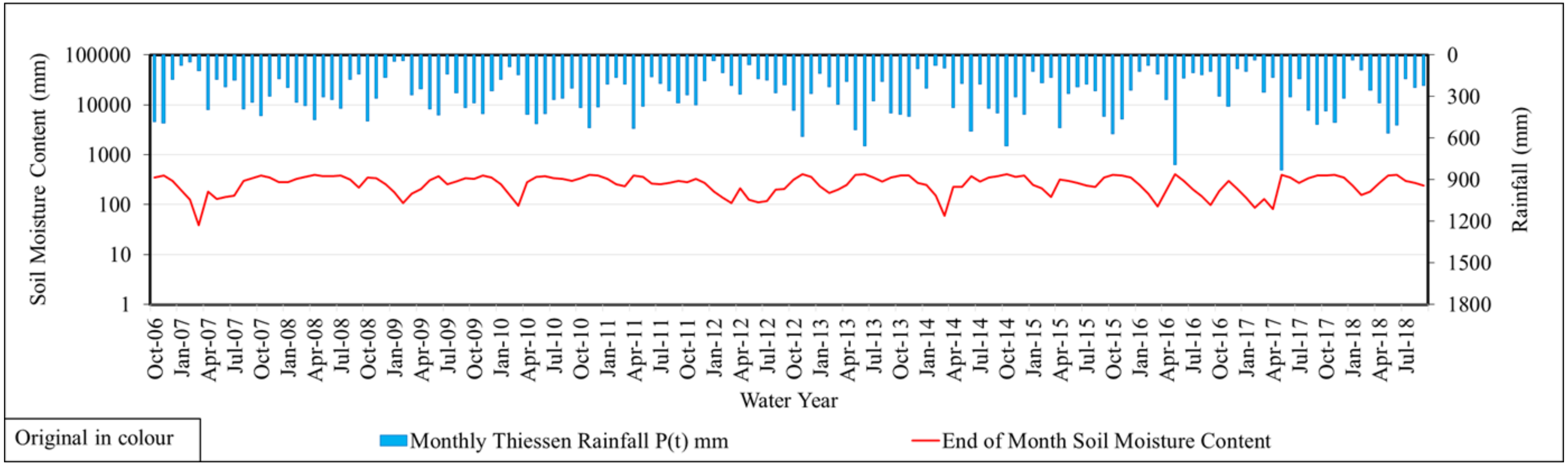


Figure C-12: Soil Moisture Variation during Transferability Option 3 - Rathnapura Watershed

