# EVALUATION OF TANK MODEL PARAMETERS FOR SPATIAL TRANSFERABILITY WITHIN KALU RIVER BASIN OF SRI LANKA

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Supervised by

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Thesis submitted in partial fulfilment of the requirements for the degree of Master of Science in Water Resources Engineering and Management


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September 2019

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Syed Mustafa Hedait Date

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

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Professor N.T.S. Wijesekera Date

# EVALUATION OF TANK MODEL PARAMETERS FOR SPATIAL TRANSFERABILITY WITHIN KALU RIVER BASIN OF SRI LANKA


## ABSTRACT

Increasing population, varying climatic condition, and water crisis necessitate water resource planning and development. Incorporating the subwatershed management approach leads to viable options when making decisions on water resources planning and development. Meanwhile, the approach needs streamflow management by incorporating spatial variability of characteristics which requires a hydrologic model and estimation of parameters with gauged data. However, due to non-availability of gauged streamflow at the subwatershed level hinders the estimation of model parameters for each subwatershed. Therefore, it's necessary to identify a suitable lumped model and evaluate the transferability of model parameters for streamflow estimation, which could provide important insights to support the planning and development of watershed management in a distributed manner.

In this study, first, an extensive review was conducted on lumped conceptual hydrologic models to support and facilitate the information for choosing a suitable lumped model for the study. Secondly, the model calibrated and validated using eight years of daily input data from 2009/2010 to 2016/2017, using a semi-automatic calibration method for Ellagawa main and Ratnapura subwatershed of Ellagawa. Hereafter, the calibrated and validated parameters for both watersheds were compared to find out the variation and similarities of parameters. Then, the calibrated parameters for Ellagawa main watershed transferred to Ratnapura and from Ratnapura to Ellagwa watershed, and the applicability of the parameters transfer evaluated in the main and subwatershed for streamflow estimation.

Attribute ranks, of the assessment, revealed that the Tank model with having 4.2 scores got high ranks in the shortlisted 4 models. The model successfully calibrated with the MRAE values of 0.450 for Ellagawa and 0.415 for Ratnapura watershed. The calibrated parameters verified with the MRAE values of 0.452 and 0.361 for Ellagawa and Ratnapura watershed respectively. When the calibrated parameters for Ellagawa transferred to Ratnapura and from Ratnapura to Ellagawa for the data period from 2009/2010 to 2016/2017 which was same for both watersheds, the transferred parameters to Ratnapura simulated the overall streamflow of the watershed with significant MRAE value of 0.445, while transferred parameters of Ratnapura to Ellagawa, showed a decline in the model performance with the MRAE value of 0.551.

Findings of the study revealed that the Tank model is the right lumped conceptual model for the transferability of parameters across the scale in a watershed. In the first case of parameter transfer of the model from main to subwatershed the transferred parameters estimated the subwatershed response with a high level of accuracy. Similarly, the calibrated parameters of the subwatershed estimated the behavior of the main watershed satisfactorily, while, compared to the first case the model showed a significant decline in the performance. This indicates the applicability of a calibrated lumped model of the main or subwatershed to other ungauged sub or main watershed for streamflow estimation to achieve the objective of subwatershed management and accurately make the decisions on water resources planning and management.



**Keywords:** Subwatershed Management, Parameter Transferability, Lumped Modeling

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# EVALUATION OF TANK MODEL PARAMETERS FOR SPATIAL TRANSFERABILITY WITHIN KALU RIVER BASIN OF SRI LANKA

## 1 INTRODUCTION

### 1.1 Overview

Increasing population, varying climatic conditions, and water crisis necessitate water resources planning and management. If these vital resources mange in an efficient and equitable way would play a substantial role in the supporting and resilience of the ecosystem. The health and well-being of artificial and natural ecosystems are really dependent on the efficient and sustainable management of water-related issues such as lack of sanitation, depletion of water for cultivation, and controlling of damages associated with hydrological extremes linked to floods and droughts. Besides, water resources in many regions of the world are stated as under stress due to dynamic climate patterns. It's also important to know the dynamics and availability of water for drinking, irrigation, hydropower generation, etc. in a watershed. Therefore, proper management of Water resources ensuring water security and can be a primary target of a social development that will embrace the entire society (Cosgrove & Loucks, 2007; Frone & Frone, 2015).

However, the process of management and development of these vital resources is challenging due to the spatial and temporal variation of water-related problems. Most of the time these problems vary very significantly from one area to another, sometimes even within a watershed and from one season to another (Biswas, 2008). It's also difficult to manage water resources problems over a large area of the watershed which is spatially very varied because of its nested nature. In addition, effective integrated water resources management is estimated based on the wide participation of stakeholders and obtaining environmental objectives by applying the decisions on the watershed scale of management. However, the opportunities for stakeholder participation and advantages in the practical and spatial scope of the policy-making process are impacted by the geographic scale of the watershed (Jeffrey, 2016).

Hence, there is a need to apply a subwatershed management approach for river basins to make accurate and appropriate decisions for addressing the aforementioned problems (Jackson & Mcintyre, 2018). The subwatershed Management approach gives solutions to spatially distributed problems and helps to prioritizes activities associated with these problems and contributing effectively to the management, conservation, and protection of water resources in a watershed. This is in line with the Integrated Water Resources Management that improves the involvement of all stakeholders in water resources management (Ezekiel & Nyanchaga, 2017).

Meanwhile, a precise and reliable forecast of a watershed response across the scale is tremendously important to civic society due to its application in decision making for planning and managing watershed in distributed manner (Takeuchi et al., 2005). Prediction of long-term runoff is essential for various application in water resources planning and development, such as pollution control, planning of water supply and irrigation project, delineation of river floodplains and daily management of reservoirs, canal systems, conservation, recreational purposes, etc. (Patil, 2011b).

On the other hand, many river basins in the world are scarcely gauged and having observed data only for small or large scale of the basin area. This at that point may end up an obstacle to the utilization of hydrologic models. Specifically, the unavailability of observed data jeopardizes the estimation of the optimum parameters of hydrologic models. (Mwakalila, 2003). Hence, the estimation of an ungauged watershed for spatially distributed watershed management is one of the most problematic and challenging tasks for hydrologists. Developing practical predictions of these watersheds is crucial for evaluating water resources which are usually located in the upstream regions of the watershed (Takeuchi et al, 2005).

Generally, in such circumstances the hydrologist preferring to estimate streamflow from rainfall and meteorological data of the nearby gauged watershed having hydrological similarities (Gitau & Chaubey, 2010a). Transferring hydrologic data (e.g. parameters of the calibrated model, hydrologic indices, streamflow record) from a neighbor gauged watershed to the target ungauged watershed is typically used for water quantity studies (Gitau & Chaubey, 2010a). For successful transfer of the hydrologic information between watersheds, it is important to ensure that the donor (gauged) and receiver (ungauged) watersheds are similar to each other in terms of physical and hydrologic characteristics (Patil, 2011a).

As a tool for modeling and transferring hydrologic data to an ungauged watershed, there are many models to choose from. These models can be very simple such as lumped conceptual models, while others are entirely physically-based distributed models having a high temporal and spatial resolution. It’s also worth mentioning, many simple models showing identical performance in simulation to complex hydrological models. Therefore, for the selection of a suitable model, priority is given to the simple model having comparatively good performance (Ekenberg, 2016). In addition, considering the principle of parsimony, if a model showing predicted results close to the observed data with the minimum required input data and simple structure, is considering the best hydrological model (Project, 2017).

Considering the criteria for best hydrologic models, the application of lumped hydrologic models is easy and needs less amount of data for running. Generally, these models presenting the transformation process of rainfall to streamflow. In spite of having a simple structure and easy developing procedure, the models proved to be efficient for water resources management. In addition, the time interval for simulation in these models provides the opportunity to develop the model for various catchments and pave the way for inter-comparison analysis (Perrin, et al., 2001).

Similarly, unavailability of reliable hydro-meteorological data across the scale at subwatershed level and lack of guidance for model selection are the major issues, that hydrologists and researchers are confronted in Sri Lanka (Jayasinghe & Rajapakse, 2017). Hence, it's necessary to identify an appropriate lumped model and assess the transfer across the scale for streamflow estimation to support water resources planning and development. This study conducted on the Ellagawa main and Ratnapura subwatershed of Ellagawa at Kalu Ganga river basin, Sri Lanka. The river originates in the hills located in the central part of the country and empties into the Indian ocean at Kalutra district. The study area is given in Figure 1-1 and Figure 1-2.

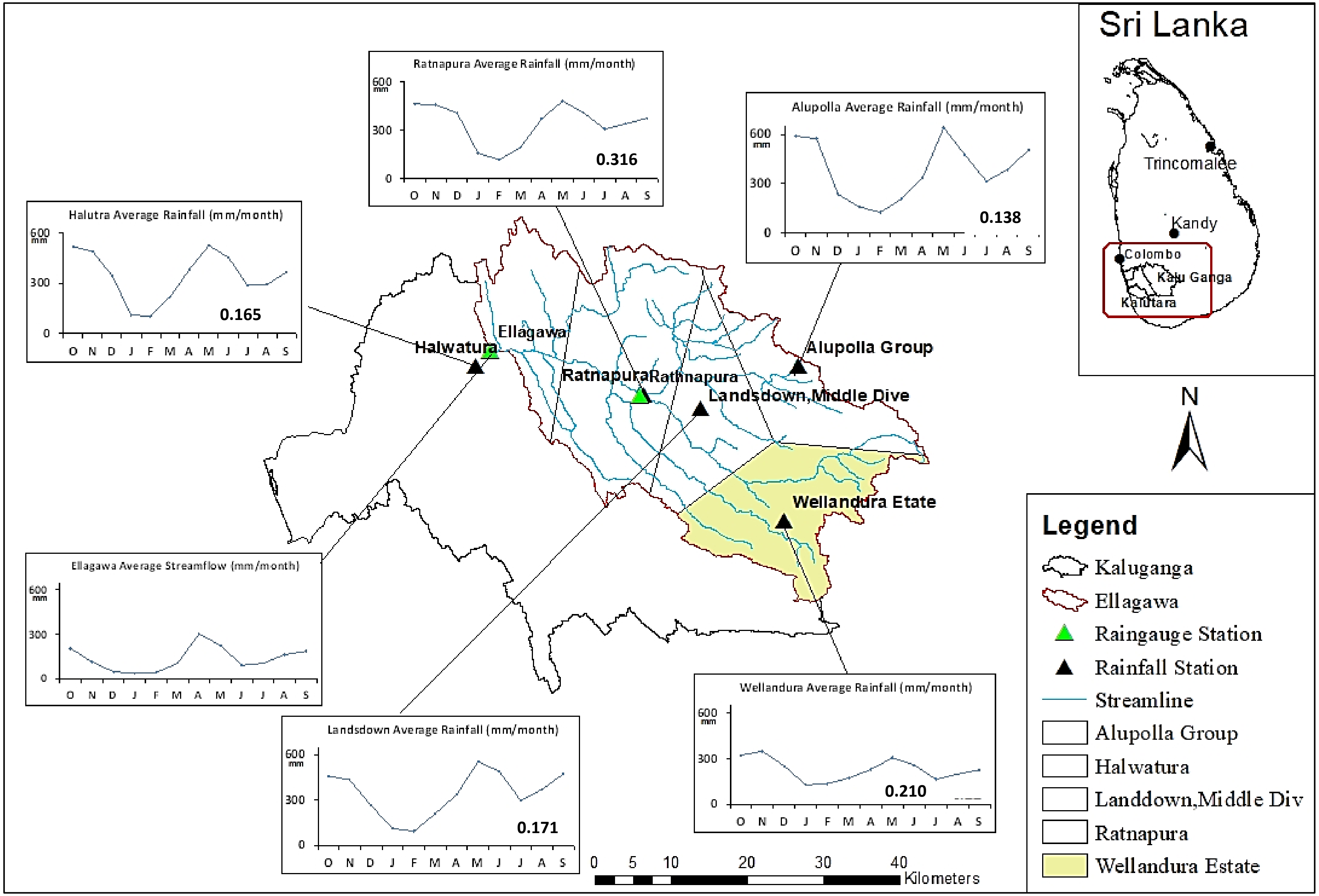



Figure 1-1 Map of Kalu Ganga river basin with Ellagawa watershed

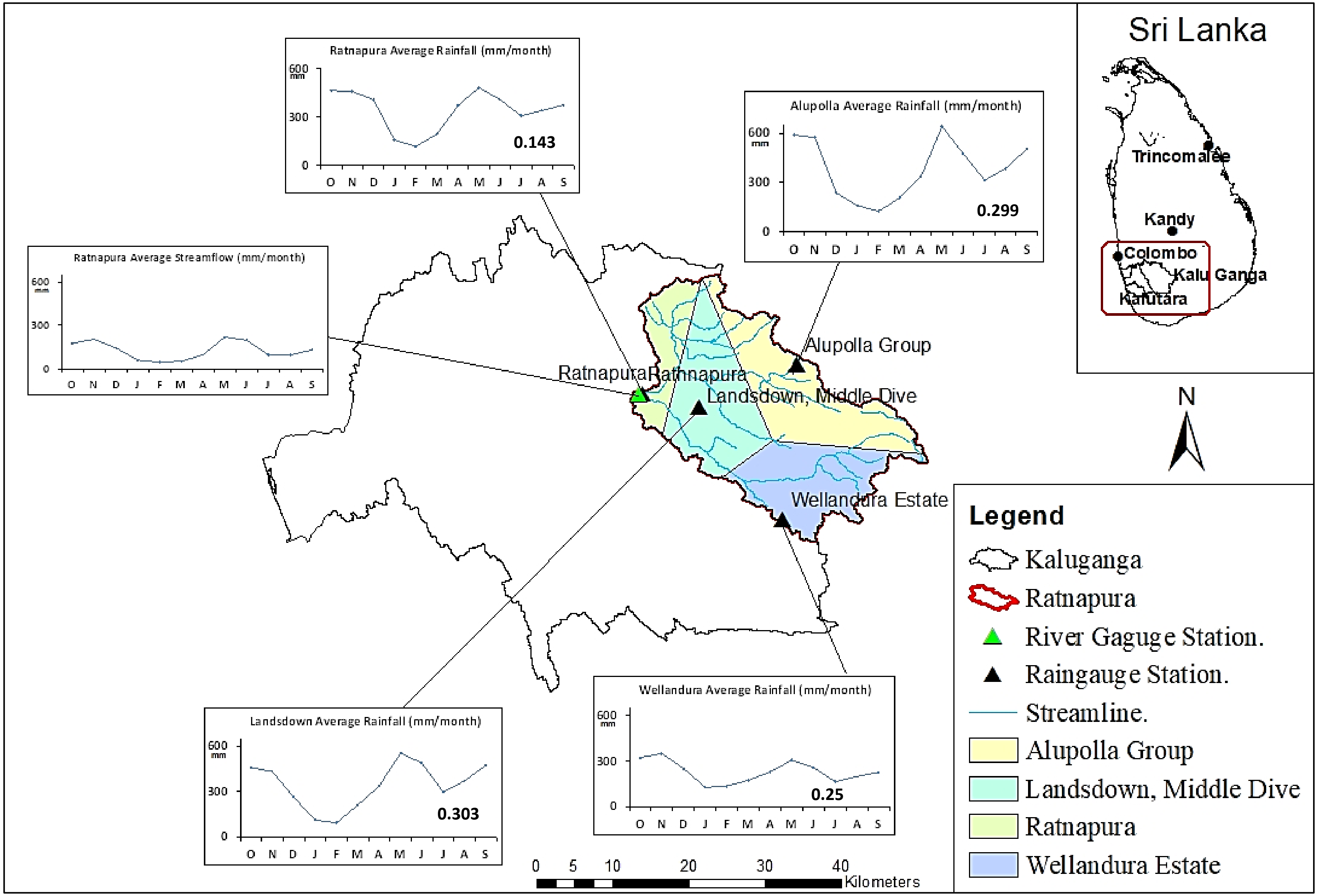



Figure 1-2 Map of Kalu Ganga river basin with Ratnapura watershed

## 1.2 Problem Statement

Spatial transferability of parameters from main to sub and sub to the main watershed for streamflow estimation using a lumped model for water resource development.

## 1.3 Objective of the Study

### 1.3.1 Overall objective

To identify suitable lumped model and evaluate the transferability of parameters from main to sub and sub to the main watershed for streamflow estimation.

### 1.3.2 Specific objective

1. Literature review on the application of lumped models for water resources planning and management.
2. Develop a lumped watershed model for Elagawa and Ratnapura watersheds.
3. Calibrate and validate the model for both watersheds.
4. Comparison of the optimum parameters and transferring the parameters from main to sub and sub to the main watershed.
5. Evaluate the applicability and propose recommendations on the spatial transferability of the lumped model parameters.

# 2 LITERATURE REVIEW

## 2.1 General

Water is a vital substance of life for all living beings on the earth's surface. As the population grows, the consumption of water goes up, and accordingly, the pressure increases on limited resources of water. In the meantime, change in climate, which is intimately linked to population growth also leads to increased pressure on the existence of water resources. Therefore, it's crucial to manage these vital sources sustainably. Incorporating a spatially subwatershed management approach leads to viable options and can improve stakeholder involvement when planning and managing water resources. Streamflow management by incorporating spatial variability of characteristics requires a hydrologic model and estimation of parameters with observed data. However, due to non-availability of gauged streamflow across the scale in a watershed hinders the estimation of parameters. Therefore, it is important to identify the available recommended options to fill this gap in the modeling of ungauged main or subwatershed when the sub or main watershed is gauged.

The objective of this state of the art is to review options on the transferability of lumped model parameters and select a suitable model and method of parameters transfer for simulation of daily runoff in an ungauged sub or main watershed when one of them is gauged. For conducting this literature review, four guidelines, 50 research papers, 4 textbooks, 10 monographs related to lumped hydrological modeling were reviewed.

Comparison of the models carried out in two stages. At the first stage, preliminary screening of lumped hydrologic models was carried out according to 15 criteria. As a result of the first assessment 4 models (IHACRES, SRM, WatBal, and Tank Model) were shortlisted. In the second stage, shortlisted models were reviewed in detail, and comparison is made according to 8 shortlisted criteria considering the objective of the study. At this stage, attribute ranks were given to 4 shortlisted models and the final decision is made for the model suitability.

The result of the review on IHACRES, WATBAL, SRM, and Tank Model, for the transferability of parameters, revealed that the Tank model is simple and easier tools to operate and needs less amounts of input data for prediction of catchment response in a daily basis. The review also found that streamflow data of ungauged sub or main watershed for distributed watershed management can be estimated by transferring the model parameters using spatial proximity method from the main gauged to ungauged subwatershed or vice versa. As a result of the review, the Tank model selected the most suitable option for Parameters Transferability to support the objective of distributed watershed management.

### 2.2 Watershed Management

A watershed is a natural and complete topographic and hydrologic unit that accumulates and converges all the precipitation falling on it to a shared outlet. Therefore, a watershed is an ideal entity for the planning and management of its resources (Desai & Ukarande, 2016). The main objective of watershed management is to organize all activities in a watershed for conserving soil, plants, and water, to bring integrity in management and achieve the objective of integrated watershed management. During the process of managing its crucial to mutually consider all social, economic, and environmental aspects (Blau, 2010).

Water is one of the main resources of the watershed which has an excess in some regions as well as scarcity in some parts of the world due to overconsumption. Therefore, proper utilization of water resources and preservation is highly essential when it comes to water resource management. In water resource management identification and protection of river basins and watershed areas is one of the main focused fields. Usually, the focus is given to river basins but it’s also important to study and focused on subwatershed areas within the main watershed. Because any changes occur in subwatershed likely to affect the functionality and the wellbeing of the main watershed. Therefore, it is essential to focus on the protection and preservation of subwatershed in water resource management in terms of a distributed manner. Management practices for a watershed are gradually developed and mainly focussing on water, biota, land, and other resources for the wellbeing of economic, social, and environmental conditions of a specific region (Wang et al., 2016).

Problems related to water resources are spatially and temporally very varied. These problems neither similar nor persistent or constant over time and space (Biswas, 2008).

In addition, inadequate budget and stuff downsizing are the factors frequently causing tremendous challenges to water engineers when they are deciding on the protection, restoration, and management of water resources. It’s also difficult to manage water resources problems over a large and spatially varying area of a watershed. Hence, there is a need to apply the distributed watershed management approach for making accurate and appropriate decisions for managing these problems.

The distributed watershed Management approach gives the solution to problems related to water within a specific area and prioritizes a set of activities to deal with these problems. The main objective of the distributed watershed management approach is to support the management, conservation, and protection of water resources along a particular watershed. This is in line with the integrated water resources management that improves the involvement of all stakeholders in water resources management (Jackson, & Mcintyre, 2018). In addition, it suggests the principles, procedures, and organized arrangements to protect, use, develop, and conserve water resources on a subwatershed scale. Moreover, it promotes afforestation and reafforestation of the watershed to improve on water quality and quantity and establish mechanisms and services for improving the public and communities' contribution in water resources management (Ezekiel & Nyanchaga, 2017).

## 2.3 Watershed Models

Hydrologic models are very essential tools for water resources planning and management in a watershed (Devia et al., 2015). According to Moradkhani & Sorooshian (2008), a model is the simplification of the real-life system. The most suitable model for a specific objective is to give simulation results close to the real-life system with the development of a small number of parameters and a simple structure of the model. Basically, hydrological models are using to simulate various hydrologic processes and estimate the behavior of a hydrologic system for future change. The characteristics of a model are defining by various parameters of the model. Watershed models simulate hydrologic responses of a watershed in a more integrated way. They incorporate a whole watershed area for simulation of the various hydrologic process, while other models simulate single or multiple processes at relatively small spatial resolution (Desai & Ukarande, 2016).

Currently, many rainfall-runoff models are using by modelers; however, the usage of these models are really relying on the objective of modeling. Some of these hydrological models are using only for research studies to improve the understanding of the hydrological process that controls the behavior of the real-life system. While other types of models are developing for planning and designing purposes. These models helping decision-makers to consider social, economic, physical, and ecological behavior of the real-world system for making effective and efficient decisions on the management of the system (Moradkhani & Sorooshian, 2008).

Various classification of hydrologic models has been made by researchers and practitioners to expedite the understanding and application of these models. It should take into account that almost all hydrologic models are not very varied from one another and almost following the same concept. The main variance can be pinpointed in the developing and operation procedure of the models (Jajarmizadeh et al., 2012).

Classification of the hydrologic models can be carried out based on parameters, inputs, and range of physical principles using in the models. According to the parameters as a function of the models, the models are categorizing into lumped and distributed, and considering the statistical behavior, the models can be grouped as deterministic and stochastic models (Gupta et al., 2015).

In hydrologic modeling, parameters of the models can be presented as lumped, semi-distributed, or distributed form. In the lumped approach catchment characteristic, the input and output of the model are averaging over space (Knapp et al., 1991). While in semi-distributed models some spatial variation is considering; and in fully distributed approach variation is considering for each grid cells. Although in a semi-distributed approach the hydrologic process is representing at small spatial extent respect to a lumped modeling approach, it’s not repressing runoff for every single cell as it is in fully distributed models (Jan et al., 2017).

Furthermore, based on the process extent, the hydrological models are grouping into continuous and event-based models. In event-based modeling, the catchment response is simulating for a single event of rainfall. In contrast to event-based modeling, in continuous modeling various hydrologic processes combining over a long temporal resolution (Chu & Steinman, 2009).

## 2.4 Status of Lumped Models for Watershed Management

Most of the time hydrologists are really depending on lumped conceptual models for understanding and estimating the behavior and response of a hydrologic system. These models include a number of interrelated storages of water (e.g. surface, subsurface, intermediate, sub-base, base storages of ground, slow and fast responses) that represent the behavior of various parts of a hydrologic system and processed precipitation into streamflow. Having a very simple structure frequently less than 10 parameters these models calibrating against physically observed data in the field (e.g. streamflow) (Wagener et al., 2001).