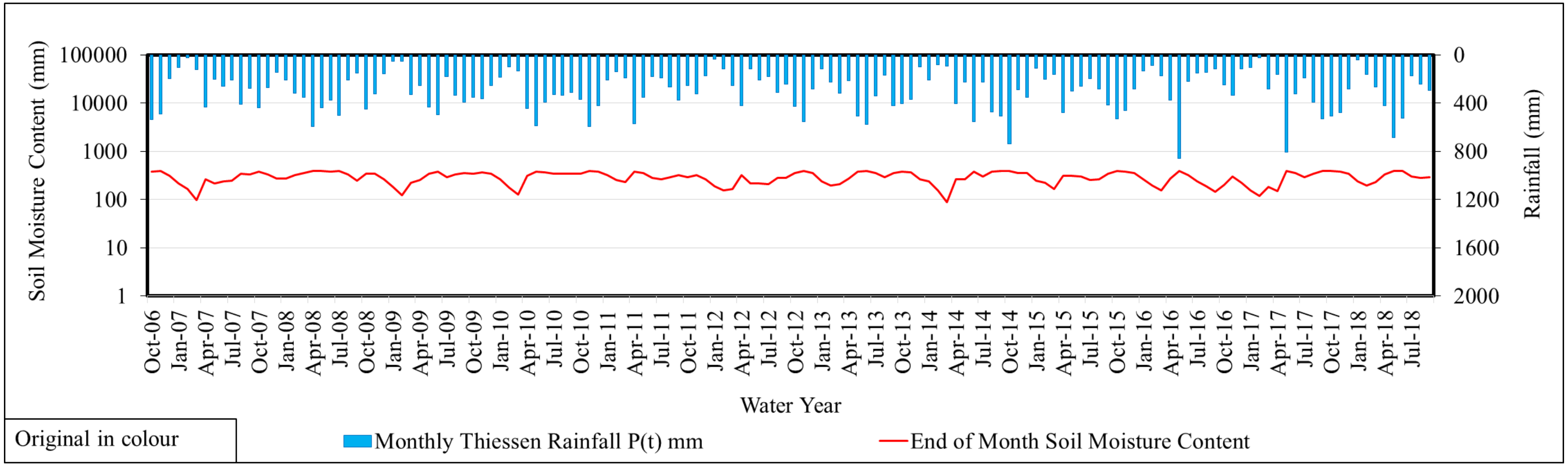


Figure C-13: Soil Moisture Variation during Transferability Option 3 - Ellagawa Watershed

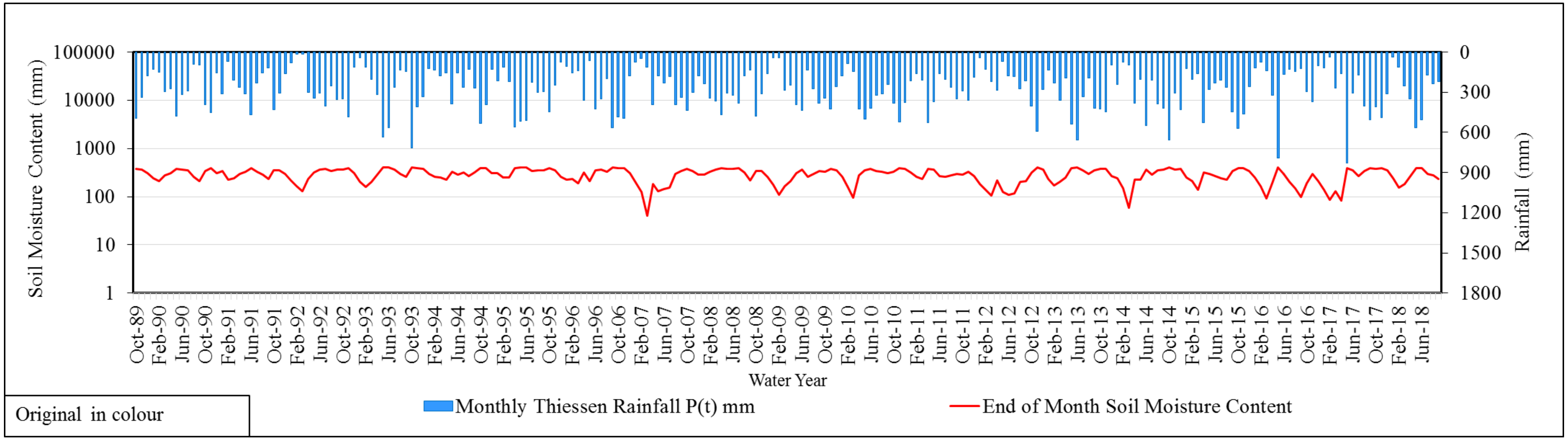


Figure C-14: Soil Moisture Variation during Transferability Option 3 - Rathnapura Watershed

Table C 1: Differences in Water Quantity for Transferability Option 3 – Rathnapura Watershed

Year	|Qo-Qs| (mm)											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1989										38.23	117.40	2.39
1990	5.44	8.50	7.45	24.69	224.60	27.18	43.17	3.04	8.88	29.84	110.80	6.36
1991	29.09	4.76	17.55	14.82	26.83	152.48	6.76	84.31	11.14	16.77	57.77	21.88
1992	14.65	16.10	11.71	8.94	60.14	93.85	43.73	36.96	74.75	183.31	1.32	0.85
1993	6.59	3.60	27.52	6.31	34.30	261.83	102.84	17.34	27.44	104.09	116.39	73.43
1994	30.52	23.61	6.63	28.51	98.30	77.05	27.88	59.64	70.74	19.76	64.47	22.27
1995	31.64	32.97	22.13	63.52	178.06	141.74	0.18	26.40	65.20	91.14	7.78	28.28
1996	20.30	14.52	15.58	78.54	6.11	44.87	2.96	33.85	78.02			
2006										43.11	7.43	0.99
2007	13.82	13.89	24.99	67.19	93.21	115.57	75.33	6.55	117.98	37.41	33.97	38.46
2008	32.62	64.90	64.40	71.54	30.95	37.08	9.09	65.34	38.85	17.39	31.81	40.98
2009	4.85	13.33	35.17	58.48	120.16	49.52	113.72	66.15	1.36	22.44	103.84	28.68
2010	23.23	14.42	11.43	17.07	134.69	13.55	38.25	5.12	22.15	25.05	78.05	3.23
2011	61.95	4.72	17.11	5.10	16.81	61.88	31.54	21.69	85.97	14.86	31.90	8.84
2012	6.42	22.44	40.19	78.58	33.49	45.25	73.81	28.33	38.39	5.22	41.49	96.41
2013	11.97	28.08	42.87	8.55	74.05	174.21	41.08	35.02	0.45	180.29	124.96	2.61
2014	8.26	7.34	35.46	4.90	6.09	133.52	8.06	12.77	146.84	119.56	74.48	76.38
2015	19.93	8.58	32.05	99.60	87.52	60.11	35.23	23.24	146.76	108.04	91.28	38.10
2016	0.21	24.42	39.42	35.06	86.82	34.46	25.39	25.00	29.64	23.59	24.61	10.59
2017	10.73	13.09	28.77	44.28	63.76	45.70	20.17	43.48	34.10	62.80	186.20	61.65
2018	7.44	21.71	31.98	11.86	50.90	95.64	32.12	19.20	7.99			
Average (mm)	17.88	17.95	26.97	38.29	75.09	87.66	38.49	32.29	52.98	60.15	68.73	29.60
Average (m3/s)	129.85	130.36	195.89	278.14	545.45	636.70	279.58	234.51	384.84	436.92	499.26	214.99
Maha Season (mm)	17.88	17.95	26.97							60.15	68.73	29.60
Yala Season (mm)				38.29	75.09	87.66	38.49	32.29	52.98			

Table C 2: Error Percentages in Seasonal Flows for Transferability Option 3 – Rathnapura Watershed

Year	Seasonal Flow (Qs)(mm)		Seasonal Flow (Qo) (mm)		% Error (Maha	% Error (Yala)
	Yala	Maha	Yala	Maha		
1989		815.23		994.64	18%	
1990	974.53	860.12	1282.25	989.32	13%	24%
1991	904.12	601.58	1124.53	611.77	2%	20%
1992	1124.18	808.29	1424.68	1016.61	20%	21%
1993	1392.23	1327.18	1773.70	1668.59	20%	22%
1994	660.78	1038.35	967.15	929.16	12%	32%
1995	1703.55	715.68	2125.85	751.51	5%	20%
1996	1149.85		1320.58			13%
2006		810.78		811.94	0%	
2007	374.83	1053.88	837.56	782.12	35%	55%
2008	1359.20	480.75	1258.20	560.66	14%	8%
2009	757.47	707.79	1166.85	600.33	18%	35%
2010	1003.29	1053.18	1128.58	956.83	10%	11%
2011	846.47	390.67	919.17	421.80	7%	8%
2012	161.31	902.37	459.14	852.61	6%	65%
2013	1467.77	745.44	1134.41	488.63	53%	29%
2014	862.84	1124.08	839.67	874.37	29%	3%
2015	625.42	954.51	172.95	780.72	22%	262%
2016	650.82	227.84	713.55	268.82	15%	9%
2017	1099.07	910.43	1063.66	646.03	41%	3%
2018	995.22		957.42			4%
Average (% Error)					**18%**	**34%**