Lumped conceptual models need very basics and simple computer skills and low data requirements for their development. Hence, these models are user attractive especially in the areas where sufficient data is not available. Most frequently, these models are using for the evaluation of the potential impact of land use and climate changes on watershed hydrology (Collet et al., 2015; Merritt et al, 2004; Fabre et al., 2015).

The results of these models associated with a number of uncertainties because of various sources of errors and assumptions. Erroneous input data, uncertainty in numerical calculation and approximation, uncertainty, and non-uniqueness of the structure of the model are the main sources that account for uncertainties in the process of modeling. Moreover, variability in parameters for various climatic regions and the anthropogenic situation is another source of uncertainty that causes difficulty in differentiating parameters equifinality (Seibert & McDonnell, 2010; Brigode et al, 2013).

These kinds of deficiencies noticed in a large number of climate impact studies. Most of the time it is assuming that uncertainty arising from climate or water use scenario is greater than the uncertainties associate in the process of modeling. Considering the principles of water resources management; the simple developed models do not depend only on the estimation of precise runoff estimation of a watershed but it's important to assess the uncertainties systematically and tackle the problems (Ajami et al., 2008).

For estimating uncertainties in the modeling process one of the most effective methods is the Bayesian inference method. This approach provides information on how epistemic uncertainties treated in a best way and assures the applicability of the theory of probability. The procedure, presenting the evaluation of the model readability using a number of tests. These testes making it easy to understand the comparative merits and structure or variation of the same models. Most of the time structural deficiencies somewhat alleviated the process of simulation (Beven et al., 2011; Bloschl & Montanari, 2010).

## 2.5 Transferability of Model Parameters

Various tools that can simulate hydrologic responses over time and space intervals are necessary for making accurate and reliable decisions on the planning and development of water resources so that to integrate the social, economic, and environmental viewpoints (Tessema, 2011). Reliable and accurate simulation of hydrologic processes are crucial to civic society because of their application in planning and developing water resources (Bao et al., 2012).

Many national and international organizations are making independent decisions on control measures for managing natural disasters and the natural environment in a sustainable way (Shakti et al., 1970). Accurate and reliable prediction generates the widest possible information which is crucial for making these decisions (Mango et al., 2011). Estimation of river streamflow over a long period of time is important for various applications in water resources management, such as management of dams and canals on daily bases, planning of water supply and irrigation project, and demarcation of floodplains (Patil, 2011a).

However, unavailability and lack of observed data for many watersheds is a global issue (Sellami et al., 2014). Most of the time the available observed data is uncertain and intermittent. And the availability of hydrologic data for the study area is very rare cases (Loukas & Vasiliades, 2014). This at that point hindering the application of hydrologic models that for the long term needed to evaluate the effects of climate and land use changes on watershed hydrology and for short term to predict the floods, availability of water, and droughts (Winsemius et al., 2009).

Forecasting of hydrologic processes in ungauged watershed is one of the most challenging tasks in hydrology. The international association of hydrological sciences took some steps and named the decade from 2003 to 2012 as a Decade of Predictions in Ungauged Watersheds. The main focus of these initiatives was to enhance the capacity of the scientific community in a coordinated way in order to make accurate estimations in ungauged watersheds (Sivapalan et al., 2003). Estimation and practically forecasting of ungauged or scarcely gauged watershed is tremendously important for water resources planning and development (Zhang & Chiew, 2009).

In such cases the hydrologist estimating the river flow from precipitation and other hydrological data or from analysis of time series data in a gauged watershed located nearby the target ungauged watershed (Gitau & Chaubey, 2010b). Transferring the parameters of hydrologic models, hydrologic indices, and streamflow values from gauged (donor watershed) to ungauged (receiver watershed) is generally used for assessing water quality (Oudin et al., 2008). For successful transfer of hydrologic data between watersheds, its crucial to make sure that the gauged and ungauged watersheds are comparable in terms of hydrologic characteristics (Patil, 2011a).

Most of the time, the relationship between rainfall and runoff of a gauged watershed is developed using regression analysis. The coefficient of regression is regionalized referring them to the physical characteristics of the watershed to obtain a suitable coefficient for ungauged watersheds (Bao et al., 2012). To improve the process of regression additional variables such as antecedent wetness indices, years and temperature are also including in the regression. Although including these additional variables can improve the accuracy of streamflow estimation, the data requirements for the process are hindering the application of this approach broadly (Nandagiri, 2007).

There are so many studies in the context of data transfer from gauged to the ungauged watershed. Heuvelmans et al., (2004) studied the spatial variation of the SWAT model parameters to identify the zones where the transferability of the model parameters from one watershed is feasible to another without significant loss in the model performance. The study investigated two approaches for parameter transfer: a single parameter method and parameter sets method. The assessment revealed that the parameter set approach outperformed a single parameter approach and suggested as a suitable method for parameter transfer. Another study tested the parameters transfer across the scale. The study evaluated the transferability of the main watershed to two subwatersheds. The evaluation found that the optimized parameters of the main watershed provide very accurate estimation for the subwatersheds, which were very similar in terms of hydrologic characteristics (Arthur, 2003).

## 2.6 Selection of Model

In this section, an extensive review of lumped hydrological models carried out to select a suitable lumped model for assessment of the parameter transfer of the lumped model for spatially distributed watershed modeling. The main objective of this assessment is to support and facilitate the information for selecting the right lumped conceptual model which would be the most suitable tools for evaluation of the parameters transfer from main to sub and sub to the main watershed.

An approach for selection suitable lumped model was applied in two stages. At first, large numbers of lumped models were reviewed and assessed according to 15 criteria. As a result of the first assessment, 4 models were shortlisted. Hereafter, in the second stage of selection process shortlisted 4 models were reviewed in detail and comparison of the models carried out according to 8 shortlisted criteria considering various objectives of the study. At this stage, attribute ranks were given to the 4 shortlisted models and the final decision is made for the model suitability.

The review is organized and structured in the following subsections: the first section of the review described 4 shortlisted models in detail. In the following section of the review 15 selected criteria (Assign considering objective of study and modeling) were described in detail. In the last section, the given qualitative weightage to each model is converted to the quantitative and total attribute of ranking is calculated for each model, and the model with high ranks identified as a suitable model for the study.

### 2.6.1 Description of shortlisted models

This part provides a detailed description of 4 shortlisted models in the second step of the selection process. Some models do not accomplish all shortlisted criteria for model evaluation, but may be performed well for solving partial problems related to water resources management.

### 2.6.2 Lumped hydrologic models

Lumped hydrologic models considering the whole catchment as a unit for the estimation of various hydrologic processes. Lumped model parameters are averaging the spatial behavior of the hydrologic system. Therefore, having a simple structure, less data demand, easiness in the application and fast setup and calibration is often attracting the choices of modelers for selection of these models.

Although, simulation of hydrologic processes in lumped modeling most of the time very simplified, this approach very often leading to reasonable results, specifically if the objective of the study is the streamflow estimation only (Carpenter & Georgakakos, 2006; Brirhet & Benaabidate, 2016). Heterogeneity in catchment land use and soil type may alter the rainfall-runoff process.

To overcome the aforementioned deficiency in lumped modeling, sometimes efforts are making and restricting the area extent for simulation to the area having relatively similar properties. In this approach, the catchment is dividing considering the variation of soil and land use type, and then the model is developing for different land use and soil type in a watershed (Basri, 2013). Inputs for the lumped modeling are taken average over the entire watershed. Obtaining such data is relatively easy and the input, output, and parameters estimated in the simulation process are average of the entire watershed.

The detailed shortlisted models in this review are not capable of representing all hydrologic processes required for water resources management. Particularly, infiltration, snowmelt, reservoir routing is not presenting by some models. However, they can successfully figure out partial water resources problems such as modeling the climate change impact on watershed hydrology. The following sections describe the shortlisted models in more detail.

### 2.6.3 IHACRES model

The IHACRES is a watershed-scale hydrologic model that stands for the Identification of unit Hydrographs and Component flows from Rainfalls, Evaporation and Streamflow data. The model founded by the joint work of an institute of hydrology in England, the research center of Australian National University, and Canberra (Littlewood et al., 2003). The model using the unit hydrograph approach for the lumped simulation of a watershed response. The potential of model considering the process extent is flexible and can be apply for the continuous and event-based simulation of a watershed. The spatial and temporal resolution of the model is also not limited and can be applied for various sizes of the watershed using data with temporal resolution equal to or greater than one minute. Rainfall and streamflow are the minimum input data for the model calibration. While evaporation, temperature, and basin size are the optional input data for the model development. Soil, land use and topography are not required for the model development.

The model is applicable for both event and continuous streamflow modeling and can estimate unit hydrographs, dividing of hydrograph for water quality assessment, environmental variation – studies of hydrological regime, Slow Flow Index (SFI) estimation, analysis of relationships between DRCs and Physically, obtaining of Dynamic Response Characteristics (DRCs), filling missing streamflow data, hydrometric data quality control and quality assurance (Littlewood et al., 2003).

### 2.6.4 Snow Melt-Runoff Model

The Snowmelt-Runoff Model (SRM) is founded by Martinec, in the Swiss Snow and Avalanche research center at Davos. Since, 1975 Martinec, has substantially improved the model with the collaboration of Al Rango and Michael Baumgartner. The model specifically designed to estimate runoff from snowmelt in mountainous areas where snow is the dominant contributor to the runoff of a watershed.

Review of the literature shows the various successful application of the model across the globe. There is not any spatial limitation for the model and can be applied almost for any spatial extent and elevation of a watershed. Review of the model applications revealed that so far, the model has been successfully applied for the watershed size ranging from 0.76 to 917,444 $km^2$. The computation procedure of the model is easy to understand. It is also undergone successfully in the world metrological test. The model applied over 100 basins by various agencies working in the field of water resources management. Recently, the model applied for the evaluation of climate change impact on snow cover (Martinec et al., 2008).

SRM model most frequently applies for the estimation of daily streamflow in mountainous areas dominated by snow. The WinSRM computer programing environment provides modified depletion curves which linked areas covered by snow to cumulative snowmelt depth estimated by the model. In addition, the curve can be used for the assessment of the reserved snow for seasonal streamflow estimation. The performance of the model really depends on the deviations of estimated precipitation and temperature from observed data. While errors in the model can be decreased by cyclic updating of the model (Martinec et al., 2008).

The required input data to the model includes basin area, zone areas, area-elevation curve, precipitation, temperature, and area covered by snow. The model has eight parameters, consist of runoff coefficient for the snow, runoff coefficient for the rain, degree-day factor or melt coefficient, lapse rate of temperature, critical temperature, area contributing in rainfall, coefficient of recession, and lag of watershed. The WinSRM which includes well-organized support for climate change modeling is freely accessible from USDA- ARS website (Shalamu et al., 2012).

### 2.6.5 WATBAL model

WatBal model is using water balance concept for modeling the watershed response to potential climate change. The model was developed using Visual basic programming tools in the Mirco Soft Excel spreadsheet (Donald E & P. Golder, 1997).

The WatBal model basically includes two key parts. The first part is water balance, applying continual function representing inflow and outflow to a conceptualized watershed. The component contains five parameters considering direct runoff, surface flow, subsurface flows, base flows, and maximum water holding capacity of the soil. And the second component applying the prominent method (Priestley Taylor radiation) for estimating potential evapotranspiration (Donald E & P. Golder, 1997).

The model deals with changes in the moisture content of the soil with respect to precipitation, streamflow, and actual evapotranspiration. In addition, potential evapotranspiration is using to remove water from the soil moisture. Precipitation, streamflow, and evapotranspiration are the required input data for model development. The evapotranspiration can be estimated internally using climatological data. The model is account for estimating potential evapotranspiration, surface flow, sub-surface flow, albedo, and effective precipitation (Yates, 1994).

The model uses a differential equation for the calculation of soil moisture balance. And storage is considering as a lumped single vessel. For computing and adjusting the effective precipitation snow melt element of the streamflow is using. The potential of the model considering spatial and temporal extent is not restricted and can be used for the daily and monthly time intervals for any scale of the watershed (Yates, 1994).

### 2.6.6 Tank model

Tank Model was originally developed by Sugawara in 1967 keeping in mind the hydrologic condition of Japan. In Japan evapotranspiration is comparatively not very much high, basins are small in size, river gradients are steep and time of concentration is small. The original model included three tanks that laid vertically in series, later on, Sugawara suggested m x n structure of the model for non-humid basins. According to the climate and characteristics of watershed components, special consideration and correction are required for the application of the model (Hong et al., 2015).

Precipitation and evapotranspiration are the main Input to the model. Outputs from each zone of the model are carried forward as input to the next zone. Water in all the three tanks from top moves to both horizontally and vertically. Discharge through the infiltration outlet of the first tank is the inflow to the second tank. Similarly discharges through the infiltration outlets of second and third tanks are the inflows to the third and fourth tanks respectively (Sugawara, 1961).

The Tank model gives the estimation of the various components of streamflow such as surface runoff from the first tank, intermediate flow from second tank and sub-base, and base flow from the third and fourth tank respectively (Surya et al., 2014). There are many reports on the application of hydrologic models for the analysis of the characteristics of river flow using the data of rainfall and climate. A tank model is a method that is based on the hypothesis that the flow of runoff and infiltration is the function of the water amount in the soil (Sugawara, 1961).

The Tank model which has been widely used for Japanese river basins showed satisfactory results in the case of the Sri Lankan river basin (Wijesekera & Musiake, 1990). The findings of another study using the Tank model in Vietnam during the time interval 1962–2014, captured the changing point in annual precipitation and streamflow of a watershed (Phuong et al., 2018). Having a simple structure, the Tank model has been broadly used for the streamflow modeling of many watersheds. In most cases, the model used for the simulation of watershed response on daily time resolution (Phien & Pradhan, 1983).

### 2.6.7 Comparison of selected models

In this part, an attempt is made to make comparison of the shortlisted models concisely described in the previous section. For the evaluation, various criteria were used. These criteria are describing in the following section.

1. **Capability of water resource management:** Identification of model performance in estimation of low, medium, and high flow regions is crucial with respect to the objectives such as environmental management, water resources management, flood management, etc. Hence, according to the criterion if a model is showing good performance for all high, medium, and low flow regions, given high weightage. While if a model showed good performance in two regions of the streamflow threshold given medium, and having good performance only in one region of the streamflow is given low weightage.
2. **Processes to be modeled:** The type and number of the processes that a model has the capability of the simulation are the main criteria for choosing the right model to serve the objective of the study. In order to select a suitable model for a case-specific study, the required process for the study and level of accuracy is taking into account. A model having the potential of simulating all basic hydrologic processes such as snow accumulation and melt, infiltration, and reservoir routing given high weightage, while for models simulating partially of basics hydrologic

process given medium weightage, and for models simulating limited hydrologic process given low weightage.

3. **Simulation extent:** In event-based hydrologic modeling the watershed response is estimating to a single precipitation event. While in continuous simulation the watershed response is estimating to a number of precipitation events and their cumulative effects over a longer time resolution that contains both dry and wet conditions. Hence, fine-scale hydrologic simulation is especially useful for estimating and understanding the detailed hydrologic process and its associated parameters that can be utilized for obtaining course scale hydrologic simulation. Therefore, models suitable for both event and continuous simulation high weightage is given while having suitability for event-based and Partially for continuous simulation medium weightage is given. And models having suitability only for event-based simulation given low weightage.
4. **Transferability of parameters:** In this criterion climatic regions, watershed size, and hydrologic variation of the donor (gauged watershed) and receiver (ungauged watershed) were considered in the context of parameter transferability of the shortlisted models. The models having the capability of the parameters transfer from gauged to the ungauged watershed with climatically, size, and hydrologically varying watersheds given high weightage while having the capability for climatically same and either size or hydrologically varying watersheds given medium weightage. And the models showed the capability of parameters transfer from gauged to the ungauged watershed with having similar climatic, size, and hydrologic characteristics are given low weightage.
5. **Temporal resolution:** Temporal resolution is playing a key role when making decision on model selection for the case-specific study. Considering the objective of the study, if it's planned to estimate storm discharge through the modeling process, then models having the potential of fine-scale temporal resolution are the best option to choose from. While for studying drought, water resources, and climate change, the selection of continuous models with coarse-scale time resolution is the right decision. A model having the capability of simulating the hydrologic process on hourly, daily, and monthly given high weightage while

having a temporal resolution of daily and monthly given medium weightage, and models having the capability of only monthly resolution given low weightage.

6. **Accessibility of the model:** According to the accessibility, hydrologic models can be categorized into four large groups: commercial models, exclusive models, partially free models, and freely available models. Accessibility to all components of the public domain models is completely free whereas, some components of partial free models need to be purchased. On the other hand, access to commercial models needs to be purchased. Although access to exclusive models is completely free, the permission of the developer or owner is required prior to the development of the model. According to the criterion of availability, if a model is freely available given high weightage while partially free models given medium weightage, and for commercial and exclusive models given low weightage.
7. **Data requirement for modeling:** Data requirement for hydrologic models vary from model to model and objective of the study. Although some hydrologic models need less amount of data, others need physical data such as soil, land use, topography, morphological, and vegetation data. Most of the time considering the objective of the study, preference is given to the model which produced a satisfactory result with minimum input data requirement. Hence, considering the criterion, a model needs less input data requirements for running given high weightage and models with moderate data requirements given medium weightage. While models having intensive data requirements given low weightage.
8. **User-friendliness:** Available Manual and developed user interface for model development considered under the criteria of user-friendliness. For the successful application of a model two types of manuals are necessary. The manual to describe the hydrologic process and mechanistic of simulation of these processes (called technical manual) and the manual to give instruction on the application of model (called user manual). In addition, the availability of the user interface is also important. The user interface is the space where a modeler is interacting with the system for applying the tasks of modeling. If for a model manual with the user interface is available high weightage is given, while for models having manuals and partially active user interface medium weightage is given. And for models, only with a manual low weightage is given.

9. **Type of Watershed** Watershed classification is carried out according to the various aspects of hydrology. Considering the land use watershed can be grouped into urban, agricultural, mountainous, deserts, forest, marsh, or coastal or combination of two or more of the previous types. Hydrologically, these watersheds are behaving very differently from each other. Hence the application of the models was reviewed in different types of the watershed; models with having successful application in all types of watersheds given high weightage while for models between successful application for all types and only one type medium weightage is given. And models which performed well only in one type of watershed low weightage is given.
10. **Spatial extent:** Spatial extent affects the performance of a model and for various sizes of the watershed the result of the modeling can be different. In order to choose the right model to fulfill the objective of the study, the restriction of the watershed size should be considered for models. Hence, according to this criterion comparative studies on the applicability of hydrologic models for various sizes of the watersheds were considered and watershed size limitations were identified for the shortlisted models. Models having flexibility with size restrictions given high weightage while In between no restrictions and limited medium weightage is given. And for models having Limited extents only, low weightage is given.
11. **Details of output:** Outputs of the model is one of the main criteria for the model choice. The required variables and details for the study are considering while the decision is making on the selection of the right model to fulfill the objective of the study. Models simulating Soil moisture, evapotranspiration, streamflow components, given high weightage, and in between the very detailed and only streamflow are given medium weightage. While for only streamflow low weightage is given.
12. **Global popularity:** To find out the global popularity of selected hydrologic models, text mining tools were used to determine the number of applications of selected hydrologic models in various regions across the globe. models having worldwide, regional and local popularity given high weightage while having regional reputation given medium weightage. And for models only with local popularity low weightage is given.

13. **Research application worldwide:** According to this criteria text mining tools were used to find out the numbers of applications of the selected hydrologic models in research studies. Models with not having or a very low number of applications in research work across the globe are given high weightage while for only a limited application in studies  medium weightage is given. And for models having many applications across the glob low weightage is given.
14. **Research application for the river basin of Sri Lanka:** Wijesekera (2010) Reviewed the literature on surface water hydrology and climate change in the context of Sri Lanka. The review concluded that there is a lack of modeling efforts of surface water, water resources, flood modeling, etc. Hence, according to this criterion, the modeling efforts for the river basin of Sri Lanka reviewed and models haven't applied or had a very low number of applications in the context of research work in Sri Lanka given high weightage while models with only a limited application in research studies medium weightage are given. And models having many applications in dry, wet and intermediate zones low weightage is given.
15. **Ease of modeling:** Some hydrologic models can be included automatic, global, and multi-objective optimization functions and easy development procedures whereas other models use third party software for optimization and even some models do not have automatic optimization tools. Models having optimization tools, specialized expertise not required, easy to understand the conceptualization, flexible graphical outputs, and with low computational requirements given high weightage while In between high and low categories medium weightage is given. And for models not having optimization tools, specialized expertise required, difficult to understand the conceptualization, less flexible graphical outputs, and with high computational requirements given low weightage.

    The explanation of the qualitative scale for the criteria evaluation is summarized and given in in Table 2-1.

Table 2-1 Qualitative Scale of Criteria for Evaluation

| No | Shortlisted criteria | High weightage | Medium weightage | Low weightage |
|---|---|---|---|---|
| 1 | Capability of water resource management | Good performance in high, intermediate and low flow | Good performance in intermediate and high or low flow. | Good performance in high or low flow |
| 2 | Processes to be Modelled | Simulation of snow accumulation and melt, infiltration, and reservoir routing | Simulation of snow accumulation and melt, either infiltration or reservoir routing | Simulation of snow accumulation |
| 3 | Simulation Extent | Suitable for Event and Continuous Simulation | Suitable for Event-based simulation and Partially for Continuous simulation | Suitable only for event-based simulation |
| 4 | Transferability of parameters | Successful transfer of Parameters from gauge to ungauged watershed with climatically, size and hydrologically varied | Successful transfer of Parameters for climatically same and either size or hydrologically varying watersheds | successful transfer of Parameters from gauge to ungauged watershed with climatically, size and hydrologically similar |
| 5 | Temporal Resolution | Hourly, daily, monthly | Hourly, Either daily, Monthly | Monthly |
| 6 | Availability of the model | Freely available | Partially free | Commercial |
| 7 | Data requirement for modeling | less data requirement | Moderate data requirement | Intensive data requirement |
| 8 | User-friendliness | Tutorials available with programming environment | Tutorial available and partially active programming environment | Only Tutorial available |

Table 2-1 (Continued)

| No | Shortlisted criteria | High | Medium | Low |
|---|---|---|---|---|
| 9 | Type of watershed | Successful application in all types | Successful application in between two or more than two and all types | Successful application only in one type of watershed |
| 10 | Spatial extent | No size restrictions | In between no restrictions and limited restriction | Limited extents only |
| 11 | Details of output | Provide information on soil moisture, evaporation, subsurface flow, groundwater flow | In between the very detailed and only streamflow | Only streamflow |
| 12 | Global popularity | Worldwide, regional and local applications | Regional applications | Local applications |
| 13 | Research application worldwide | No or very low number of applications | Only a limited spatial coverage | Many applications in dry, wet and intermediate zones |
| 14 | Research application for the river basin of Sri Lanka | No or very low number of applications | Only a limited spatial coverage | Many application (in the dry, wet and intermediate zone) |
| 15 | Ease of modeling | Availability of optimization tools, specialized expertise not required, not difficult to understand conceptualization, flexible graphical outputs, low computational requirements | In between high and low categories | Non-availability of optimization tools, specialized expertise required, difficult to understand conceptualization, less flexible graphical outputs, high computational requirements |

### 2.6.8 Evaluation of the Criteria for Model Selection

Fifteen criteria given in Table: 2-1 were evaluated for all shortlisted models. Each criterion is ranked into tree classes; high, medium, and low weightage. In addition, the shortlisted models were evaluated further according to eight shortlisted criteria considering specifically objectives of the study. For both evaluation of the model (according to detail and shortlisted criteria) score is assigned from 1 to 5 for each criterion. High weightage is given 5 scores, and for medium and low weightage assigned 3 and 1 scores respectively. The cumulative score of each evaluation calculated and then the result of both evaluations averaged for all shortlisted models. And accordingly, considering the cumulative scores of each hydrologic model the comparison is made between all shortlisted models.

The qualitative weightage of the criteria is given in Table 2-1.

Table 2-2 Comparison of selected lumped models

| Criteria | Model Name | | | |
|---|---|---|---|---|
| | IHACRES Model | SRM Model | WATBAL model | Tank Model |
| Criteria1 | High | Low | High | High |
| Criteria2 | Low | Medium | Low | High |
| Criteria3 | High | Medium | Low | High |
| Criteria4 | Low | High | Medium | High |
| Criteria5 | High | Medium | High | Medium |
| Criteria6 | Low | Medium | High | High |
| Criteria7 | Medium | Low | High | Medium |
| Criteria8 | High | Medium | Low | High |
| Criteria9 | Medium | Low | High | High |
| Criteria10 | Low | Medium | Medium | High |
| Criteria11 | Low | High | Medium | High |
| Criteria12 | Medium | High | Low | Medium |
| Criteria13 | Low | Medium | High | Medium |
| Criteria14 | Medium | High | Medium | Low |
| Criteria15 | High | Medium | Low | High |

The qualitative weightage is converted to quantitative weightage and the result of conversion is given in Table 2-3.

Table 2-3 Changing the qualitative weightage to quantitative

| Criteria | Model Name | | | |
|---|---|---|---|---|
| | IHACRES Model | SRM Model | WATBAL Model | Tank Model |
| Criteria1 | 5.0 | 1.0 | 5.0 | 5.0 |
| Criteria2 | 1.0 | 3.0 | 1.0 | 5.0 |
| Criteria3 | 5.0 | 3.0 | 1.0 | 5.0 |
| Criteria4 | 1.0 | 5.0 | 3.0 | 5.0 |
| Criteria5 | 5.0 | 3.0 | 5.0 | 3.0 |
| Criteria6 | 1.0 | 3.0 | 5.0 | 5.0 |
| Criteria7 | 3.0 | 1.0 | 5.0 | 3.0 |
| Criteria8 | 5.0 | 3.0 | 1.0 | 5.0 |
| Criteria9 | 3.0 | 1.0 | 5.0 | 5.0 |
| Criteria10 | 1.0 | 3.0 | 3.0 | 5.0 |
| Criteria11 | 1.0 | 5.0 | 3.0 | 5.0 |
| Criteria12 | 3.0 | 5.0 | 1.0 | 3.0 |
| Criteria13 | 1.0 | 3.0 | 5.0 | 3.0 |
| Criteria14 | 3.0 | 5.0 | 3.0 | 1.0 |
| Criteria15 | 5.0 | 3.0 | 1.0 | 5.0 |
| Shortlisted | 3.3 | 2.8 | 3.3 | 4.5 |
| Detailed | 2.4 | 3.6 | 3 | 3.8 |
| Shortlist & Detailed | 2.8 | 3.2 | 3.1 | 4.2 |

From the result of attribute ranks, it can be concluded that the Tank model with obtaining 4.2 scores got the first position in the selected models. The model has the capability of simulating various hydrologic processes with simple structure and easy development procedure.  The literature review showed that the Tank model can successfully simulate the response of various watersheds having different climatic and hydrologic conditions. In addition, the model has various successful application for estimation long term historical runoff and analysis of water table.

SRM model is another option for parameter transferability which obtained slightly high scores than the WatBall model. The model can apply for process and event-based modeling. Moreover, the temporal and spatial flexibility of the model is the main advantages of the model. As a third option, IHACRES hydrologic model can be proposed for parameter transferability.

## 2.7 Objective Functions

The process of a model calibration accomplishes by analogizing the estimation of the model output to observed data. In order to make this comparison, an optimization technique with objective function considering the objective of the modeling is adopted to the subset of available data. These functions are statistical error indicators giving information on the goodness of a solution to a particular problem. Therefore, to obtain the best solution its crucial to choose a suitable objective function with respect to the application where the solution will be utilized. The selection of the objective function is a subjective decision which really effects the value of optimum parameters in the calibration process. Thus the obtained set of optimum parameters according to an objective function may not be optimum in the framework of other functions (Diskin & Simon, 1977).

Numerous objective functions are utilizing for the calibration of hydrologic models. Although visual comparison of the observed and simulated hydrograph gives a rapid evaluation of model output, it is subjective, particularly when a number of comparable, but not similar estimation of the model is comparing in order to find the best match of observed and estimation of the model. To figure out, and noticed the strength and weaknesses of a model in particular regions of simulation, many statistical methods of the match were utilized and discussed by researchers.

Green & Stephenson (1986) reviewed twenty-one objective functions and concluded that the evaluation of model performance really depends on the objective of simulation. For instance, if the objective of modeling is to study flood, it makes a little sense to assess the model performance in low flows and shape of the hydrograph. In addition, if it's required to study the process of routing and its effect, then the importance is given to the recession limb and concentration curve of the hydrograph. The study suggested the application of percentage errors in volume, percentage errors in peak, and summation of absolute residuals or summation of squares for the simulation of a single event. The study also recommended the Nash- Sutcliff objective function in order to measure the model performance over a number of precipitation events for flood analysis (Green & Stephenson, 1986).

World metrological organization also listed four objective functions and associated merits and demerits in the project of inter-comparison of gray-box models. The objective functions were discussed and listed in the WMO guideline consist of the Ratio of Absolute Error to mean, the Root Mean Square Error, the Nash-Sutcliffe, Mean Absolute Error, and the Mean Ratio of Absolute Error (WMO, 1975). A study to evaluate the functioning performance of hydrological models in the alpine flood forecasting system used NSE for the performance evaluation of the model (Achleitner et al., 2012). Another study also used NSE for simulating hourly streamflow to manage flood risk (Badrzadeh et al., 2015)

Moreover, MRAE is another objective function which has mostly been used for hydrologic modeling of Sri Lankan watersheds. In order to estimate the streamflow at Putupaula in the Kalu river basin, the MRAE function applied to assess the performance of the Tank model (Wijesekera & Musiake, 1990). In a case-specific study of flood management and groundwater recharge, the MRAE objective function used to assess the performance of a Mathematical model (Nallaperuma & Wijesekera, 2016). Similarly, the MRAE function is used in the computation and optimization of the parameters of Snyder's Synthetic unit hydrograph model (Thapa & Wijesekera, 2017). In the following section, the shortlisted objective functions briefly reviewed.

### 2.7.1 The Nash-Sutcliff Efficiency

The Nash-Sutcliffe Efficiency is a statistical indicator proposed by Nash & Sutcliff. The efficiency is a standardized statistic that measures the comparative degree of the variance of the difference between observed and simulated variables respect to the variance of observed variables (Nash & Sutcliffe, 1970).

$$\mathrm{NSE} = 1 - \frac{\Sigma(\mathrm{Y_{obs}} - \mathrm{Y_{sim}})^2}{\Sigma(\mathrm{Y_{obs}} - \mathrm{Y_{mean}})^2} \qquad \text{Eq. 2.1}$$

In the Eq.2.1, Ymean shows the mean of the observed variables, Yobs shows observed variables and Ysim shows the simulated variables.

The interval of NSE is ranging from negative infinity to one. The value of one is the representation of the best match. Therefore the structure of the NSE presents efficiency or yield comparable to the coefficient of determination (Servat & Dezetter, 1991).

The NSE function is squaring the difference between simulated and observed variables, which may cause overestimation of large and underestimation of small values in a time series (Krause & Boyle, 2005). In a case-specific study to evaluate the performance of a model and estimate the accuracy of the model systematically, the Nash Sutcliffe efficiency underestimated the low flows, while the study subjected NSE as the best objective function for capturing peak flow errors (Moriasi et al., 2007). From the review of the literature, it can be concluded that the NSE objective function is not a suitable choice for the assessment of model performance when the objective of the study is to manage water resources. Whereas the function application is highly suggested for flood analysis (Ji Li et al., 2017).

### 2.7.2 The Mean Ratio of Absolute Error (MRAE)

The Mean Ratio of Absolute Error (MRAE) is one of the error indicators that measure the difference between observed and simulated variables with reference to the observed variables on the same date.

$$\mathrm{MRAE} = \frac{1}{n}\Sigma\frac{|Q_C - Q_o|}{Q_o} \qquad \text{Eq. 2.2}$$

In Eq.2.2, Qo shows observed variables, Qc shows simulated variable and n shows the number of the variables.

The zero value for the objective function is the representative of the best match between the observed and simulated variables. The application of MRAE found most frequently for water resources management studies. Wijesekera & Musiake (1990) used the MRAE function for the evaluation of the Tank model performance for streamflow estimation at Putupaula in the Kalu river basin. In another case study of flood management and groundwater recharge, the MRAE objective function applied for the performance evaluation of a mathematical model (Nallaperuma & Wijesekera, 2016). Similarly, the MRAE function is used in the computation and optimization of the parameters of Snyder's Synthetic unit hydrograph model (Thapa & Wijesekera, 2017).

As mentioned previously, the MRAE compares the variance between observed and estimated values of the model concerning each observed flow at a particular time. Hence, the MRAE provides better results when distinct data are available in the observed dataset. The function gives instructions on the strength of the model in predicting as well as the distribution of the errors.

### 2.7.3 The Mean Absolute Percentage Error (MAPE)

The objective function of the Mean Absolute Percentage Error (MAPE), generally uses for regression problems as a loss function in a model to evaluate the performance. The reason for its frequent application in model performance is its very simple explanation in terms of relative error (Myttenaere & Golden, 2017).

$$\mathrm{MAPE} = \frac{100}{\mathrm{n}} \Sigma \frac{|\mathrm{Q_C} - \mathrm{Q_o}|}{\mathrm{Q_o}} \qquad \text{Eq. 2.3}$$

In Eq.2.3, Qo shows observed variables, Qc shows simulated variable and n shows the number of the variables.

Although the objective function of (MAPE) is probably the most commonly used goodness-of-match measure, it does not fulfill the criterion of validity. The study argued that the distribution of the MAPE is generally skewed to the right, with the existence of outlier values (José et al., 2013). The function is biased when used to select among competing for prediction methods. In such circumstances, the study proposed to used alternative function to assess the model performance (Tofallis, 2017)

### 2.7.4 The Root Mean Square Error (RMSE)

The objective function of Root Mean Square Error (RMSE) is one of the most commonly used error-indicators in the statistic that estimates the difference between the decision and observed variables (Anthony G, 1992). The objective function is given in Eq.2.4.

$$\mathrm{RMSE} = \sqrt{\frac{\Sigma(\mathrm{Y_o} - \mathrm{Y_S})^2}{\mathrm{n}}} \qquad \text{Eq. 2.4}$$

In Eq.2.4, Yo shows observed variables, Ys shows simulated variable and n shows the number of the variables.

The RMSE is used very often in low flow simulation. A study applied RMSE for the performance evaluation of a hydrological model for the low flow modeling of a watershed (Nicolle et al., 2014). Patry & Mario (1983) also used the RMSE objective function for the comparison of observed and simulated streamflow to evaluate the performance of the model using the nonlinear function for runoff estimation.

In the same way, in a study to select a suitable model for low flows the objective function RMSE applied to assess the model performance for the Meuse river basin (Booij et al, 2009). Another study concluded that the application of RMSE objective function is effective when the observed and simulated values of the model perfectly matched. Unless, the objective function will not estimate the accuracy and will lead to an erroneous assessment of the model performance (Jin Li, 2017).

### 2.7.5 Identification of criteria for the selection of objective function

For the selection of an appropriate objective function to fulfill the objective of the study, two criteria were applied for the evaluation. These two criteria considering an approach for the measurement of errors and the objective of the modeling.

According to the first criteria the objective functions were classified into three major groups. (1) Relative Measurement, that measures the robustness of the link between observed and forecast of the model. These objective functions overstating the larger values while small values are ignoring. (2) Scale-Dependent Error Measure, these objective functions estimate the deviation in the data units. These objective functions can estimate the model performance relatively very well, while substantial deviation may happen in the evaluation of the various scale of the data. (3) Measures Based on Relative errors, these objective functions are not subjective to scale therefore very often using to compare the model performance over various scales of the datasets. The functions are not very sensitive to large errors mostly happens on a large scale. Considering the objective of the study the objective functions MBR is given a high rank, SDM is given medium and RM is given low rank (Hwang, Ham, & Kim, 2012).

According to the second criterion, the objective functions classified into three groups. (1) the objective functions are suitable for water resources management. These functions capturing the errors of intermediate flows between the observed and simulated flows comparatively with high accuracy. (2) the objective function suitable for flood management. The strength of these functions is comparatively well capturing of high flow errors between observed and calculated flows. (3) objective functions suitable for environmental flow management. These functions are relatively good at capturing low flow errors. Hence, according to the objective of the study the objective function which is suitable for intermediate flow management is given high rank. While the objective function suitable for high and low flows management given intermediate and low ranks respectively.

### 2.7.6 Evaluation of criteria for objective functions

Evaluation of the shortlisted objective functions carried out according to the criteria considering the objective of the study and capability of measuring the errors. Each objective function evaluated according to the selected criteria and attribute ranks is given to functions. High rank is given 3 marks while medium and low rank is given 2 and 1 marks respectively. The attribute ranks of each objective function are given in Table 2-4.

Table 2-4 Attribute ranks of objective functions

| No | Criteria | Objective function | | | |
|---|---|---|---|---|---|
| | | NSE | MRAE | MAPE | RMSE |
| 1 | Measurement of Error | RM [2] | MBR [3] | RM [2] | SDM [1] |
| 2 | Objective of Modeling | Flood Management [2] | Water Resources Management [3] | Environmental Management [1] | Environmental Management [1] |
| Total Score | | 4 | 6 | 3 | 2 |

From the result of attribute ranks, it can be concluded that the MRAE objective function with having 6 scores got first place in the shortlisted functions. Hence, the Mean Ratio of Absolute Errors selected as a suitable objective function for the evaluation of the model performance.

## 2.8 Calibration and Verification of Hydrologic Models

Parameters estimation of hydrologic models in such a way to match closely physically observed data in the field is called calibration. The core objective of this process is to improve accuracy and decrease the level of uncertainties in the prediction of the model.

In this process parameters of the model are adjusting considering the suggested interval and the estimated result of the model is comparing to the real behavior of the hydrologic system (Kumarasamy & Belmont, 2018).

The method for parameter estimation is categorizing into priori and posteriori estimation. In priori method, the optimum parameters are identifying without comparing the prediction to observed data. While posteriori method optimum parameters of the models are obtaining by close matching of prediction to the observed response of a particular watershed under the study. Hence, calibration of hydrological models can only be carried out when observed historical data such as rainfall, evaporation, and runoff is available for a watershed of under the study. (Sivakumar & Berndtsson, 2010).

In addition, another method for parameter estimation is called regionalized. The method basically using for developing conceptual hydrologic models in an ungauged watershed. In this approach, a regression relationship is using to estimate model parameters for a large number of watersheds using the calibration process considering the land use, soil types, and other characteristics of the watersheds. Hereafter, the regionalized parameters of a model are transferring to other ungauged watersheds having similar hydrologic characteristics (Sivakumar & Berndtsson, 2010).

Furthermore, the calibration process is dividing into manual and automatic. In manual calibration, the process is controlling by the expert modeler, while in automatic calibration computer associate with an algorithm for obtaining optimum parameters(Van Liew et al., 2005). Boyle et. al (2011) developed a new approach called hybrid multi-criteria approach including the benefits of automatic and manual calibration.

## 2.9 Warm-up Period

In the hydrologic simulation, identification of initial conditions is crucial for predicting the accurate response of a watershed. Considering the importance of the issue, it should be well understood and explain in research work. while, insight into the issue still needs refinement (Kim et al., 2018). In order to get the initial condition, a model is running adequate times to get the dynamic equilibrium of the hydrologic process and model parameters (Daggupati et al., 2015). The recommended time interval for warming up of a hydrologic model is ranging from one to several years that might cause underutilization of hydrologic data (Kim et al., 2018).

Hoad (2008) recommended 5 methods for model warming up. The first approach is to get the realistic condition by running the model sufficient times and the data used for warming up of the model is deleting from the simulation process. In the second method warming up is set in the model, so that the modeling will initiate in a realistic situation. The third method firs recommending to get partial initial condition for the model and hereafter running the model sufficient times to get the satisfactory initial condition for the model. In this method the data period used for warming up of the model removing from the simulation process. The fourth method is neglecting the bias effect by running the model for a very long time. In the fifth method, a short transient simulation run is using for stabilization of the initial condition of the model.

Mahajan & Ingalls (2005) evaluated six methods for obtaining the initial condition in steady-state modeling. The result of the study concluded that no single method is applicable to all kinds of models. Some approaches showed very good results for longer run length while others worked well for a short run of the model and some methods showed very good suitability for the systems utilizing at a very low level.

From the literature, it can be concluded that if the involvement of a user in the process of warming up of a model found effective, then the graphical method is the best choice to apply for obtaining the initial condition. While the heuristic approach can effectively utilize where automation of the process is possible. To add up prior to decision making on selecting a suitable method for warming up of a model, it would appear reasonable to test the method using an initialization bias test.

### 2.10 Selection of Tank Model Structure and Parameters

The Tank model is a lumped conceptual hydrologic model founded by Sugawara in (1956). The model composed of several tanks placed vertically in a sequence on top of each other. Rainwater is feeding and evapotranspiration is subtracted from the top tank. If sufficient moisture is not available at the top tank then the evapotranspiration is extracted from the next tank in a series and so on to the bottom. The water in tank discharging from the side and bottom outlets of the tanks representing the runoff and infiltration of the watershed respectively. In spite of the simple structure of the Tank model, the behavior of the model is complex due to various types of responses corresponding to various types of rainfall (Sugawara, 1967).

The Tank rainfall-runoff model showed robust capability in the simulation of various types of watersheds. Many modelers preferring the application of Tank model, because of its simple structure and easy computation. Despite having a simple structure, the simulation results of the Tank model is comparable with more complex hydrologic models (Kuok et al., 2011).

Accuracy in the modeling process is really dependent on the structure of the model. Hence, it's necessary to select a suitable structure and number of Tanks prior to the initiation of the calibration process. Selecting a suitable structure of the model improving the hydrograph matching of the simulated and observed streamflow. Sugawara recommended various structures of the Tank model such as parallel exponential, storage type, exponential, overflow, and series storage types for rainfall-runoff modeling. While assessment of the models showed that the series storage type of the Tank model is the best and most appropriate structure for rainfall-runoff simulation.

Basri (2013) in a study revealed that the selection of a suitable structure of the tank model depends on the land use, soil, and rainfall type of a watershed. Considering the type of land use the study applied model with one tank for urbanized area and three and four tanks for garden and forest respectively.

Ou et al. (2017) investigate the impact of impermeable surface on the peaks and volume of stormwater in an urban watershed using the Tank model. The study classified the watershed area into pervious and impervious area. For the simulation of the impervious area of the watershed, the model with one tank similar to the settlement tank with one side outlet and for the pervious area, the model with two tanks was selected as a suitable structure for the study.

After the consecutive improvement in the structure of the Tank model, Sugawara recommended four storages concept for runoff estimation. According to the concept of a Tank model, the output from the side outlets of the first Tank simulating surface flow, and output of the second Tank presenting the intermediate flow of the watershed. And accordingly, outputs of the side outlet of the third and fourth tanks presenting the simulation of sub-base and base flows respectively (Sugawara, 1967).

Beside Sugawara, Wijesekera & Musiake (1990) applied the simple tank structure with four tanks for the streamflow modeling of the Kalu river basin at Putupaula. The study showed that the Tank model which has widely used for the Japanese river basins showed a satisfactory result in the case of the Sri Lankan river basins.

Sugawara (1984) further improved the structure of the Tank model by incorporating components for the snowmelt and a separate structure for soil moisture to consider the contribution of snow and variation of the soil moisture content in the simulation process respectively. The soil structure of the model is account for primary and secondary soil moisture content and added to the bottom of the first Tank in a series.

Kuok et al (2011) assess the number of Tanks to find suitable numbers of Tank to incorporate in the structure of the model. The study evaluates three four and five storages with three different time intervals for the Tank model. The result of the study concluded that the suitable and best number of Tanks for the humid region is four.

According to the literature review, considering the type and climatic zone of the watershed the series storage type of the model with four tanks was selected as a suitable structure of the Tank model for the study.

## 2.11 Optimization of the Tank Model Parameters

The tank hydrologic model is a simple lumped conceptual model that comprises several tanks placed on top of each other. Precipitation gives as a main input to the model. The water is discharging through the side and bottom outlets of the tanks. The output of the side outlets simulating runoff components of the watershed. While bottom outlets of the tanks are showing the process of infiltration through the zonal structure of watershed. Each component of runoff controlling by variables called parameters. the variables (parameters of the model) should set up in such a way to closely match the prediction of the model to the real hydrologic behavior of the watershed (Sugawara 1967).

For many years the optimization of the Tank model parameters was carried out by trial and error method. Recently an automatic calibration method was developed to determine the runoff and infiltration coefficients (Sugawara 1967). Setiawan et al. (2003) suggested the Marquardt algorithm for optimization of Tank model parameters, which is simple to apply and effective in finding the optimum parameters even for a very high nonlinear problem. Phuong et al. (2018) assess streamflow variation of a watershed using the Tank model. Trial and error techniques were used for the optimization of the model parameter. The objective function of Nash-Sutcliff was used to assess the performance of the model.

Ou et al. (2017) applied the Solver tools of Microsoft Excel for the optimization of Tank model parameters. The tools were commanded to minimize the objective function of root mean square error (RMSE). In another study Arifjaya et al. (2011) also used excel solver to predict water balance and component of runoff. Meanwhile, Setiawan (2002) used Artificial Neural Networks (ANN) and Genetic Algorithm to optimize Tank model parameters and storage function respectively.

From the literature review, it can be concluded that the Parameters optimization of the Tank model is challenging because of having many discrete functions in the mathematical calculation of the model. Many efforts have been made to optimize the tank model parameters using various techniques of optimization but still, there is not a single method to apply for model optimization (Setiawan et al., 2003).

According to the literature review, easy to use, and open-source availability, the Micro Soft Excel solver tools selected for the semi-automatic optimization of the Tank model parameters.

## 2.12 Selection of Suitable Method for Estimation of Areal Average Rainfall

Representative rainfall of a watershed is one of the main required data of hydrologic models. Hence, Selecting the most accurate method considering the objective of the modeling is essential for realistic hydrologic simulation. Therefore, it is crucial to review the available options and select a suitable approach for estimating representative rainfall considering the density of rain gauge stations in a watershed (Zeiger & Hubbart, 2017). There are many methods for the estimation of the average rainfall of a watershed. Frequently used procedures are arithmetic mean, Isohyetal, and Thiessen polygon method (Akin, 1971).

Eruola et al. (2015) evaluate the accuracy of three empirical methods of calculating mean average rainfall over a watershed. The study stated that the Thiessen polygon and Isohyetal methods showed the least variation in the estimation of areal rainfall. While considering the deviation between Arthematic and Thiessen polygon/Isohytal method was very high. Hence, under the certain topographical condition of a watershed, the study proposed either Thiessen polygon or Isohyetal methods for the estimation of areal average rainfall.

Furthermore, a study considered the importance of representative rainfall in hydrologic modeling and compare the performance of methods often applied for the estimation of average rainfall over a watershed. The study compared the Thiessen polygon, Reciprocal Distance Squared, Kriging, and Multiquadric equation methods. The result of the study revealed that the Thiessen Polygon, Reciprocal Distance Squared method, and Multiquadric method applied successfully. While, the Kriging method using two variograms models showed unstable behavior (Barbalho et al., 2014).

Singh & Birsoy (1975) made the comparison of nine different methods for estimation mean aerial rainfall. The study conducted in the five study areas of three continents. The methods applied to estimate the mean average aerial rainfall on daily, monthly, and annual bases. The comparison showed that almost all methods commonly yield similar performance. Therefore, the study proposed a simpler method can be applied for estimation mean aerial rainfall for most hydrologic problems.