Table C 3: Differences in Water Quantity for Transferability Option 2 – Rathnapura Watershed

Year	|Qo-Qs| (mm)											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2006										77.21	27.69	2.69
2007	14.79	14.29	25.08	67.66	93.43	115.77	75.50	6.25	118.15	37.34	33.96	38.46
2008	32.61	64.90	64.40	71.54	30.95	37.08	9.09	65.34	38.85	17.39	31.81	40.98
2009	4.85	13.33	35.17	58.48	120.16	49.52	113.72	66.15	1.36	22.44	103.84	28.68
2010	23.23	14.42	11.43	17.07	134.69	13.55	38.25	5.12	22.15	25.05	78.05	3.23
2011	61.95	4.72	17.11	5.10	16.81	61.88	31.54	21.69	85.97	14.86	31.90	8.84
2012	6.42	22.44	40.19	78.58	33.49	45.25	73.81	28.33	38.39	5.22	41.49	96.41
2013	11.97	28.08	42.87	8.55	74.05	174.21	41.08	35.02	0.45	180.29	124.96	2.61
2014	8.26	7.34	35.46	4.90	6.09	133.52	8.06	12.77	146.84	119.56	74.48	76.38
2015	19.93	8.58	32.05	99.60	87.52	60.11	35.23	23.24	146.76	108.04	91.28	38.10
2016	0.21	24.42	39.42	35.06	86.82	34.46	25.39	25.00	29.64	23.59	24.61	10.59
2017	10.73	13.09	28.77	44.28	63.76	45.70	20.17	43.48	34.10	62.80	186.20	61.65
2018	7.44	21.71	31.98	11.86	50.90	95.64	32.12	19.20	7.99			
Average (mm)	16.87	19.78	33.66	41.89	66.55	72.22	42.00	29.30	55.89	57.82	70.86	34.05
Average (m3/s)	122.51	143.65	244.51	304.28	483.43	524.60	305.05	212.82	405.94	419.95	514.68	247.33
Maha Season (mm)	16.87	19.78	33.66							57.82	70.86	34.05
Yala Season(mm)				41.89	66.55	72.22	42.00	29.30	55.89			

Table C 4: Error Percentages in Seasonal Flows for Transferability Option 2 – Rathnapura Watershed

Year	Seasonal Flow (Qs)(mm)		Seasonal Flow (Qo) (mm)		% Error (Maha	% Error (Yala)
	Yala	Maha	Yala	Maha		
2006/2007		650.20		811.94	20%	
2007/2008	373.30	1053.79	837.56	782.12	35%	55%
2008/2009	1359.20	480.75	1258.20	560.66	14%	8%
2009/2010	757.47	707.79	1166.85	600.33	18%	35%
2010/2011	1003.29	1053.18	1128.58	956.83	10%	11%
2011/2012	846.47	390.67	919.17	421.80	7%	8%
2012/2013	161.31	902.37	459.14	852.61	6%	65%
2013/2014	1467.77	745.44	1134.41	488.63	53%	29%
2014/2015	862.84	1124.08	839.67	874.37	29%	3%
2015/2016	625.42	954.51	172.95	780.72	22%	262%
2016/2017	650.82	227.84	713.55	268.82	15%	9%
2017/2018	1099.07	910.43	1063.66	646.03	41%	3%
2018	995.22		957.42			4%
Average % Error					**22%**	**41%**

Table C 5: Differences in Water Quantity for Transferability Option 3 – Ellagawa Watershed