In a similar study a comparison of thirteen various methods is made in two study areas of the USA, and one area in Britain. For the application of the methods daily, monthly and yearly time resolution data were utilized. All methods generally produced comparable results. Hence the study suggested the simpler method for estimation of mean aerial rainfall (Singh & Chowdhury, 1986).

From the literature, it can be concluded that almost all methods yield comparable results. Hence, a simpler method which considering the area weightage of the rainfall station in a watershed can be applied for computation of mean areal rainfall. In this study considering the simplicity and easiness of application, Thiessen polygon method applied for the estimation of mean areal rainfall.

## 2.13 Identification of Low, Medium, and High Flow Regions

Identification of flow regions is essential when the performance of a model is evaluating with respect to the suitability of the model for specific engineering applications such as water resources planning and development, drought, and flood management (Moriasi et al., 2008). However, there is a lack of insight into the identification of flow thresholds (Wijesekera, 2018).

EPA. (2007) classified the flow duration curve into five regions: The probability of exceedance from 0 to 10% marked as high flows, from 10 to 40% marked for moisture condition, from 40 to 60% marked mid-range flows, from 60-90% of probability of exceedance marked for dry conditions, and from 90 to 100% marked as a low flow region. Smakhtin (2001) reviewed the current state of environmental flow hydrology and stated that the flows between 70 to 99% of the probability of exceedance frequently marking as a low flows region. While, high streamflow often marked from 5 to 10% of the available flows (Risley et al, 2008). Geological Survey with respect to water extractions marked the 50 and 90% of available flow as boundaries for flow threshold (Searcy, 2005).

Yilmaz et al. (2008) Suggested processed based techniques for the evaluation of the model. In the study, the demarcation of the flow duration curve subjectively carried out by separating the curve into three parts. The flow probability of exceedance axis from 0 to 2 marked for high flow segments and from 0.2 to 0.7 for medium and from 0.7 to 1 marked as low flow segment.

Wijesekera (2018) proposed a method for the demarcation of flow thresholds on the flow duration curve. At first, the intermediate flow period was demarcated on the "Probability of Exceedance" axis by combining the flow magnitude and slope variability information. The step type behavior of slope curves demonstrates the consistency of each order of magnitude with the length of each step (having the same slope value). Accordingly, with the evidence from the slope of flow duration curves, the onset of the consistent flow period was determined by first selecting the appropriate step and then selecting the probability of exceedance which is closer to the high flow region.

From the literature, it can be concluded that the flow thresholds look to have moveable boundaries. Hence, in this study, a method suggested by Wijesekera (2018) applied for the demarcation of the flow thresholds.

### 2.14 Filling in the Missing Data

One of the serious challenges for any hydrologic analysis is missing observation in time series data. Similarly, reliable prediction of a watershed response required complete sets of meteorological and hydrological data which is in rare cases available for a watershed. Therefore, to address the challenge and fulfil the objective of the reliable prediction, various interpolation methods can be used for the estimation of missing observation in time series (Wan Ismail et al., 2017).

The selection of a suitable interpolation method for the estimation of missing observation is evaluated in so many studies. Caldera et al. (2016) investigated the efficiency of seven interpolation techniques for estimating the missing observation in the time series of rainfall data to recommend an appropriate method for the mountainous area of Sri Lanka. Probabilistic and Linear Regression methods showed reasonably good results for the station having a high correlation with the neighboring stations. While, inverse distance, normal ratio, and squared method comparatively performed well for the stations having a low correlation with the neighboring stations.

Another study made the comparison of Normal ratio, Inverse distance, Coefficient of correlation, and Arethematic average methods for the estimation of missing observation in the rainfall and streamflow data. The estimation of missing observations in six rainfall stations showed comparable performance of all methods for three stations. Meanwhile, the coefficient of correlation is the second best method for all stations. On the other hand, for the estimation of missing observation in the streamflow data, the normal ration method performed well compared to all other methods. The study concluded that there isn't a single best method of interpolation to perform comparatively well for all stations (Wan Ismail et al., 2017).

Silva et al. (2007) investigated the efficiency of three frequently used and one newly introduced method of interpolations to propose a suitable method considering the climatic region of  Sri Lanka. The study suggested the application of Inverse distance for the stations in the low country, Normal ratio for the stations in mid, up and intermediate country, and the simple Arithmetic average for the stations located in upcountry. While the newly introduced Areal precipitation method outperformed the other three methods for the wet region of the country. The new method of interpolation considering the spatial distribution of data without taking into account the historical return of the evens. In this method point, rainfall of the stations extended to the Thiessen boundaries of the study area.

From the literature, it can be concluded that considering the location of the Kalu Ganga river basin in the wet region of the country the Aerial Precipitation method is the most appropriate method for the estimation of missing rainfall data of Ellagwa and Ratnapura watershed.

# 3 METHODOLOGY

The methodology flow chart for the study is given in Figure 3-1.

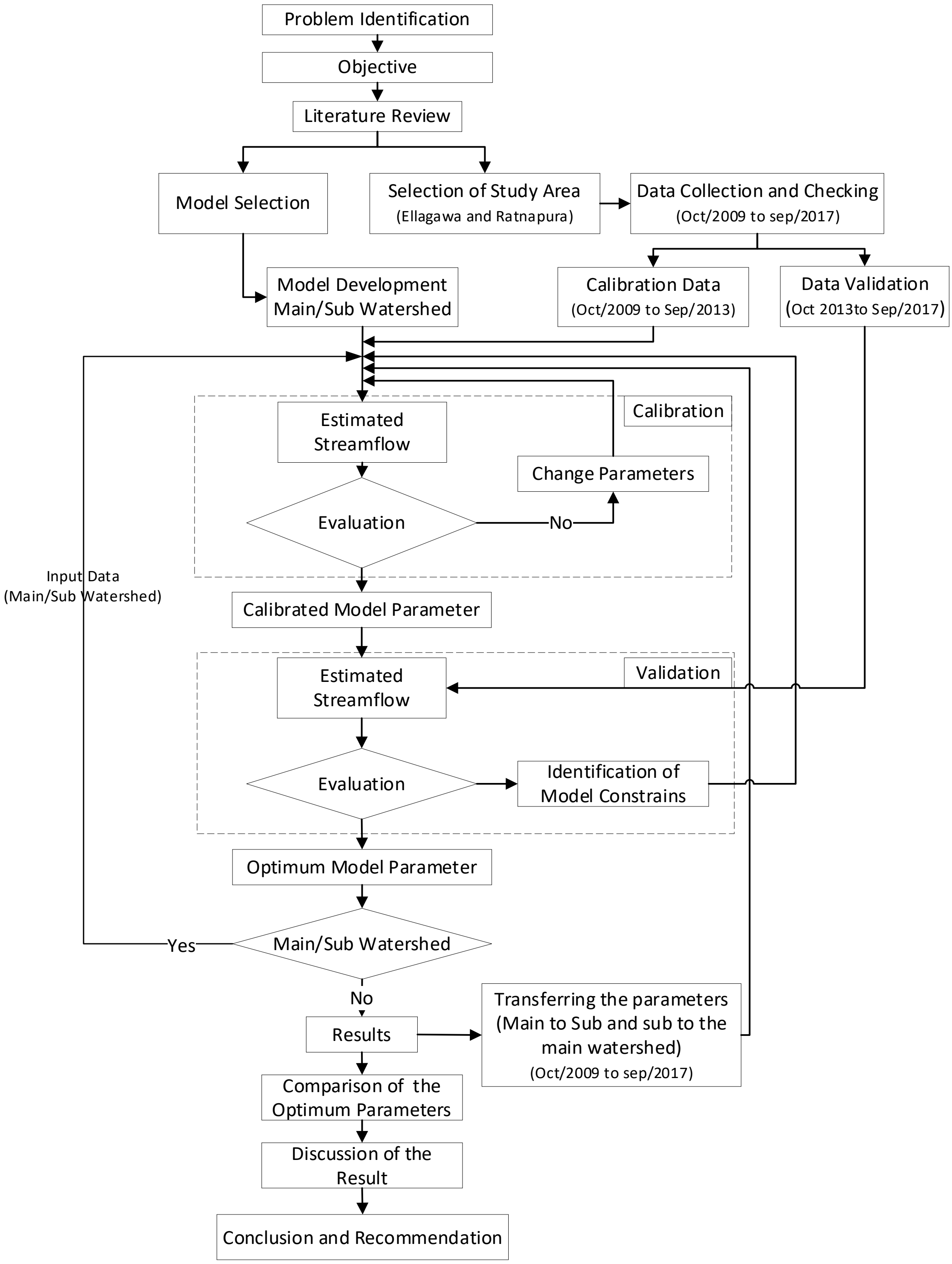



Figure 3-1 Methodology flow chart

This section provides a summary of the methods that were followed in the study and illustrated in Figure 3-1. At first, the problem of the spatial transferability of lumped model parameters for streamflow estimation was identified. Considering the nature of the problem, the overall and specific objectives of the study were determined. Hereafter, an extensive review of the literature and assessment was conducted to review the available options on the transferability of lumped model parameters and select a suitable model for the study. The review included four guidelines, 100 research papers, 4 textbooks, 10 monographs, and 5 guidelines related to parameter transferability and lumped hydrologic modeling. Comparison of the models carried out in two stages. At the first stage, preliminary screening of lumped hydrologic models was carried out according to the 15 criteria and 4 models (IHACRES, SRM, WatBal, and Tank Model) were shortlisted. In the second stage, the shortlisted models were reviewed in detail, and further assessed according to 8 shortlisted criteria considering specifically the objective of the study. At this stage, attribute ranks were given to 4 shortlisted models and the final decision was made based on high scores for the model suitability.

In the meantime, according to the objective of the study and considering the location and availability of the data, Ellagawa, main and Ratnapura, subwatershed of Ellagawa in the Kalu Ganga river basin were selected as a study area. Henceforward, the required data included eight years of daily rainfall, streamflow, and pan evaporation from October 2009 to September 2017 were collected for the Ellagawa and Ratnapura watershed. The required data were obtained from the various departments of Sri Lanka and online sources. Rainfall and pan evaporation from the department of metrology, streamflow from the department of irrigation and topographic, soil, and land use maps with 1:50000 spatial resolution, were obtained from the survey department. Besides, DEM with 30m spatial resolutions for the study area downloaded from the USGS database. Next, to confirm the accuracy of hydrologic data, a systematic approach of data checking and transformation was applied for the collected data. The approach included both graphical and statistical data checking methods.

After data checking, the obtained dataset was divided into two subsets for the calibration and verification of the model. The dataset used in the calibration of the model included rainfall, streamflow, and pan evaporation from 2009/2010-2012/2013. Similarly, the dataset from 2012/2013-2016/2017 was used for the verification of the model. Subsequently, the model calibrated and validated using the automatic calibration method for Ellagawa and Ratnapura watershed. The performance of the model evaluated based on the 6 criteria considering the objective of the modeling. Hereafter, the calibrated and validated parameters of the Ellagawa and Ratnapura were compared to find out the variation and similarities of the parameters. Then, the calibrated parameters of Ellagawa main watershed transferred to Ratnapura and from Ratnapura to Ellagwa watershed, and the applicability of the parameters transfer evaluated in the main and subwatershed for streamflow estimation. Finally, considering the result of the study the recommendations were made on the transferability of lumped model parameters for spatially distributed modeling that will lead to viable options when a decision is making on the planning and management of water resources.

# 4 DATA AND DATA SCREENING

## 4.1 Data Checking Methods

Accuracy of hydrological analysis and accordingly the right decision for water resources management really depends on the accuracy of hydrological data. It's indispensable to make sure the data using for frequency analysis or simulation of the hydrologic system is stationary, consistent, and homogenous. In order to confirm the accuracy of hydrologic data, a systematic approach of data checking and transformation was applied for the data screening of Ellagawa and Ratnapura watershed. The approach included both graphical and statistical data checking methods briefly described below.

### 4.1.1 Exploratory data analysis

Graphical methods of data checking were applied for the data collected for both Ellagaw main and Ratnapura subwatershed. The objective of the visual data screening is to assess the data for inconsistencies and outliers. At first, a rough screening of the collected data was carried out, and monthly, the annual and seasonal sum of the time series were computed to verify the total for water year and seasons. Hereafter, the daily, monthly, annual, and seasonal data were plotted and trends or discontinuities in the data were noted.

Furthermore, graphical screening included streamflow plots versus rainfall to evaluate the watershed response to a representative rainfall is rational or not. During visual data checking the erroneous points circled and either removed from analysis or applied statistical transformation method for amendment.

### 4.1.2 Statistical methods for data screening

In this section of data checking the statistical tests for the quality assurance of the times series of rainfall, streamflow, and pan evaporation were applied. These tests are proposed to be used as one part of the data checking procedure along with the quality control of time series and visual exploratory data screening. Estimation of annual water balance to check the watershed behavior, Spearman’s rank correlation test for the absence of trend in time series, and Double mass analysis for the homogeneity and consistency were applied as statistical data checking tests for the time series.

## 4.2 Study Area

This study conducted on the two subwatersheds, Ellagawa and Ratnapura of Kalu Ganga river basin of Sri Lanka. The river basin covering 2,690 km$^2$ area of the country. The river originates in the hills located in the central part of the country and discharges to the Indian sea at Kalutra district. Considering the climatic zones of the county the basin is completely located in the wet zone. The annual average rainfall of the basin estimated 4040 mm varying from 2000 mm in the plain area to 6000 mm in the mountainous area of the county. Ratnapura is one of the subwatersheds of Ellagawa covering 628 km$^2$ and 1391 km$^2$ area of the Kalu Ganga river basin respectively. There are two river gauging stations in the study area; one at Ellagawa and another at Ratnapura subwatershed. Four rain gauging stations, Alupolla Group, Landsdown, Ratnapura, and Wellandura tea factory located inside the boundary of Ellagawa and Ratnapura, while due to the availability of data Halwatura which lies little away from the boundary of Ellagawa watershed were selected. The locations and density of rain gauging and stream gauging stations of Ellagawa and Ratnapura watershed and the recommended density by the WMO guideline are given in Table 4-1 and Table 4-2 for Ellagawa and Ratnapura watershed respectively. And the boundaries of the study areas are given in Figure 4-1.

Table 4-1 Distribution of gauging stations of Ellagawa watershed

| **Gauging Station** | **Number of Stations** | **Station Density (km$^2$/station)** | **WMO Standards (km$^2$/station)** |
|---|---|---|---|
| Rainfall | 5 | 290 | 575 |
| Streamflow | 1 | 1391 | 1875 |
| Evaporation | 1 | 1391 | 50000 |

Table 4-2 Distribution of gauging stations of Ratnapura watershed

| **Gauging Station** | **Number of Stations** | **Station Density (km$^2$/station)** | **WMO Standards (km$^2$/station)** |
|---|---|---|---|
| Rainfall | 4 | 150 | 575 |
| Streamflow | 1 | 603 | 1875 |
| Evaporation | 1 | 603 | 50000 |

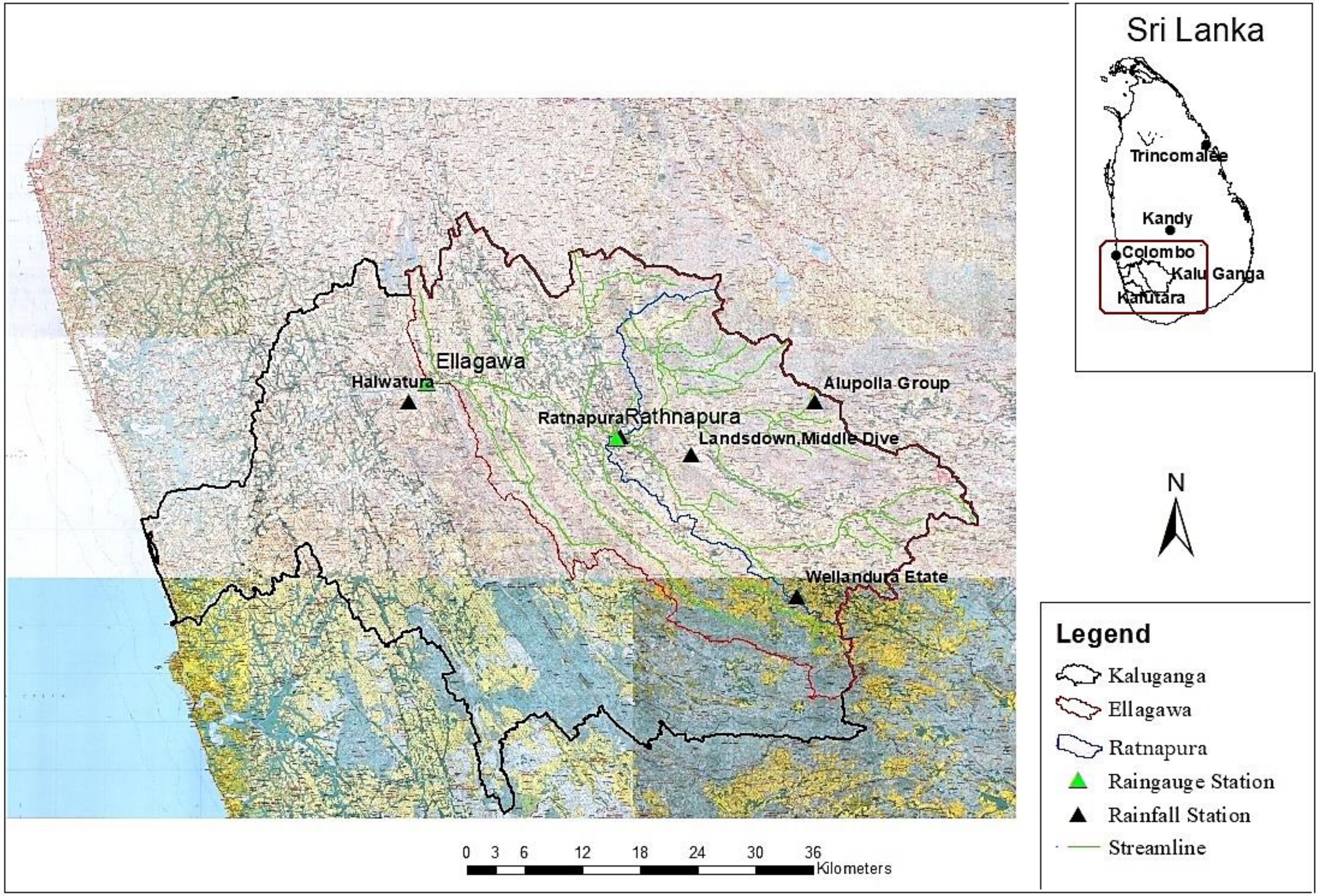



Figure 4-1 Map of Kalu Ganga river basin with Ellagawa and Ratnpura watershed

## 4.3 Data Summary

For the continuous rainfall-runoff simulation of a watershed long term rainfall, streamflow and evapotranspiration data is required. Therefore, considering the objective of the study eight years of rainfall, streamflow, and pan evaporation data on a daily time resolution from October 2009 to September 2017 were obtained for Ellagawa and Ratnapura watershed. The required data were collected from the various department of Sri Lanka and open online sources. Rainfall and pan evaporation from the department of metrology, streamflow from the department of irrigation and topographic, soil, land use maps with 1:50000 spatial resolution, were obtained from the survey department. In addition, DEM with 30m spatial resolutions for the study area downloaded from the USGS database. Types, spatial and temporal resolutions, and sources of the collected data are given in Table 4-3.

Table 4-3 Data summary of Ellagawa and Ratnapura watershed

| Data Type | Spatial Resolution | Station Name | Data Period | Source |
|---|---|---|---|---|
| Rainfall | Daily | Alupolla Group | 2009/10 to 2016/17 | Department of Meteorology & Irrigation Department |
| | | Halwatura | | |
| | | Landsdown | | |
| | | Ratnapura | | |
| | | Wellandura tea factory | | |
| Streamflow | Daily | Ellagawa | 2009/10 to 2016/17 | Department of Irrigation |
| Pan Evaporation | Daily | Ratnapura | 2009/10 to 2016/17 | Department of Meteorology |
| Land Use Map | 1: 50000 | Sri Lanka | 2015 | Department of Survey |
| Topographic | 1: 50000 | Sri Lanka | 2015 | Department of Survey |

## 4.4 Visual Data Checking

Time series of rainfall streamflow and evaporation data were screened visually to make sure the absence of outliers or any inconsistencies in the datasets. Daily, monthly, and seasonal streamflow responses to the rainfall were plotted and the errors in datasets were read circled on the plots. In the visual screening process of the daily and monthly data, many disparities in the streamflow response to rainfall were observed. Some of these disparities were due to missing or unrepresentativeness of the rainfall data. The data checking graphs for visual data screening are given in ANNEX B – Data Checking.

### 4.4.1 Rainfall data

In this study, daily areal average rainfall was utilized to analyze the viability of parameters transfers from Ellagawa to Ratnapura and from Ratnapura to Ellagawa watershed. Locations of the stations are given in Table 4-4.

Table 4-4 Rainfall station details of Ellagawa and Ratnapura watersheds

| **Rainfall Station** | **Coordinates** | |
|---|---|---|
| | **Longitude** | **Latitude** |
| Alupolla Group | 80$^{o}$ 34' 48''E | 6$^{o}$ 43' 12'' N |
| Halwathura | 80 $^{o}$ 12’ 0''E | 6$^{o}$ 43' 12'' N |
| Landsdown | 80$^{o}$ 27'36'' E | 6$^{o}$ 40' 48'' N |
| Ratnapura | 80$^{o}$ 24' 0''E | 6$^{o}$ 40' 48'' N |
| Wellandura tea factory | 80$^{o}$ 33’36’’E | 6o 31’48’’ N |

During data entry, it’s noticed that almost all rainfall stations had missing values. Ratnapura rainfall station had a high missing 20.51% of the total data period. While other stations have roughly 5% missing. The overall percentage of missing in the whole rainfall dataset is around 8%. According to the WMO guideline, the missing in data are in an acceptable range and after filling can be used for hydrologic analysis. Missing values in rainfall stations shown in Table 4-5.

Table 4-5 Missing days in rainfall data of Ellagawa and Ratnapura

| **Year** | **Halwatura** | **Ratnapura** | **Alupola** | **Landsdown** | **Wellandura** |
|---|---|---|---|---|---|
| 2009/2010 | – | 33 | – | – | – |
| 2010/2011 | – | 86 | – | – | 30 |
| 2011/2012 | – | 176 | 30 | 31 | 121 |
| 2012/2013 | – | 141 | 30 | 62 | 31 |
| 2013/2014 | – | 163 | – | 31 | – |
| 2014/2015 | 30 | – | – | – | – |
| 2015/2016 | – | – | – | 31 | – |
| 2016/2017 | 123 | – | – | - | – |
| Total | 153 | 566 | 60 | 155 | 182 |
| Missing (%) | 5.24% | 20.51% | 4.25% | 5.31% | 6.23% |

### 4.4.2 Streamflow data

For the calibration and verification process of the model observed streamflow of the watershed is required. Therefore, in this stud, daily streamflow was utilized for the analysis of Ellagawa and Ratnapura watershed. Locations coordinates of the stations are given in Table 4-4.

Table 4-6 Streamflow Gauging Stations Details

| **Stream gauge Station** | **Coordinates** | |
|---|---|---|
| | **Longitude** | **Latitude** |
| Ellagawa | 80º 27' 10''E | 6º 37' 20'' N |
| Ratnapura | 80 º 13' 0''E | 6º 43' 53'' N |

There were no missing values in the streamflow data for both stations.

### 4.4.3 Evaporation data

In this study pan evaporation on a daily temporal resolution was used for the modeling of Ellagawa and Ratnapura watersheds. Locations coordinates of the stations are given in Table 4-4.

Table 4-7 Evaporation station details

| **Stream gauge Station** | **Coordinates** | |
|---|---|---|
| | **Longitude** | **Latitude** |
| Ratnapura | 80 º 13' 0''E | 6º 43' 53'' N |

### 4.4.4 Daily data screening

Daily streamflow response of Ellagawa and Ratnapura watershed to the Thiessen average rainfall were plotted and the disparities were circled in red color. These irresponsive points are marked on the plots from Figure 4-2 to Figure 4-5.

In addition, watershed streamflow response to each rainfall station was plotted and the graphs are given in ANNEX B – Data Checking.

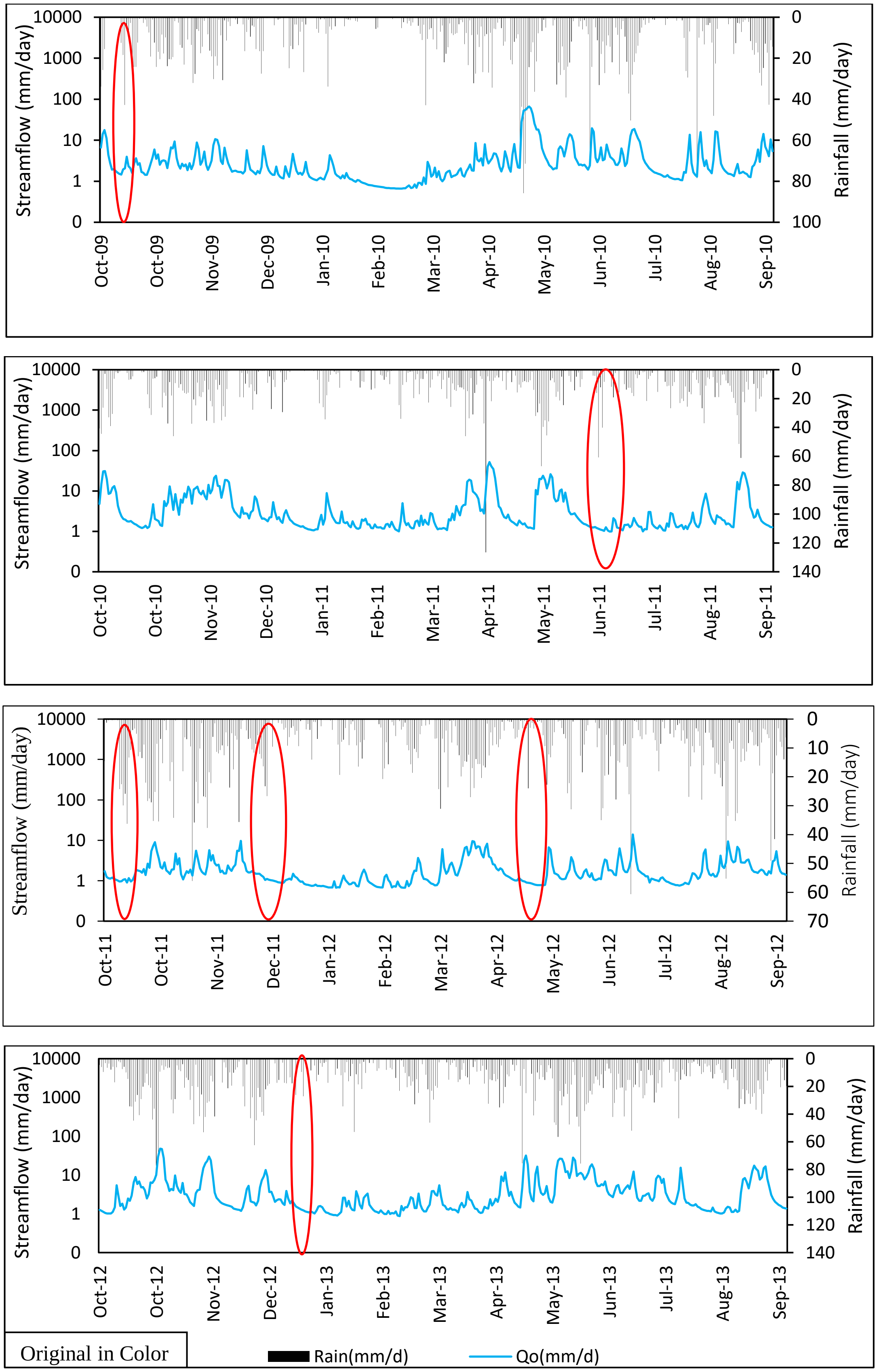



Figure 4-2 Ellagawa streamflow response to Thiessen rainfall (Calibration period)

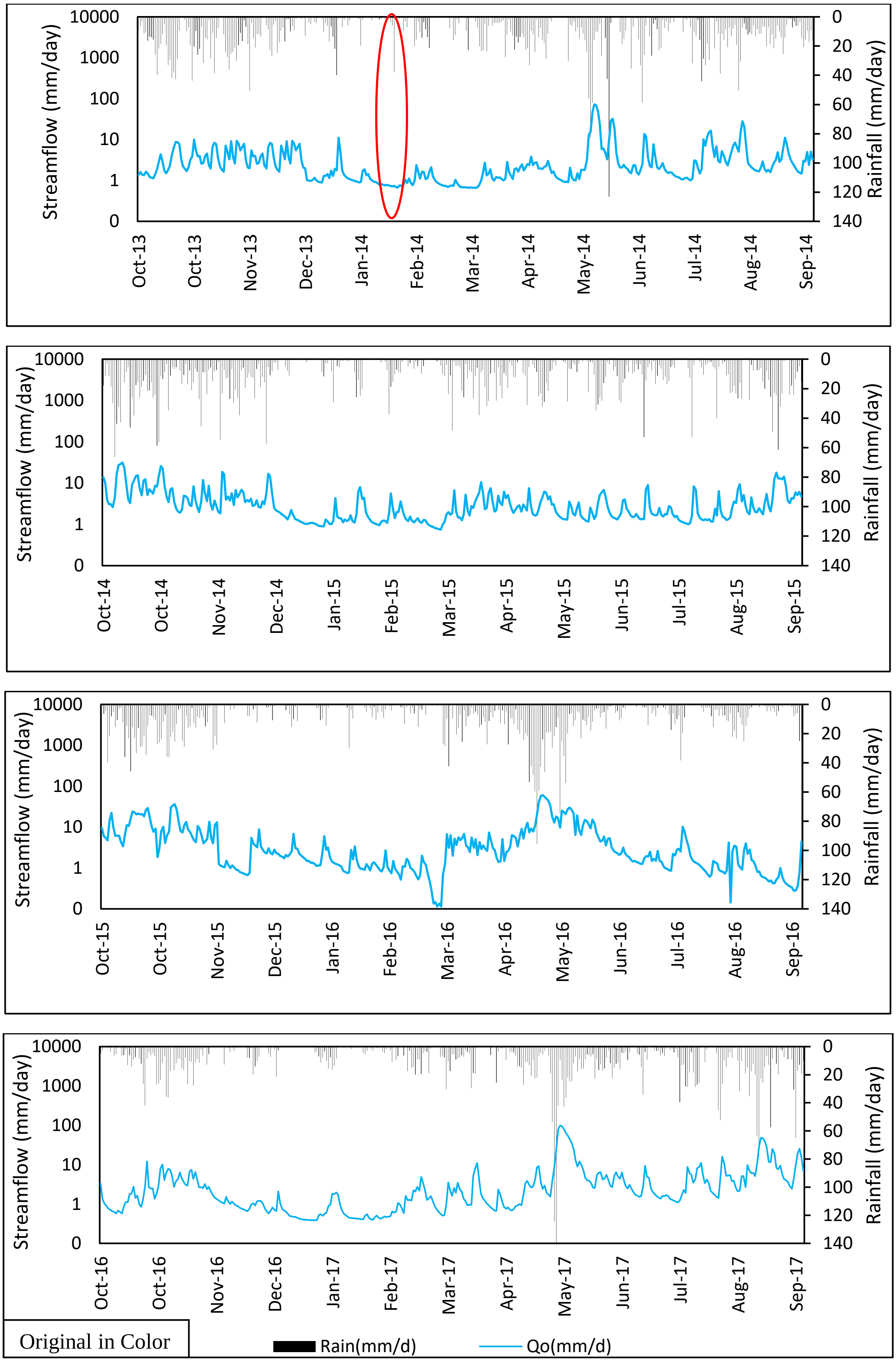



Figure 4-3 Ellagawa streamflow response to Thiessen rainfall (Verification period)

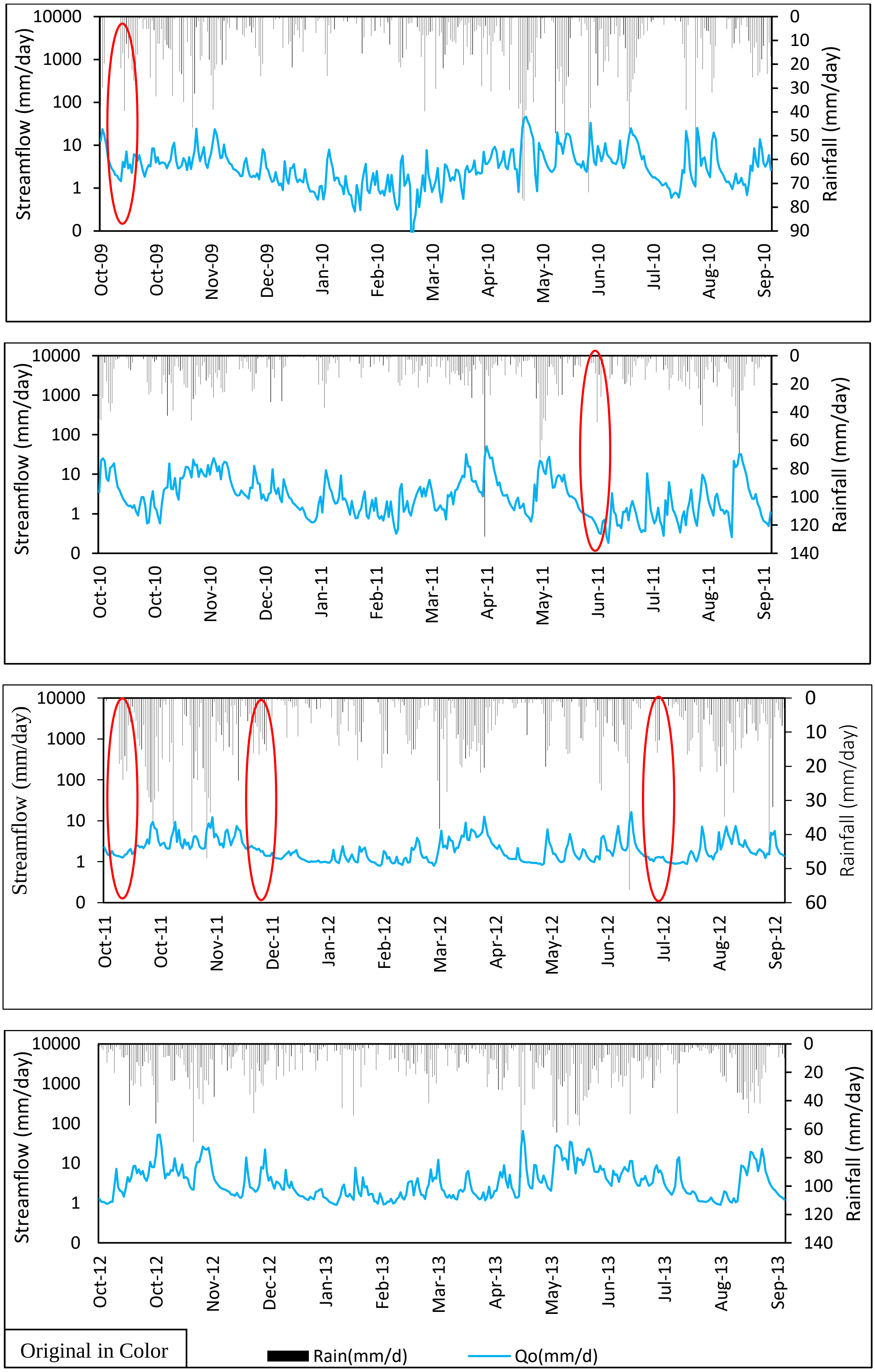



Figure 4-4 Ratnapura streamflow response to Thiessen rainfall (Calibration period)

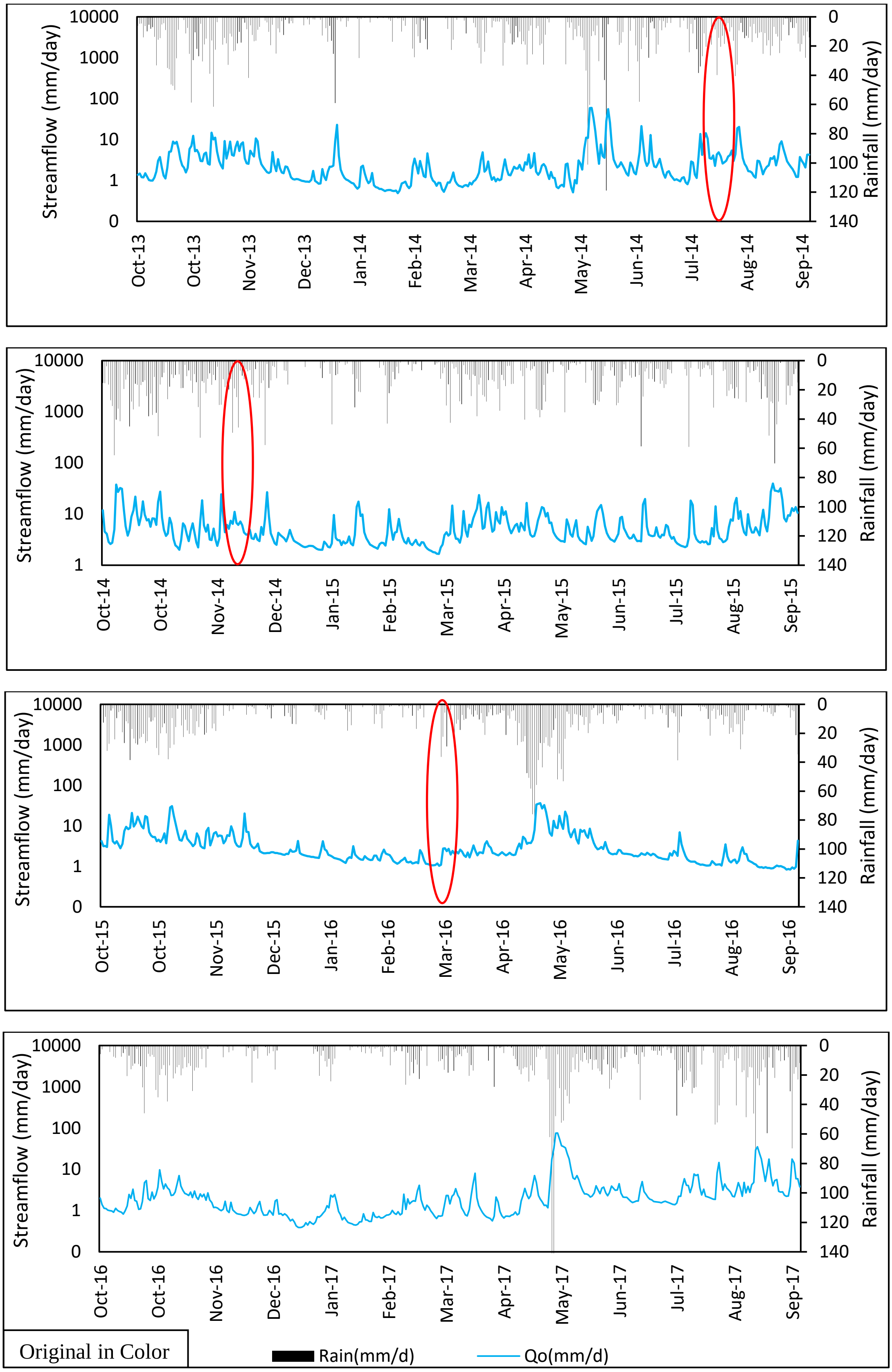



Figure 4-5 Ratnapura streamflow response to Thiessen rainfall (Verification period)

### 4.4.5 Monthly and annual data screening

The monthly average of eight years of rainfall data for all stations was estimated to understand the variation in the monthly average rainfall of the stations. The monthly average rainfall of each station is given in Table 4-8

Table 4-8 Comparison of the monthly average rainfall of stations

| Month | Monthly average rainfall (mm) | | | | |
|---|---|---|---|---|---|
| | Halwathura | Ratnapura | Alupola | Landsdown | Wellandura |
| October | 489 | 552 | 570 | 461 | 323 |
| November | 489 | 504 | 573 | 424 | 347 |
| December | 347 | 428 | 250 | 286 | 269 |
| January | 111 | 181 | 159 | 129 | 128 |
| February | 104 | 158 | 124 | 97 | 140 |
| March | 220 | 240 | 208 | 205 | 175 |
| April | 384 | 428 | 335 | 338 | 229 |
| May | 528 | 541 | 642 | 554 | 306 |
| June | 452 | 463 | 475 | 488 | 266 |
| July | 286 | 351 | 314 | 298 | 165 |
| August | 348 | 404 | 386 | 373 | 220 |
| September | 418 | 452 | 504 | 474 | 198 |
| Annual Total | 4179 | 4703 | 4540 | 4128 | 2767 |

Monthly average rainfall for all stations graphically presented in Figure 4-6.

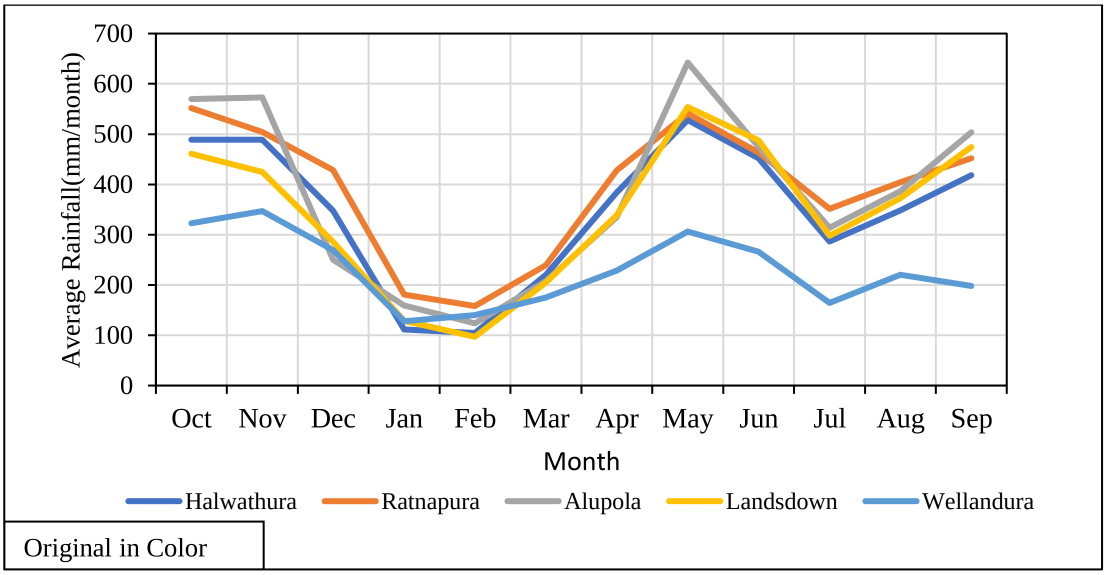


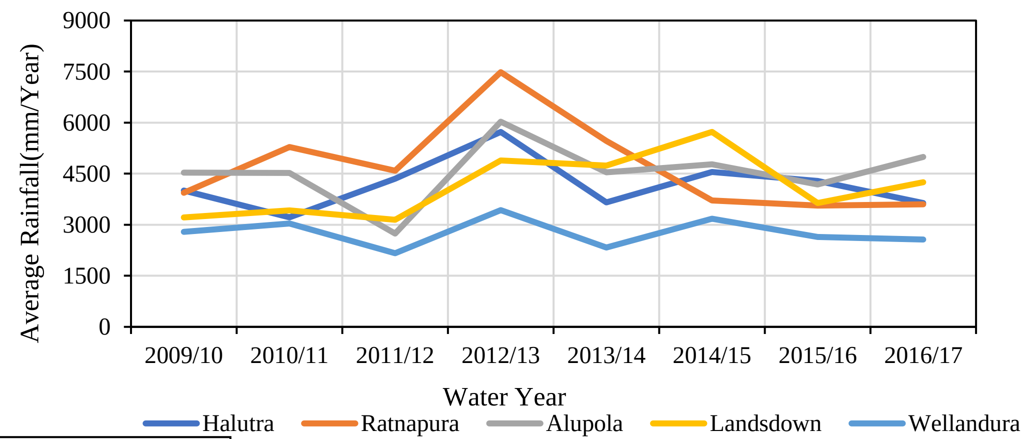

Figure 4-6 Variation of the monthly average rainfall of stations

From Figure 4-6, it can be observed that the monthly average rainfall of Ratnapura, Alupola, Landsdown, and Halwathura is roughly comparable, while Wellandura, showed a significant decrease in rainfall from April to September compared to other stations. In October and May, all stations recorded the high rainfall of the year. Similarly, the annual average rainfall of all stations was estimated and given in Table 4-9.

Table 4-9 Comparison of the annual average rainfall of stations

| Water Year | Halwathura | Ratnapura | Alupola | Landsdown | Wellandura |
|---|---|---|---|---|---|
| 2009/2010 | 4001 | 3941 | 4533 | 3218 | 2793 |
| 2010/2011 | 3218 | 5280 | 4525 | 3425 | 3032 |
| 2011/2012 | 4351 | 4585 | 2741 | 3146 | 2163 |
| 2012/2013 | 5727 | 7483 | 6027 | 4887 | 3430 |
| 2013/2014 | 3657 | 5458 | 4538 | 4741 | 2329 |
| 2014/2015 | 4552 | 3712 | 4780 | 5728 | 3177 |
| 2015/2016 | 4285 | 3563 | 4181 | 3634 | 2639 |
| 2016/2107 | 3640 | 3601 | 4992 | 4246 | 2569 |

Comparison of annual rainfall for all stations showed that there is a considerable drop in annual rainfall of Wellandura compared to other rainfall stations. Halwathura also showed an irregular pattern compared to other stations. All stations recorded high rainfall in the water year 2012/2013.




Original in Color

Figure 4-7 Annual rainfall variation at Ellagawa and Ratnapura watershed

### 4.5 Annual Water Balance

The water balance concept for a hydrologic system is based on the conservation of mass in an impenetrable system. Therefore, the annual water balance for the Ellagawa and Ratnapura watershed were estimated to assess the inflow and out of the watershed and understand the prominent variations in the water balance of watershed. The annual water balance of Ellagawa watershed is given int Table 4-10.

Table 4-10 Annual water balance of Ellagawa watershed

| Water Year | Thiessen Rainfall (mm/year) | Observed Streamflow (mm/year) | Pan Evaporation (mm/year) | Annual Water Balance (mm/year) | Runoff Coefficient |
|---|---|---|---|---|---|
| 2009/2010 | 3667.36 | 1600.16 | 942.17 | 2067.20 | 0.4 |
| 2010/2011 | 4045.01 | 1746.87 | 908.58 | 2298.14 | 0.5 |
| 2011/2012 | 3537.54 | 738.71 | 1011.83 | 2798.83 | 0.3 |
| 2012/2013 | 5696.14 | 1738.12 | 899.90 | 3958.02 | 0.4 |
| 2013/2014 | 4253.82 | 1414.76 | 922.66 | 2839.06 | 0.4 |
| 2014/2015 | 4231.31 | 1423.96 | 907.09 | 2807.35 | 0.3 |
| 2015/2016 | 3511.18 | 2098.27 | 863.67 | 1412.90 | 0.6 |
| 2016/2017 | 3693.08 | 1842.00 | 899.18 | 1851.07 | 0.5 |
| Average | 4079.43 | 1575.36 | 2504.07 | 919.38 | 0.4 |

Evaluation of the annual water balance for Ellagawa watershed revealed that there is a significant variation in the annual water balance of the water years of the collected data. The water years of 2012/13 and 2015/16 were showed the highest variation concerning other water years. Accordingly, 2016/17 also showed a decline compared to other water years. Comparison of water balance for Ellagawa watershed is shown in Figure 4-8.