Year	|Qo-Qs| (mm)											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1999										202.79	44.48	59.76
2000	42.22	26.92	22.15	38.05	30.50	123.57	37.28	151.68	10.82	86.21	25.04	14.04
2001	24.33	20.37	27.93	30.15	25.48	47.96	26.83	24.71	22.43	24.43	24.80	111.53
2002	16.18	1.14	20.02	96.15	104.62	69.89	30.35	15.69	6.53	31.28	19.29	80.59
2003	21.13	3.62	19.72	47.29	277.12	99.86	36.91	41.72	103.77	88.00	127.57	21.44
2004	13.63	26.39	35.70	8.26	109.86	51.45	83.96	32.62	32.09	230.82	81.06	61.06
2005	33.20	29.66	8.98	92.88	7.56	10.05	26.69	8.42	144.77	28.75	28.26	10.16
2006	8.99	9.10	29.03	40.68	79.11	67.58	13.97	4.79	20.27	33.61	70.90	76.39
2007	15.13	4.73	16.23	14.97	29.00	26.52	4.01	118.97	97.39	103.90	75.57	47.95
2008	46.42	100.18	131.43	174.71	108.00	183.44	105.64	116.33	2.24	45.30	86.79	4.50
2009	7.88	8.19	0.61	3.59	16.31	137.44	79.43	14.37	93.68	64.82	139.33	81.60
2010	32.62	6.85	15.93	57.79	193.78	108.16	29.68	75.61	75.08	3.10	230.71	100.30
2011	99.21	14.04	5.99	90.53	24.98	52.52	39.49	38.84	31.08	41.80	76.04	16.26
2012	8.41	6.71	15.62	24.62	1.66	1.48	27.16	38.90	21.19	103.48	87.79	127.43
2013	10.78	10.07	12.29	42.41	124.56	144.45	75.03	38.42	31.92	190.16	108.09	20.04
2014	10.53	3.51	23.81	35.65	31.06	139.00	43.41	65.26	258.94	279.29	71.74	58.73
2015	24.38	6.87	15.80	26.20	53.90	44.80	12.95	4.65	34.88	31.27	12.50	84.23
2016	16.58	0.91	16.86	14.64	13.80	124.45	4.14	4.25	10.90	16.07	15.51	22.86
2017	0.27	2.75	13.32	45.03	152.33	29.52	37.09	38.06	76.35	0.64	109.80	9.84
2018	25.88	1.74	6.26	22.26	30.35	29.21	34.64	17.69	23.88			
Average (mm)	24.09	14.94	23.04	47.68	74.42	78.49	39.40	44.79	57.80	84.51	75.54	53.09
Average (m3/s)	387.77	240.37	370.76	767.32	1197.73	1263.27	634.16	720.85	930.25	1360.17	1215.77	854.45
Maha Season (mm)	24.09	14.94	23.04							84.51	75.54	53.09
Yala Season (mm)				47.68	74.42	78.49	39.40	44.79	57.80			

Table C 6: Error Percentages in Seasonal Flows for Transferability Option 3 – Ellagawa Watershed

Year	Seasonal Flows Os (mm)		Seasonal Flows Oo (mm)		% Error (Yala)	% Error (Maha)
	Yala	Maha	Yala	Maha		
1999/2000		683.06		1027.53		34%
2000/2001	670.49	472.23	759.03	592.00	12%	20%
2001/2002	379.48	661.96	557.05	526.84	32%	26%
2002/2003	736.66	716.36	598.31	670.31	23%	7%
2003/2004	1417.12	760.82	1463.49	394.87	3%	93%
2004/2005	946.47	1201.12	928.03	590.13	2%	104%
2005/2006	604.98	787.55	614.43	751.79	2%	5%
2006/2007	761.37	921.91	667.42	718.85	14%	28%
2007/2008	462.12	987.26	656.97	525.97	30%	88%
2008/2009	2009.09	594.35	1535.45	438.87	31%	35%
2009/2010	950.93	958.75	945.63	452.56	1%	112%
2010/2011	1130.96	1380.52	1147.61	802.07	1%	72%
2011/2012	913.41	550.39	946.31	305.00	3%	80%
2012/2013	418.04	1089.29	433.72	729.29	4%	49%
2013/2014	1300.82	908.33	1008.85	401.83	29%	126%
2014/2015	877.13	1548.78	932.89	806.53	6%	92%
2015/2016	590.79	1218.59	600.99	1163.51	2%	5%
2016/2017	974.96	261.25	1143.70	299.93	15%	13%
2017/2018	988.20	1379.05	1537.41	953.29	36%	45%
2018	1341.40		1334.16		1%	
Average (% Error)					**13%**	**54.36%**