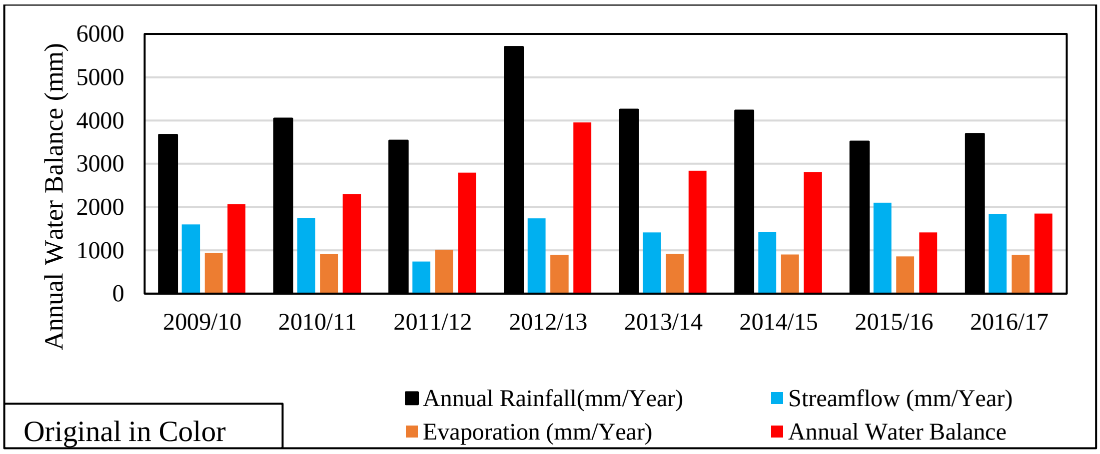



Figure 4-8 Annual water Balance of Ellagawa watershed

Annual water balance comparison of the Ratnapura watershed is given in Table 4-11.

Table 4-11 Annual water balance of Ratnapura watershed

| Water Year | Thiessen Rainfall (mm/year) | Observed Streamflow (mm/year) | Pan Evaporation (mm/year) | Annual Water Balance (mm/year) | Runoff Coefficient |
|---|---|---|---|---|---|
| 2009/2010 | 3721.82 | 1768.80 | 942.17 | 1953.02 | 0.5 |
| 2010/2011 | 3919.03 | 1876.00 | 908.58 | 2043.03 | 0.5 |
| 2011/2012 | 2980.18 | 880.93 | 1011.83 | 2099.25 | 0.3 |
| 2012/2013 | 5227.89 | 1987.01 | 899.90 | 3240.88 | 0.4 |
| 2013/2014 | 4168.64 | 1326.89 | 922.66 | 2841.75 | 0.3 |
| 2014/2015 | 4506.84 | 1047.32 | 907.09 | 3459.53 | 0.2 |
| 2015/2016 | 3452.02 | 1494.27 | 863.67 | 1957.74 | 0.4 |
| 2016/2017 | 3950.13 | 1323.84 | 899.18 | 2626.29 | 0.3 |
| Average | 3990.82 | 1463.13 | 919.38 | 2527.69 | 0.4 |

Similarly, the evaluation of the annual water balance for Ratnapura watershed also showed variation in the annual water balance of the water years. This variation is not following a similar pattern that Ellagawa showed. And the reason could be the unrepresentative rainfall of the watershed. Graphical representation of the annual water balance comparison of the Ratnapura watershed is shown in Figure 4-9.

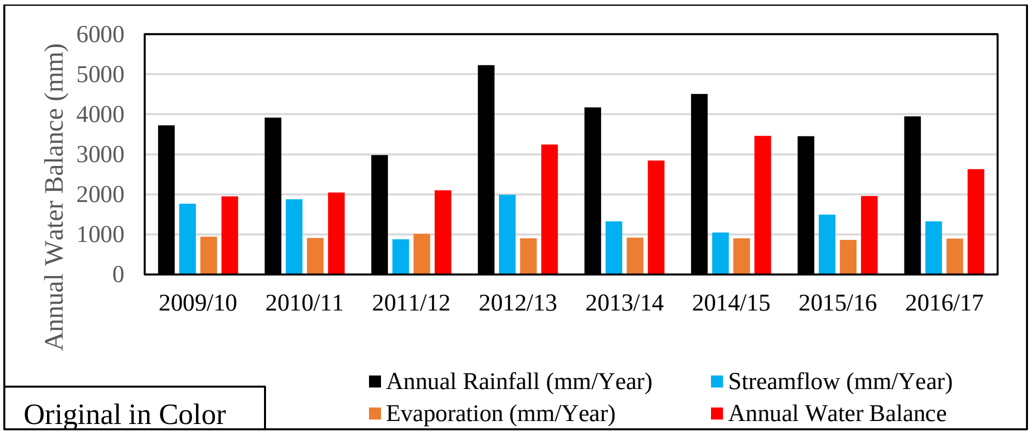



Figure 4-9 Annual water balance of Ratnapura watershed

### 4.5.1 Comparison of the runoff coefficient and evaporation at Ellagawa

The annual runoff coefficient for the Ellagawa watershed showed significant variation during the eight years of the collected dataset. The runoff coefficient for the water year 2014/15 showed a very high value of 0.6, compared to the other water years. On the other hand, for the water year 2015/16, it showed a very low value of 0.3. The reason for the low value of the runoff coefficient in this year could be the disparities in the streamflow response to rainfall and the unrepresentativeness of the watershed rainfall. In the water year, 2011/12 high evaporation and accordingly low streamflow were recorded compared to the other water years of the collected data. Comparison of annual evaporation and runoff coefficient at Ellagawa is shown in Figure 4-10.

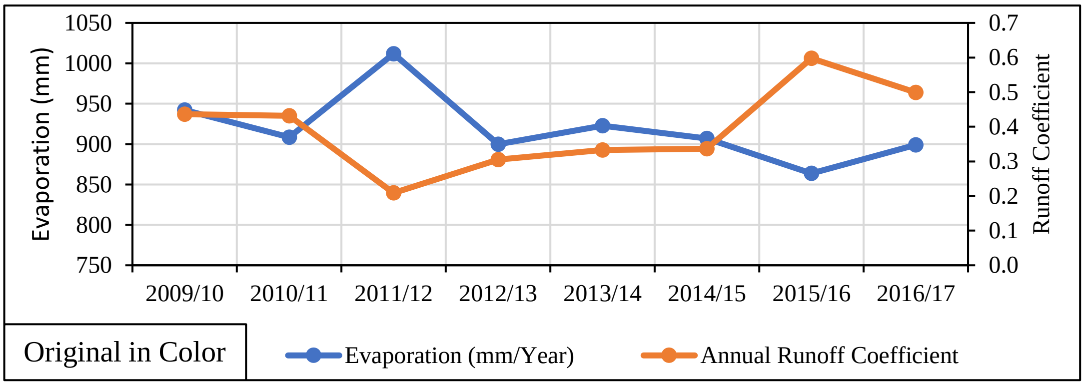



Figure 4-10 Comparison of annual evaporation and runoff coefficient at Ellagawa

### 4.5.2 Comparison of the annual rainfall and streamflow of Ellagawa

Comparison of the annual Thiessen rainfall and streamflow of the watershed showed that there are some inconsistencies in the collected dataset. Considering the representative rainfall of watershed, the streamflow response in the water year 2015/2016 is relatively very high compared to other water years. On the other hand, the streamflow in the water year 2012/2013 showed a low response to the high rainfall of the watershed. Besides, high evaporation which leads to low streamflow of the collected data duration recorded in the water year 2011/2012. Comparison of annual rainfall and streamflow at Ellagawa watershed is given in Figure 4-11.

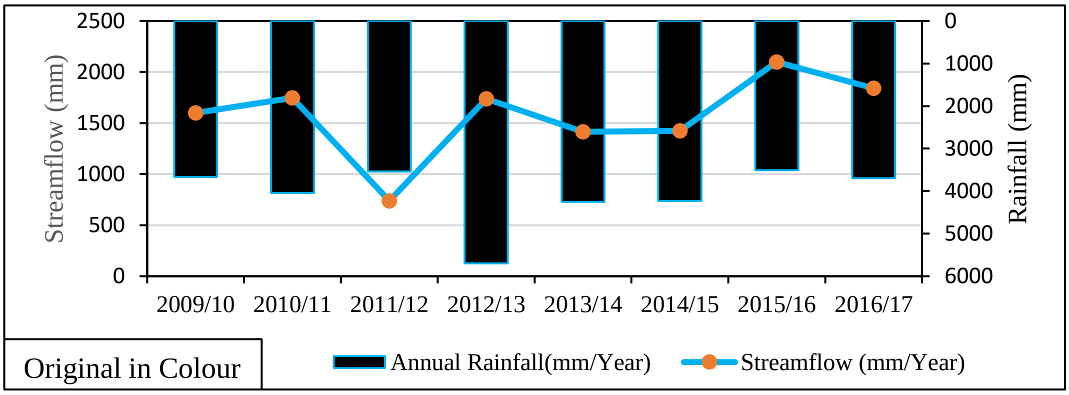



Figure 4-11 Comparison of the annual rainfall and streamflow at Ellagawa

### 4.5.3 Comparison of the runoff coefficient and evaporation at Ratnapura

Comparison of the annual runoff coefficient and evaporation of Ratnapura watershed showed a rational pattern of increase or decrease with respect to each other. The value of the runoff coefficient for Ratnapura watershed is ranging from 0.2 to 0.5. The low and high runoff coefficients of Ratnapura watershed for the collected datasets recorded in the water years of 2014/15 and 2009/10 respectively. It can be noticed that in the water year 2014/15 streamflow is not responding relative to the evaporation and rainfall of this year which leads to a low runoff coefficient in this year.

The runoff coefficient of Ratnapura and Ellagwa watershed is not following the same pattern which might be due to the variation of land use, topography, soil type, and unrepresentativeness in the watershed rainfall for these two watersheds. Comparison of the annual evaporation and runoff coefficient at Ratnapura watershed is given in Table 4-12.

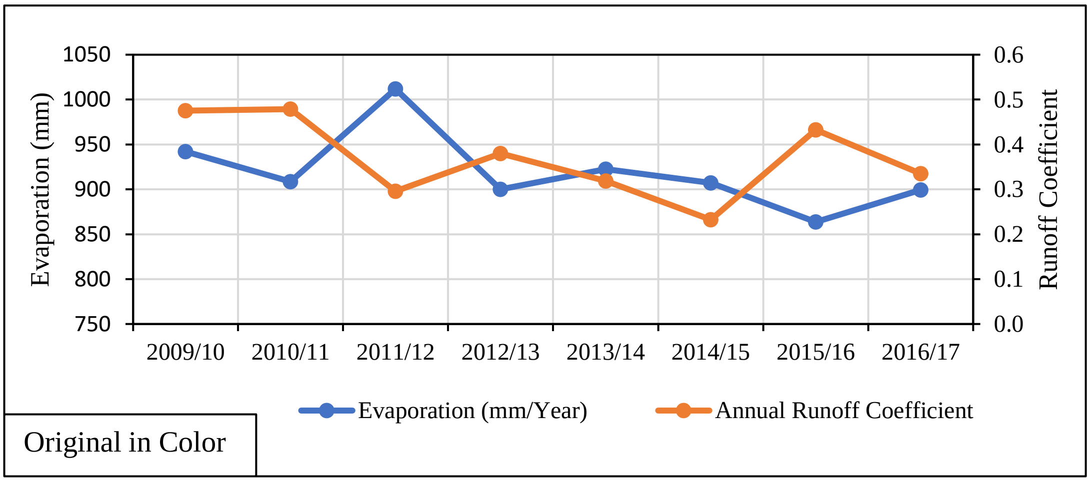



Figure 4-12 Comparison of annual evaporation and runoff coefficient at Ratnapura

### 4.5.4 Comparison of the annual rainfall and streamflow of Ratnapura

Similar to Ellagawa watershed, the water year 2011/2012 was recorded the direst year for the Ratnapura watershed in the collected datasets. Considering the representative rainfall of watershed, the streamflow response in the water years 2015/2016 is relatively high compared to the water years 2014/15 and 2016/17 whereas the representative rainfall of 2014/15 and 2016/17 is much higher than 2015/2016.

Comparison of annual rainfall and streamflow at Ratnapura watershed is given in Figure 4-13.

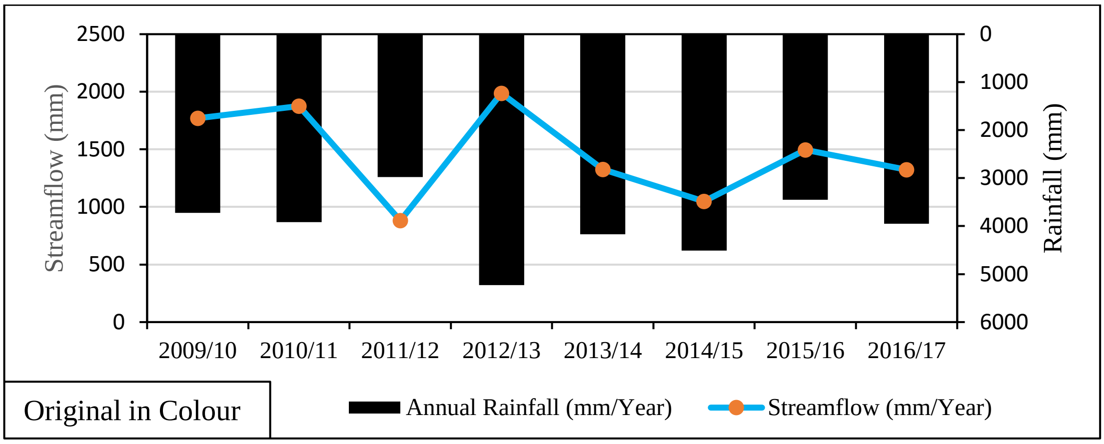



Figure 4-13 Comparison of the annual rainfall and streamflow at Ratnapura

## 4.6 Seasonal streamflow response to rainfall

There are two rainy seasons namely; Maha and Yala in Sri Lanka. In Maha Season which falls from September to March, the country experiences heavy rains and floods. In contrast, Yalla season falls from October to March in the following year. Yala season is marking by a shortage of water and dry days. Streamflow response to rainfall in both seasons at Ellagawa watershed is given in Table 4-12.

Table 4-12 Seasonal streamflow response to rainfall at Ellagawa

| Water Year | Maha Season | | Yala Season | |
|---|---|---|---|---|
| | Rainfall (mm) | Streamflow (mm) | Rainfall (mm) | Streamflow (mm) |
| 2009/10 | 1331.148 | 452.5589 | 2336.215 | 1147.603 |
| 2010/11 | 1725.661 | 800.5627 | 2319.345 | 946.3083 |
| 2011/12 | 1685.093 | 304.9959 | 1852.45 | 433.7133 |
| 2012/13 | 2730.505 | 729.2811 | 2965.639 | 1008.843 |
| 2013/14 | 1843.074 | 481.8714 | 2410.749 | 932.8901 |
| 2014/15 | 2062.415 | 821.4413 | 2168.894 | 602.5184 |
| 2015/16 | 1470.117 | 939.6607 | 2041.062 | 1158.613 |
| 2016/17 | 1144.028 | 300.6863 | 2549.05 | 1541.317 |

The seasonal variation of streamflow and rainfall at Ellagawa watershed is given in Figure 4-14 and Figure 4-15. From Figure 4-14, It can be noticed that the streamflow response to rainfall in the Maha season of 2015/16 is very high compared to other water years. While the rainfall in this year is very low with respect to the rainfall in 2012/13. Maha season of 2012/13 and 2014/15 showing higher rainfall and streamflow to other water years. While, considering the Yala season in Figure 4-15, in the year 2014/15 the streamflow response considering the rainfall in this season is comparatively very low.

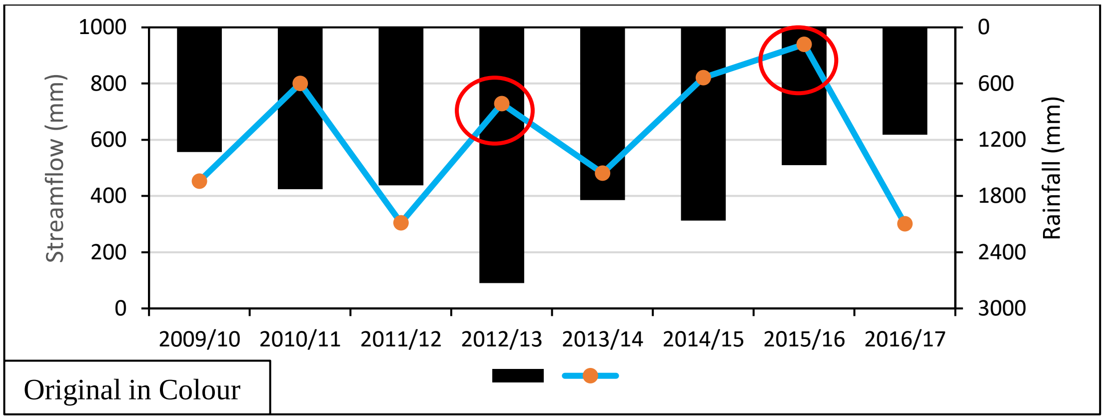



Figure 4-14 Maha season streamflow response to rainfall at Ellagawa

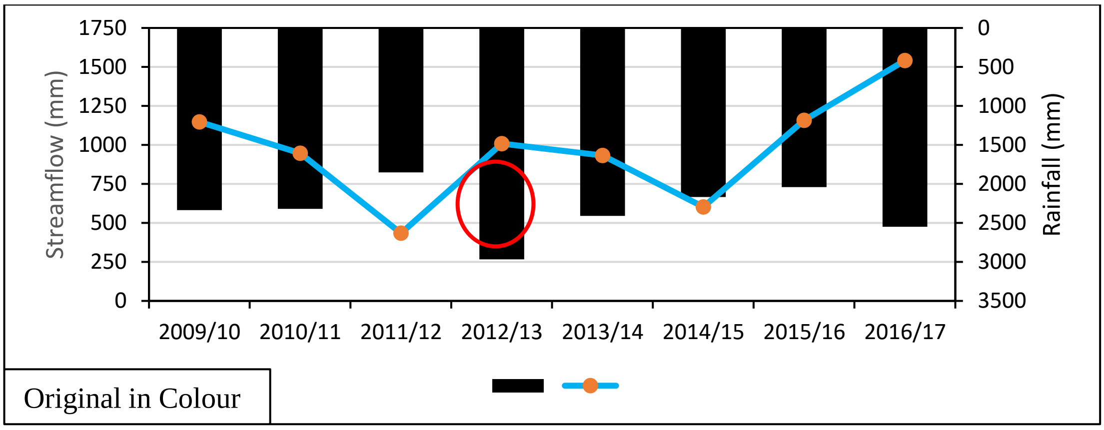



Figure 4-15 Yala season streamflow response to rainfall at Ellagawa

The seasonal variation of streamflow and rainfall at Ratnapura watershed is given in Table 4-13

Table 4-13 Seasonal streamflow response to rainfall at Ratnapura

| Water Year | Maha Season | | Yala Season | |
|---|---|---|---|---|
| | Rainfall (mm) | Streamflow (mm) | Rainfall (mm) | Streamflow (mm) |
| 2009/10 | 1476.73 | 642.51 | 2245.09 | 1126.29 |
| 2010/11 | 1703.73 | 956.83 | 2215.30 | 919.17 |
| 2011/12 | 1531.19 | 421.80 | 1448.99 | 459.14 |
| 2012/13 | 2267.25 | 852.61 | 2960.64 | 1134.40 |
| 2013/14 | 1718.45 | 487.23 | 2450.19 | 839.66 |
| 2014/15 | 2215.78 | 874.36 | 2291.06 | 172.96 |
| 2015/16 | 1418.71 | 780.73 | 2033.30 | 713.54 |
| 2016/17 | 1222.69 | 268.83 | 2727.44 | 1055.01 |

The seasonal variation of streamflow and rainfall at Ratnapura watershed is graphically presented in Figure 4-16 and Figure 4-17. It can be observed from Figure 4-16 that the streamflow response to rainfall in the Maha season of 2010/11 showing irrationality with respect to the response of streamflow in other years. Maha season of 2012/13 and 2014/15 showing higher rainfall and streamflow compared to other water years. While, considering the Yala season in Figure 4-17, in 2014/15 the streamflow response to rainfall is not rational compare to other water years. Graphical representation of Maha streamflow response to rainfall at Ratnapura is shown in Figure 4-16.

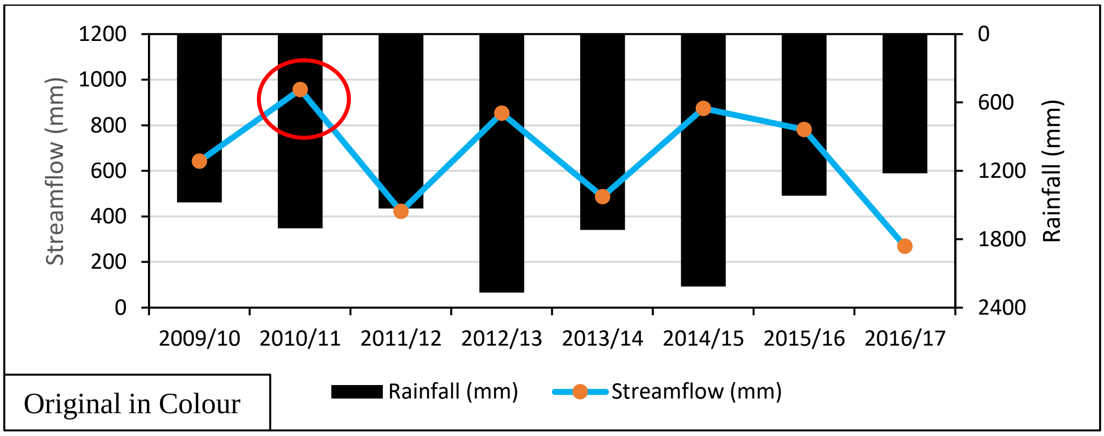



Figure 4-16 Maha streamflow response to rainfall at Ratnapura

Graphical representation of Yalla season streamflow response to rainfall at Ratnapura is shown in Figure 4-17.

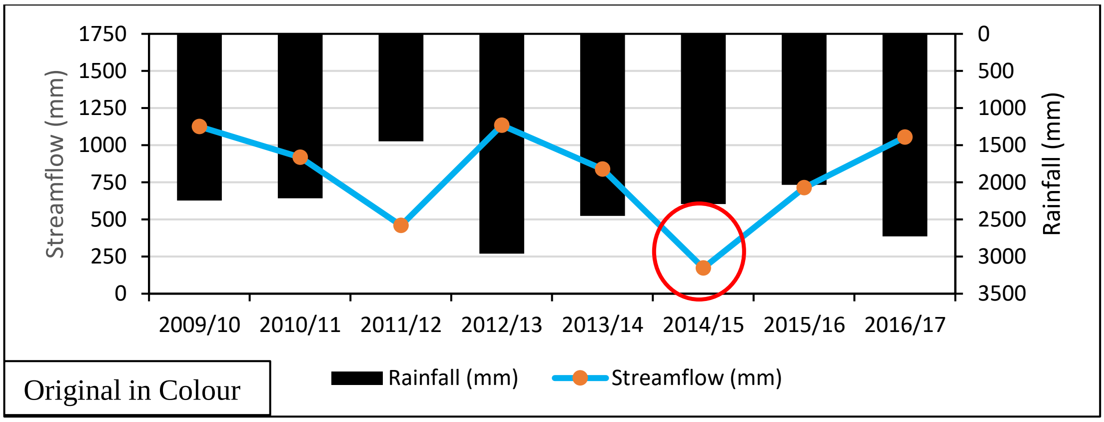



Figure 4-17 Yala streamflow response to rainfall at Ratnapura

## 4.7 Test of data for the absence of the trend

After plotting rainfall and streamflow data, the time series datasets were checked for the absence of trend. And assured the order or the decrease and increase in the magnitude of the data is free from correlation. For the verification of the unavailability of the trend in the collected datasets, the Spearman's rank correlation approach was applied for the whole data sets of rainfall and streamflow from 2009/10 to 2016/2017 for Ellagawa and Ratnapura watershed. According to the test assumption, the obtained conditions for the collected datasets were satisfied and the data proved free from the trend.

### 4.8 Test of Data for Consistency and Homogeneity

To screen the rainfall data for consistency the double mass curve approach was applied for the time series. In this approach, the data of one rainfall station is comparing to the data of several stations in the study area. The cumulative rainfall of each station plotted versus the average of cumulative rainfall of all other stations for Ellagawa and Ratnapura watershed. As the relation of these variables fixed ratio, the line graph expected to be straight for the consistent data. Any break in the line indicating an inconsistency in the time series and hence amended using the correction factor. The test of the data for inconsistency revealed that the time series of collected data for Ellagawa and Ratnapura watershed is free from inconsistency and can be used for hydrologic analysis. Graphs of the double mass curve analysis for Ellagawa and Ratnapura watershed is given in Appendix B.

# 5 ANALYSIS

To evaluate the Tank model parameters for spatially distributed modeling within a watershed, first, the model calibrated and verified for the Ellagawa and Ratnapura watershed. Hereafter, the optimized parameters of the Ellagawa transferred to Ratnapura and from Ratnapura to Ellagawa watershed to assess the applicability of parameters transfer from main to sub and sub to the main watershed. The collected eight years of datasets were classified into two parts. Four years for the calibration and four other years for the verification of the model.

## 5.1 Estimation of Areal Average Rainfall

In this study, considering the simplicity and easiness of application the Thiessen polygon method was applied for the estimation of average aerial rainfall of the watersheds. ArcGIS software was used for the creation of Thissen polygons of the watersheds. The Thiessen polygons area and weights are given in Table 5-1.

Table 5-1 Thiessen areas and weightage of rainfall stations at Ellagawa

| Rainfall Gauging Station | Thiessen Area (km$^2$) | Thiessen Weight (%) |
|---|---|---|
| Alupolla group | 191.474 | 13.770 |
| Halwatura | 230.010 | 16.541 |
| Landsdown middle div | 238.368 | 17.142 |
| Ratnapura | 438.841 | 31.559 |
| Wellandura estate | 291.870 | 20.989 |

Table 5-2 Thiessen areas and weightage of rainfall stations at Ratnapura

| Rainfall Gauging Station | Thiessen Area (km$^2$) | Thiessen Weight (%) |
|---|---|---|
| Alupolla group | 187.846 | 29.932 |
| Landsdown middle div | 190.291 | 30.322 |
| Ratnapura | 89.635 | 14.283 |
| Wellandura estate | 159.804 | 25.464 |

## 5.2 Classification of Streamflow

To evaluate the model performance for specific engineering applications such as water resources planning and management, drought, and flood management, the daily flow duration curves were prepared for Ellagawa and Ratnapura watershed. To separate the flow threshold boundaries on the probability of exceedance axis the magnitude of flow and slope variability information of the flow duration curve was used.

Graphical representation of the demarcation process of the high medium and low flows for Ellagawa watershed is shown in Figure 5-1.

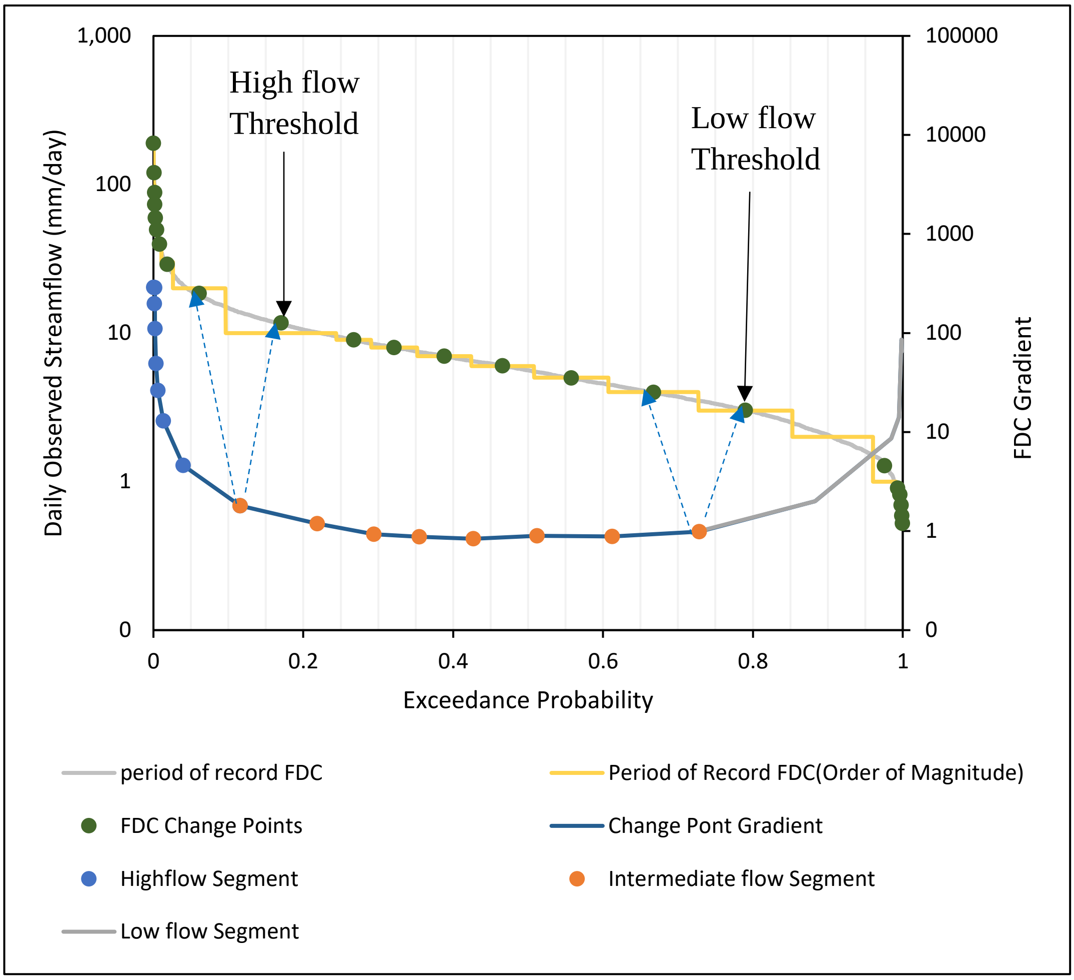



Figure 5-1 Identification of streamflow thresholds of Ellagawa watershed

The flow threshold value for Ellagawa watershed is given in Table 5-3.

Table 5-3 Identification of streamflow thresholds of Ellagawa watershed

| Flow Type | Percentage Exceedance | |
|---|---|---|
| | Calibration | Verification |
| High | < 0.18 | < 0.18 |
| Medium | > 0.18 & < 0.78 | > 0.18 & < 0.78 |
| Low | > 0.78 | > 0.78 |

Demarcation of the high medium and low flows for Ratnapura watershed is shown in Figure 5-1.

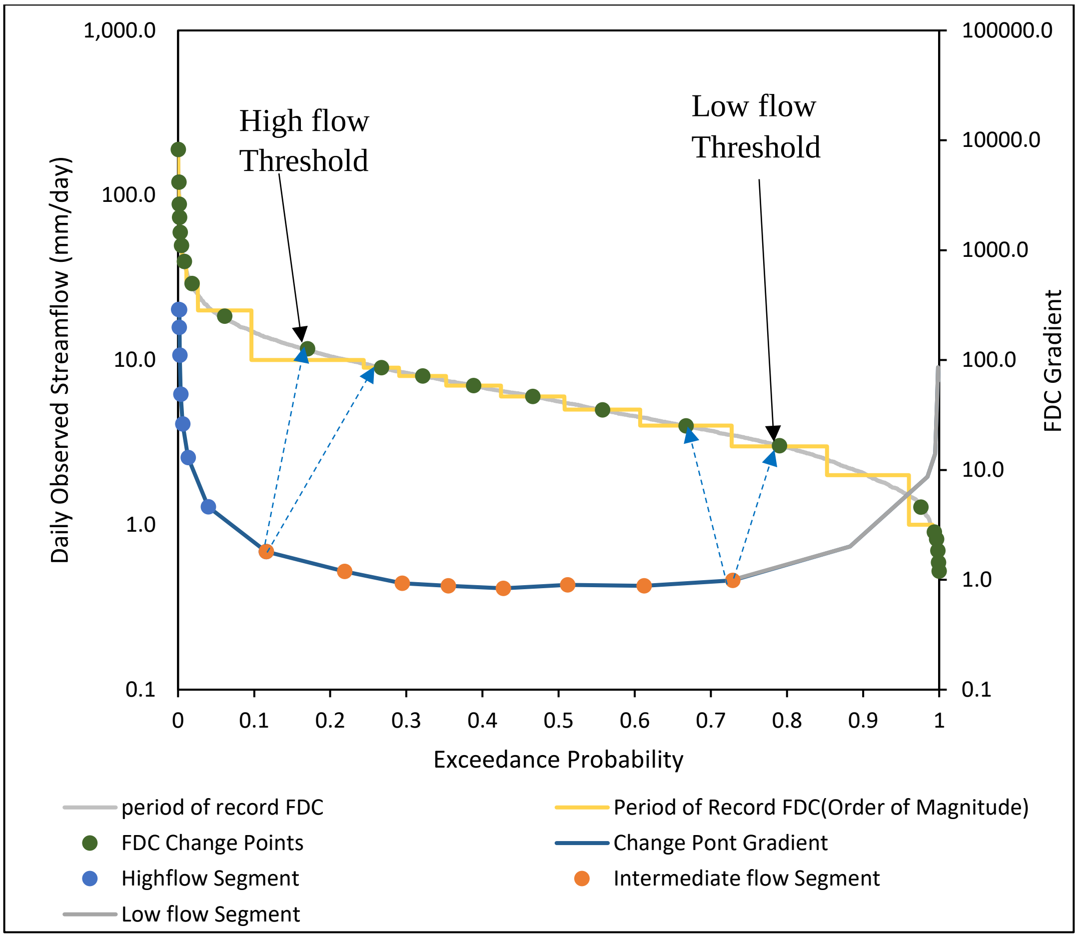



Figure 5-2 Identification of streamflow thresholds of Ratnapura watershed

The flow threshold value for Ratnapura watershed is given in Table 5-3.

Table 5-4 Identification of streamflow thresholds of Ratnapura watershed

| Flow Type | Percentage Exceedance | |
|---|---|---|
| | Calibration | Verification |
| High | < 0.18 | < 0.18 |
| Medium | > 0.18 & < 0.78 | > 0.18 & < 0.78 |
| Low | > 0.78 | > 0.78 |

Demarcation of the flow threshold boundaries revealed that the Ellagawa and Ratnapura subwatershed of Ellagawa has a similar flow regime. The probability of exceedance from 0 to 18% estimated and marked as high flows, from 18 to 78% marked as medium and, from 78% to 100% marked as a low flow region

## 5.3 Comparison of Watersheds Properties

In this section, the variation of the hydrologic, physical, and land use and land cover properties of the main and subwatershed analyzed to find out the comparability of characteristics that develop a base for the transferability of the model parameters. These properties summarised in Table 5-5 and the variation and similarity for main and subwatershed discussed in detail in the following sections.

Table 5-5 Comparison of Ellagawa and Ratnapura watersheds properties

| **Characteristics** | **Ellagawa** | **Ratnapura** |
|---|---|---|
| Area($km^2$) | 1390.563 | 627.576 |
| Elevation (MSL) (m) | | |
| Maximum | 2149 | 2149 |
| Minimum | 7 | 10 |
| Average slope (degrees) | 40 | 40 |
| Land cover ($km^2$) | | |
| Built-up Area | 18.4% | 18.5% |
| Cultivation Area | 56.0% | 55.5% |
| Forest | 17.5% | 20.5% |
| Paddy | 6.8% | 4.2% |
| Water bodies | 1.4% | 1.3% |
| Soil(km2) | | |
| Alluuvial soils of variable texture and drainage; flat terrain | 0.9% | NA |
| Bog and half-dog soils, flat terrain | 1.9% | 1.2% |
| Erosional remnants steep rock land and verious lithosols | 2.7% | 3.7% |
| Reddish Brown Earths and Immature Brown Loams; rolling and hilly | 0.4% | 0.9% |
| Red-Yellow podzolic soils and mountain regosols | 3.0% | 4.3% |
| Red-Yellow podzolic soils, steeply dissected,hilly and rolling te | 86.5% | 90.0% |
| Red-Yellow podzolic soils and mountain regosols | 4.7% | NA |
| Precipitation | | |
| Annual average (mm/year) | 3747.71 | 3882.13 |
| Discharge (mm/year) | 1604.22 | 1477.32 |
| Runoff coefficient | 0.4 | 0.4 |

### 5.3.1 Comparison of elevation

Ratnapura subwatershed is located as a headwater watershed in the upstream of Ellagawa main watershed and has great relief. The elevation of Ellagawa and Ratnapura watershed is ranging from 7m to 2149m and from 10m to 2149m, MSL, respectively.

It can be observed from Figure 5-3 that most of the high-altitude areas bounded by Ratnapura watershed. Hence, upper areas of the watershed in the basin comparatively receive higher rainfall to the lower areas of the watershed. According to the altitude-rainfall relation, the rainfall gradually reducing from the origin point of the river in the central hills of the country to where it flows to the ocean. Considering the precipitation trend with respect to the altitude the annual average rainfall of Ellagawa and Ratnapura watershed is not significantly varied. The annual average rainfall of Ellagawa is 4079.43mm/day while Ratnapura watershed is receiving 3990.82 mm/day annual average rainfall. A decline in the precipitation of Ratnapura watershed compared to Ellagwa might be due to the scale and rain gauge density impact on the estimation of representative average rainfall. In addition, there is a huge flood-prone area in the downstream of Ellagawa watershed which may cause significant variation in the model parameters account for peak flows of the watersheds.

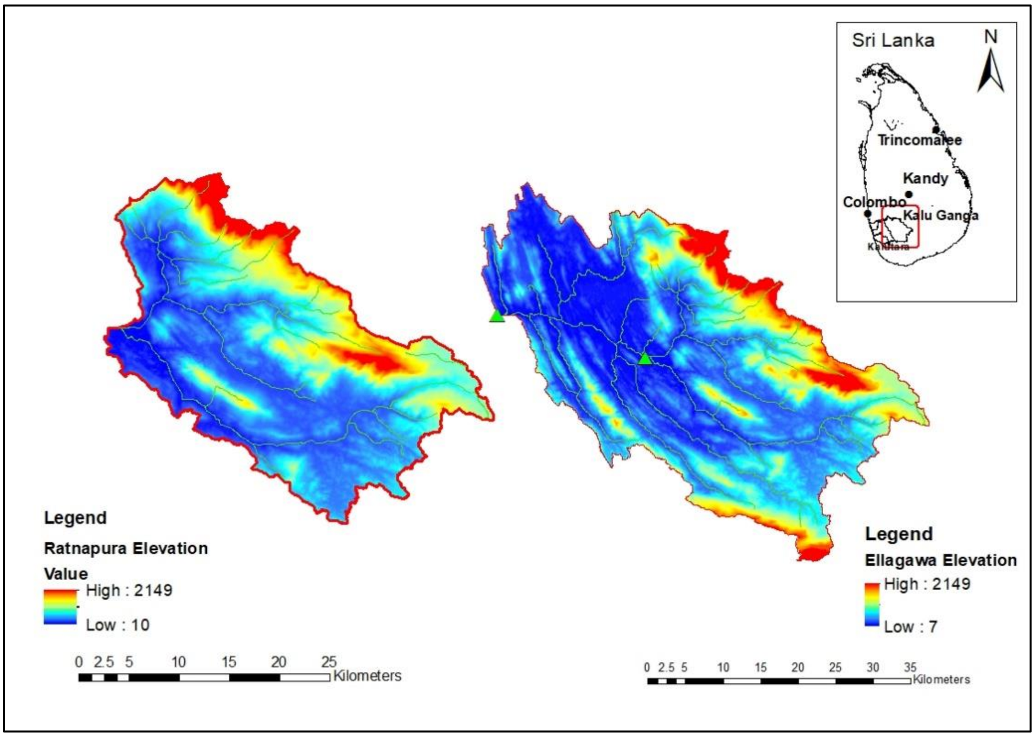



Figure 5-3 Elevation maps of Ellagawa and Ratnaura watersheds

### 5.3.2 Comparison of slope

The slope of a watershed really affects the watershed response to a precipitation event in terms of concentration-time, lag of watershed, and travel time. Accordingly, these characteristics of watershed account for the shape and peaks of a watershed hydrograph.

Hence, variation in the watershed slope influences the estimation process of model parameters. Various methods coupled with standard GIS tools can apply for the estimation of catchment average slope. In this study, the Neighbourhood method is used to calculate the average slope of  Ellagawa and Ratnapura watershed. The slope and its classification are shown in Figure 5-4. The gradient of both watersheds at the upper region is steep while in the downstream area following a mild gradient.

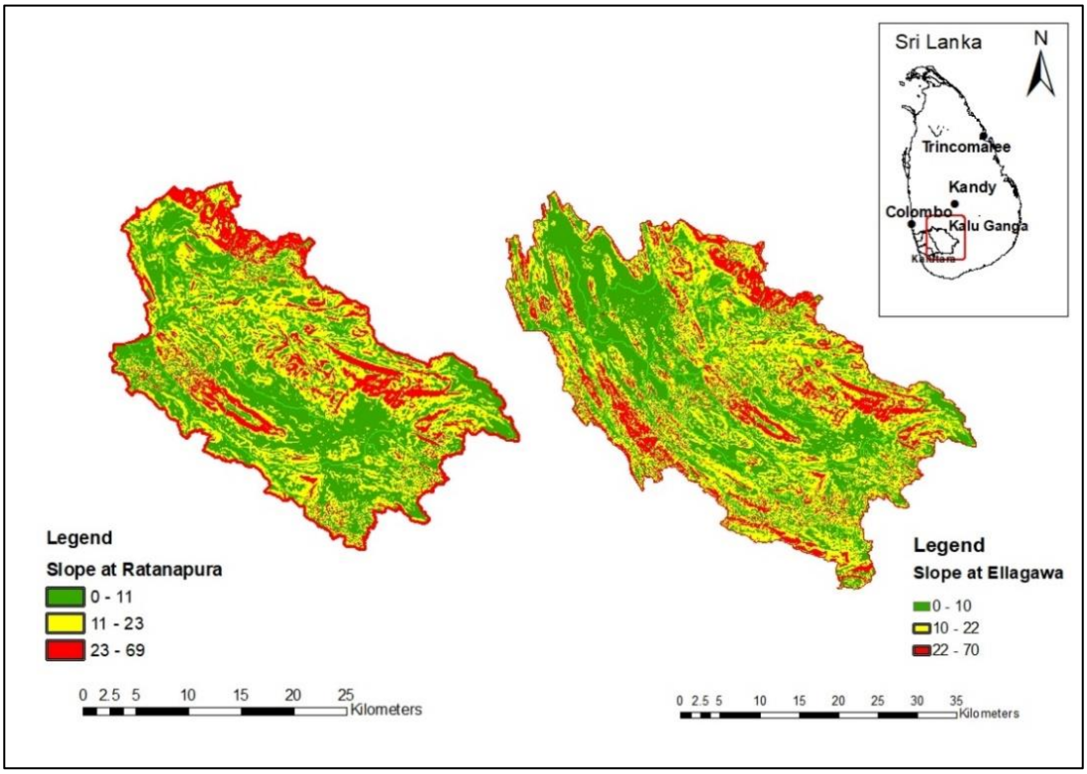



Figure 5-4 Slope maps of Ellagawa and Ratnapura watersheds

### 5.3.3 Comparison of soil types

Physical properties of soil really influence the rate of infiltration and the amount of runoff in a watershed. According to the soil map from Survey Department, Figure 5-5, Steeply dissected, Rolling te and Red-yellow podzolic soils hilly are the dominant soil types for both watersheds that covering 86.5% and 90.0% area of Ellagawa and Ratnapura watershed respectively. Two types of soil which are not contained in Ratnapura watershed, Flat terrain; Alluuvial soils of variable texture and drainage; and Red-Yellow podzolic soils and mountain regosols that roughly covering 6% area of Ellagawa watershed. Soil types which are shown in Figure 5-5 roughly comparable for main and subwatershed.

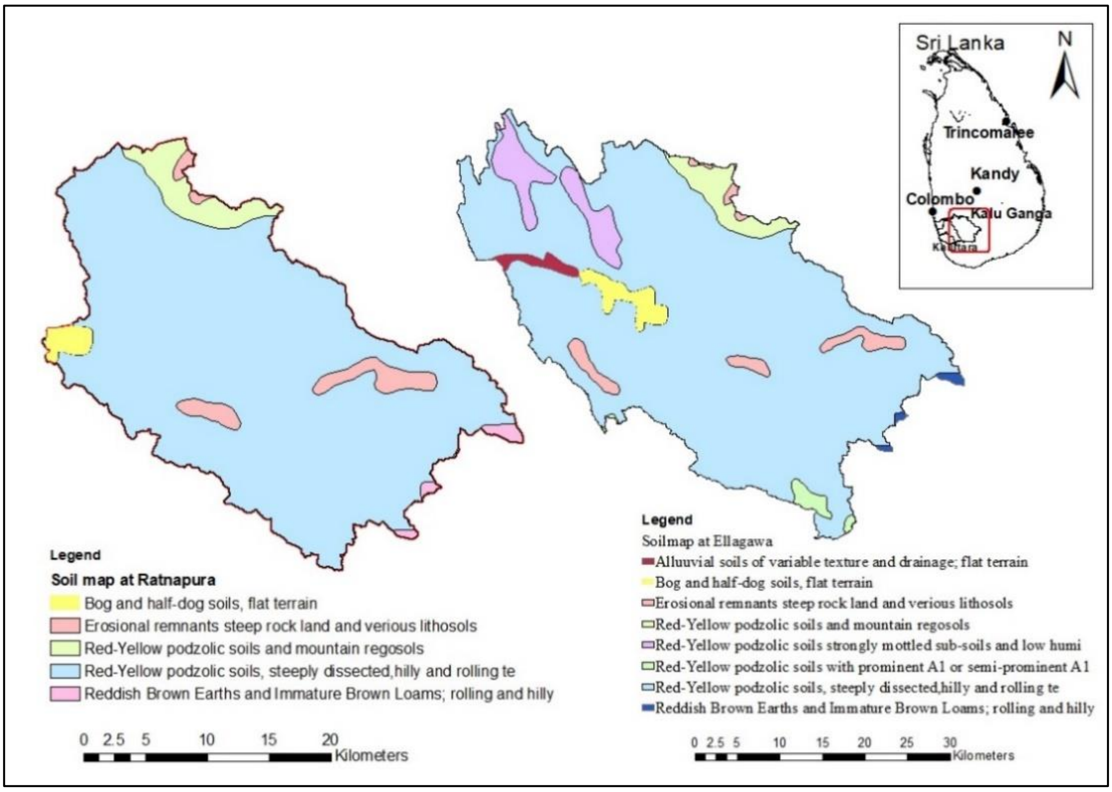



Figure 5-5 Soil maps of Ellagawa and Ratnapura watersheds

Table 5-6 Soil Comparison of Ellagawa and Ratnapura watershed

| **Soil type** | **Ellagawa** | **Ratnapura** |
|---|---|---|
| Alluuvial soils of variable texture and drainage; flat terrain | 0.9% | N/A |
| Bog and half-dog soils, flat terrain | 1.9% | 1.2% |
| Erosional remnants steep rock land and verious lithosols | 2.7% | 3.7% |
| Reddish Brown Earths and Immature Brown Loams; rolling and hilly | 0.4% | 0.9% |
| Red-Yellow podzolic soils and mountain regosols | 3.0% | 4.3% |
| Red-Yellow podzolic soils, steeply dissected, hilly and rolling te | 86.5% | 90.0% |
| Red-Yellow podzolic soils and mountain regosols | 4.7% | N/A |

### 5.3.4 Comparison of land use

Variation in land use and land cover affect the streamflow characteristic of a watershed to a great extent. Generally, it is common in practice that more the build-up or non-permeable land use results in high surface flow and infiltration become lesser. Land use and land cover pattern give a rough idea and estimate about the surface runoff over a drainage area. According to the land use map Figure 5-6 of the study area, cultivation is the dominant vegetation type for both main and subwatershed. while other land uses such as forest, build-up, paddy, and water bodies are comparatively significant for both watersheds. The impervious and partially pervious area is similar for both watershed and altogether covers around 19% of the watershed areas.  besides, cultivation as a dominant land use type covering a similar extent around 56% of both watersheds. Therefore, Ellagawa and Ratnapura watersheds can be considered rural watersheds. land cover is roughly similar for both main and watersheds. The Ellagawa watershed has somewhat less forest (4%) and more paddy (3%) than the Ratnapura watershed. Other land use types are similar for both watersheds. Build up area, cultivation, and water bodies covering similar areas of 18%, 56%, and 1% of Elagawa and Ratnapura watershed respectively.