Table C 7: Differences in Water Quantity for Transferability Option 2 – Ellagawa Watershed

Year	|Qo-Qs| (mm)											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2006										19.57	73.97	76.66
2007	15.20	4.76	16.22	15.00	28.98	26.51	4.00	118.98	97.38	103.90	75.57	47.95
2008	46.42	100.18	131.43	174.71	108.00	183.44	105.64	116.33	2.24	45.30	86.79	4.50
2009	7.88	8.19	0.61	3.59	16.31	137.44	79.43	14.37	93.68	64.82	139.33	81.60
2010	32.62	6.85	15.93	57.79	193.78	108.16	29.68	75.61	75.08	3.10	230.71	100.30
2011	99.21	14.04	5.99	90.53	24.98	52.52	39.49	38.84	31.08	41.80	76.04	16.26
2012	8.41	6.71	15.62	24.62	1.66	1.48	27.16	38.90	21.19	103.48	87.79	127.43
2013	10.78	10.07	12.29	42.41	124.56	144.45	75.03	38.42	31.92	190.16	108.09	20.04
2014	10.53	3.51	23.81	35.65	31.06	139.00	43.41	65.26	258.94	279.29	71.74	58.73
2015	24.38	6.87	15.80	26.20	53.90	44.80	12.95	4.65	34.88	31.27	12.50	84.23
2016	16.58	0.91	16.86	14.64	13.80	124.45	4.14	4.25	10.90	16.07	15.51	22.86
2017	0.27	2.75	13.32	45.03	152.33	29.52	37.09	38.06	76.35	0.64	109.80	9.84
2018	25.88	1.74	6.26	22.26	30.35	29.21	34.64	17.69	23.88			
Average (mm)	24.85	13.88	22.85	46.03	64.98	85.08	41.05	47.61	63.13	74.95	90.65	54.20
Average (m3/s)	399.90	223.43	367.69	740.90	1045.74	1369.32	660.75	766.31	1015.98	1206.30	1458.99	872.32
Maha Season (mm)										74.95	90.65	54.20
Yala Season (mm)	24.85	13.88	22.85	46.03	64.98	85.08	41.05	47.61	63.13			

Table C 8: Error Percentages in Seasonal Flows for Transferability Option 2 – Ellagawa Watershed

Year	Seasonal Flows Os (mm)		Seasonal Flows Oo (mm)		% Error (Yala)	% Error (Maha)
	Yala	Maha	Yala	Maha		
2006/2007		853.64		921.91		7%
2007/2008	634.07	1031.44	462.12	987.26	37%	4%
2008/2009	1854.45	575.75	2009.09	594.35	8%	3%
2009/2010	1124.41	748.15	950.93	958.75	18%	22%
2010/2011	1300.14	1255.43	1130.96	1380.52	15%	9%
2011/2012	1006.59	425.18	913.41	550.39	10%	23%
2012/2013	491.45	1036.40	418.04	1089.29	18%	5%
2013/2014	1465.64	703.34	1300.82	908.33	13%	23%
2014/2015	1228.20	1218.00	877.13	1548.78	40%	21%
2015/2016	769.06	1036.14	590.79	1218.59	30%	15%
2016/2017	971.52	275.40	974.96	261.25	0%	5%
2017/2018	1309.32	1083.00	988.20	1379.05	32%	21%
2018	1396.11		1341.40		4%	
Average % Error					**18.81%**	**13.29%**