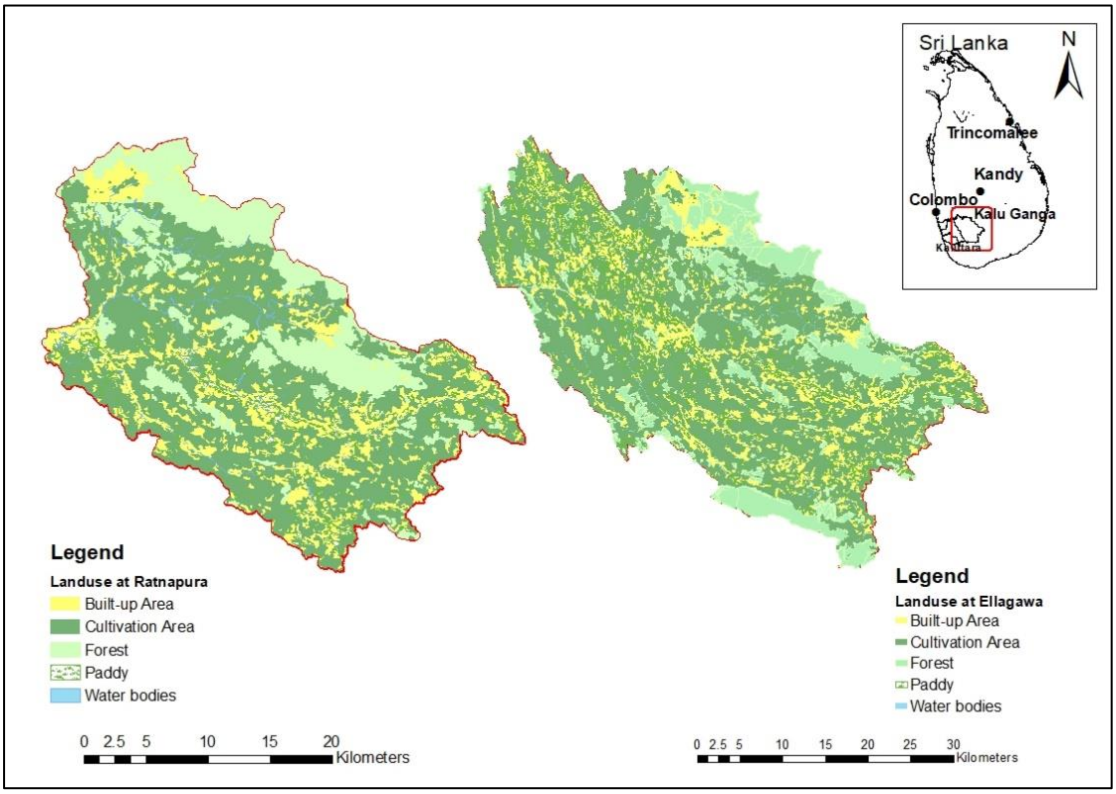



Figure 5-6 Land maps of Ellagawa and Ratnapura watersheds

### 5.4 Model Structure and Parameters

The Tank hydrologic model includes a series of Tanks that contain side and bottom outlets placed vertically in a series. The standard Tank model suggested by Sugawara in (1974) comprised four Tanks for the humid regions.

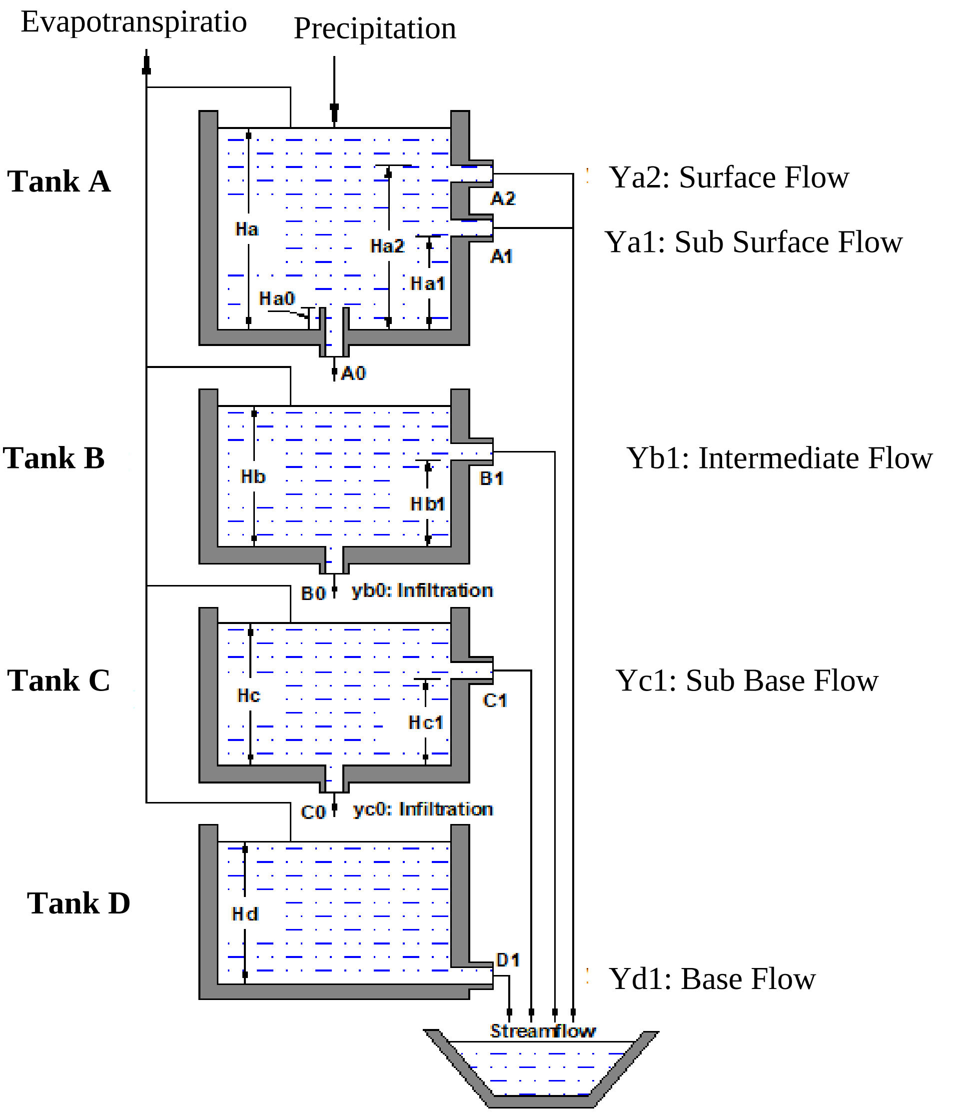



Figure 5-7 Schematic diagram of standard Tank model

The Tank model transforms the precipitation as the main input of the model to streamflow. The streamflow is computing by extracting the evapotranspiration and summation of the outputs from all side outlets of the model. The first and second side outlet of the first tank presenting the simulation process of the subsurface and surface flows respectively. The simulation output of the intermediate flows obtains from the side outlet of the second tank. Similarly, the side outlets of the third and fourth tanks are accountable for the simulation of sub-base, and base flows respectively. The water discharges through the bottom outlets of the tanks showing the infiltration process of the watershed. Each of these processes controlling by a parameter which can be categorized into three following groups:

1. Runoff parameters of the model: The parameters A1, A2, B1, C1, and D1 are called runoff coefficient, and controlling the runoff process of the watershed.
2. Infiltration parameters of the model: The parameters A0, B0, and C0 are called infiltration coefficient and accountable for the controlling of the infiltration process of the watershed.
3. Storage parameters of the model: The parameters Ha1, Ha2, Hb1, and Hc1 are called storage parameters of the model.

In Figure 5-7, the output of the side outlets of each tank; Ya1, Ya2, Yb1, Yc1, and Yd1 is subsurface, surface intermediate, sub base and base flows of the model respectively. Similarly, the outputs of the bottom outlets of each tank; Ya0, Yb0, and Yc0 are the amount of infiltration from the first, second, and third tank respectively. Storage height in each tank and position and multiplicative of the outlets govern the process of runoff and infiltration of the model. The overall water balance equation of the model is given as follows.

$$\mathrm{dH/dt = P(t) - ET(t) - Y(t)} \qquad \text{Eq. 5.1}$$

In Eq.5.1, H is the overall height of the storage in mm, P is precipitation in mm/day, ET is evapotranspiration in mm/day, Y is overall outflow in mm/day and t is time in a day. The total outflow must comprise the outflow from each tank, and it can be expressed follows:

$$\mathrm{Y(t) = Ya(t) + Yb(t) + Yc(t) + Yd(t)} \qquad \text{Eq. 5.2}$$

Whilst, the water balance equation in the individual tank can be written in the following equations:

Tank A:

$$\mathrm{dHa/dt = P(t) - ET(t) - Ya(t)} \qquad \text{Eq. 5.3}$$

Tank B:

$$dHb/dt = Ya0(t) - Yb(t) \qquad \text{Eq. 5.4}$$

Tank C:

$$dHc/dt = Yb0(t) - Yc(t) \qquad \text{Eq. 5.5}$$

Tank D:

$$dHd/dt = Yc0(t) - Yd(t) \qquad \text{Eq. 5.6}$$

### 5.5 Optimization of Tank Model Parameters

The model first calibrated and validated using eight years of daily input data from 2009/2010 to 2016/2017, for Ellagawa and Ratnapura watersheds. Then, the obtained calibrated parameters for Ellagawa watershed transferred to Ratnapura, and vice versa, and the applicability of parameter transfer evaluated for sub and main watershed.

#### 5.5.1 Warm-up period of the model for Ellagawa watershed

Model identification requires suitable initial soil moisture content of the watershed. According to the literature review, a periodic warm-up of 6 cycles was used to obtain the representative soil moisture content. During the warm-up process, it observed that soil moisture of the first, second, and third tank stabilized at the first cycle while the fourth tank showed fluctuation up to the 6the cycle.

Graphical representation of the Soil moisture behavior of Ellagawa watershed is shown in Figure 5-8.

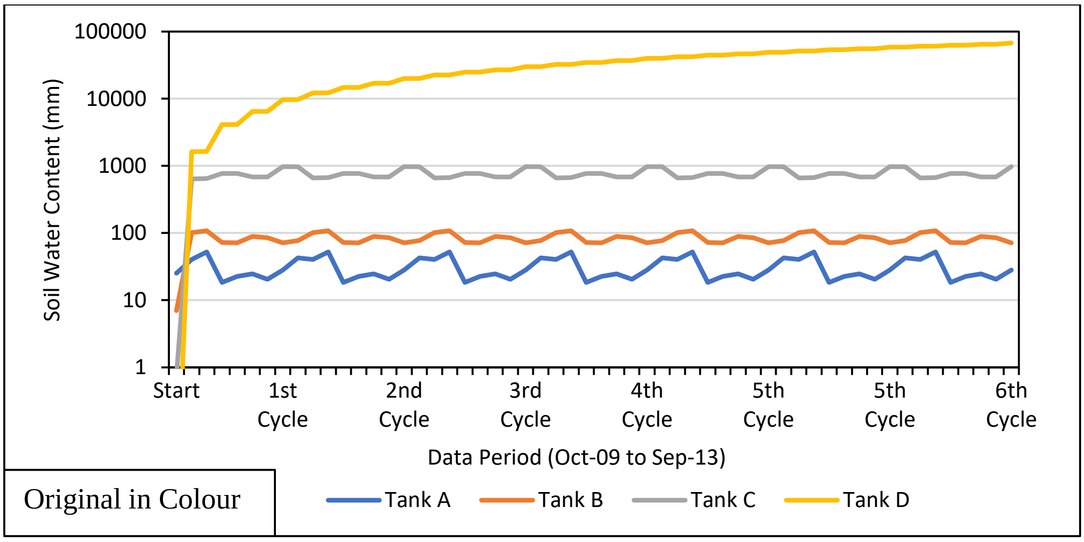



Figure 5-8 The behavior of soil moisture content at Ellagawa watershed

### 5.5.2 Calibration of the model for Ellagawa watershed

The dataset used in the calibration of the model includes rainfall, streamflow, and pan evaporation on a daily basis. Considering the objective of the modeling four years data from 2009/2010-2012/2013 were used for the calibration process. The solver tool of MS Excel was applied for the optimization of the model parameters. Optimized parameters and model performance are given in Figure 5-9 and Table 5-7 respectively.

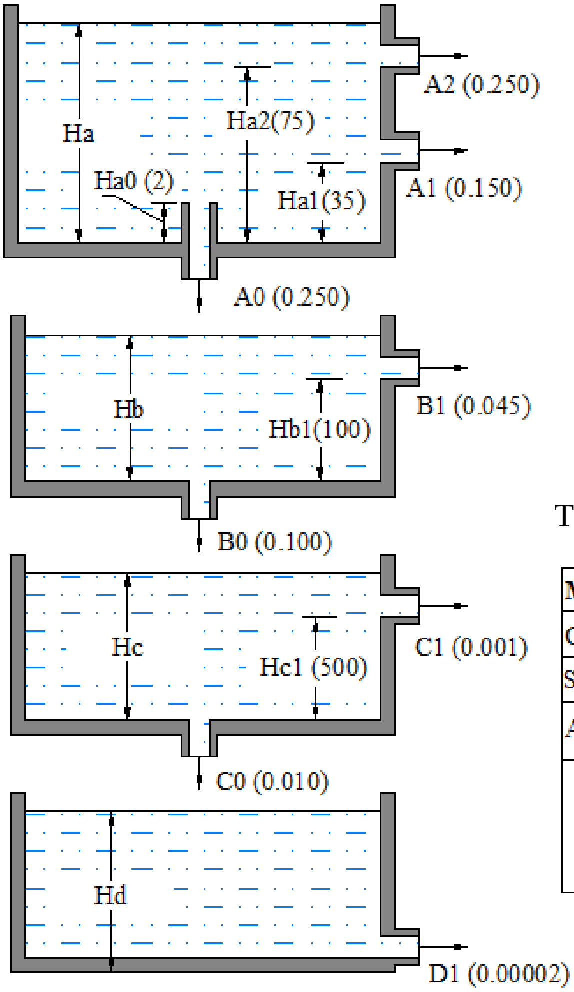



Table 5-7 Model performance indicators

| Model Performance Indicator | | Value |
|---|---|---|
| Observed Runoff Coefficient | | 0.350 |
| Simulated Runoff Coefficient | | 0.320 |
| Average Annual Water Balance Error | | 9.350 |
| MRAE | Overall | 0.450 |
| | High | 0.222 |
| | Medium | 0.056 |
| | Low | 0.149 |

Figure 5-9 Model performance during calibration for Ellagawa watershed

Water balance, outflow hydrographs and, flow duration curve, for the calibration phase of the model, plotted to evaluate the model performance. Though the reproduction of watershed response appears as in order and compatible with rainfall, the comparison with observations reflected a reasonable matching, especially in low and medium flows.

The overall MRAE value for the calibration stage of the model obtained 0.450. The annual water balance of Ellgawa watershed for the model calibration is given in Table 5-8.

Table 5-8 Annual water balance of Ellgawa watershed for the calibration period

| Water Year | Thiessen Averaged Rainfall (mm) | Simulated Streamflow (mm) | Observed Streamflow (mm) | Observed Water Balance (mm) | Simulated Water Balance (mm) | Annual Water Balance Error (mm) |
|---|---|---|---|---|---|---|
| 2009/2010 | 3667.36 | 1135.92 | 1600.16 | 2067.20 | 2531.45 | 22.46 |
| 2010/2011 | 4045.01 | 1564.40 | 1746.87 | 2298.14 | 2480.61 | 7.94 |
| 2011/2012 | 3537.54 | 844.47 | 738.71 | 2798.83 | 2693.07 | 3.78 |
| 2012/2013 | 5696.14 | 1866.12 | 1738.12 | 3958.02 | 3830.02 | 3.23 |
| Average | 4236.51 | 1352.73 | 1455.97 | 2780.55 | 2883.79 | 9.35 |

Similarly, the water balance errors estimated for the calibration phase and shown in Figure 5-10. The annual average water balance for the calibration period showed 9.350% errors.

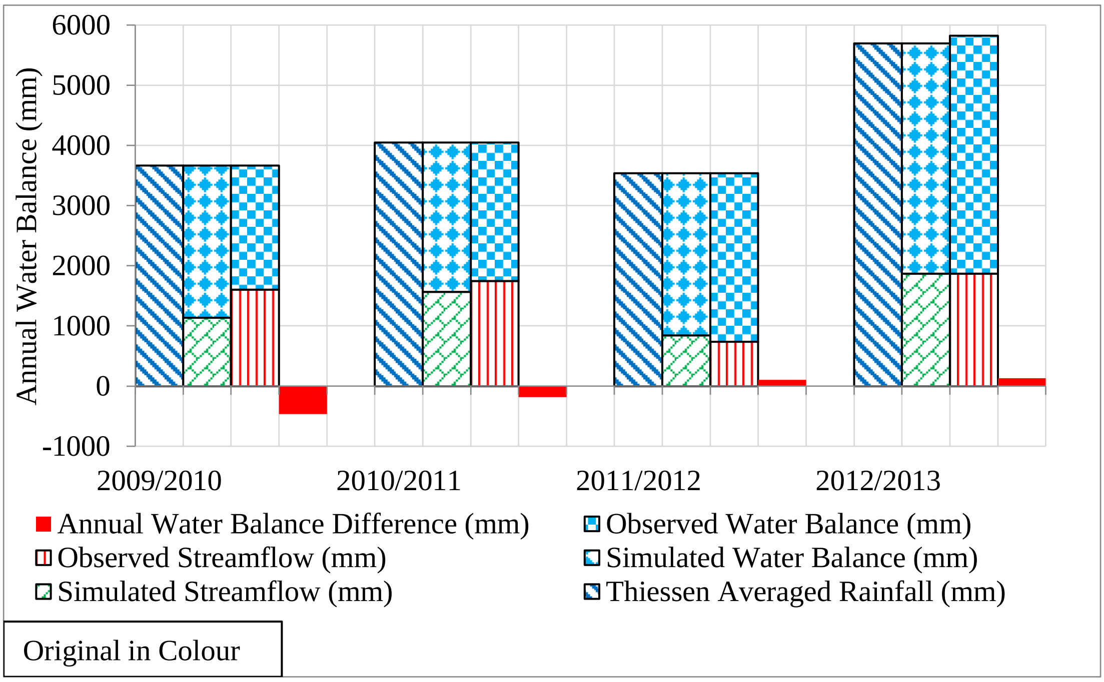



Figure 5-10 Annual water balance of Ellgawa watershed for the calibration period

The hydrograph match for the calibration period of Ellagaw watershed is shown in Figure 5-11.

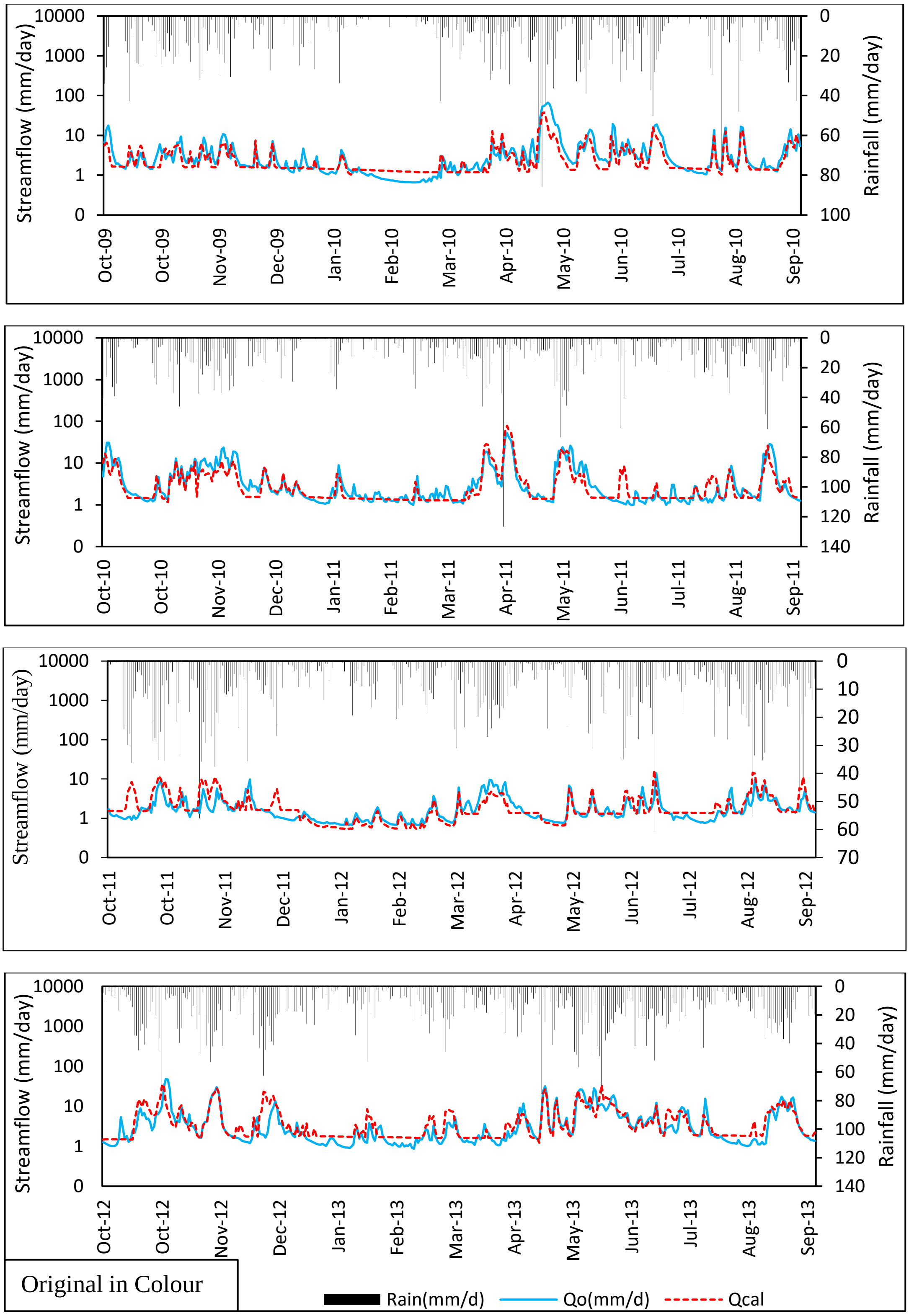
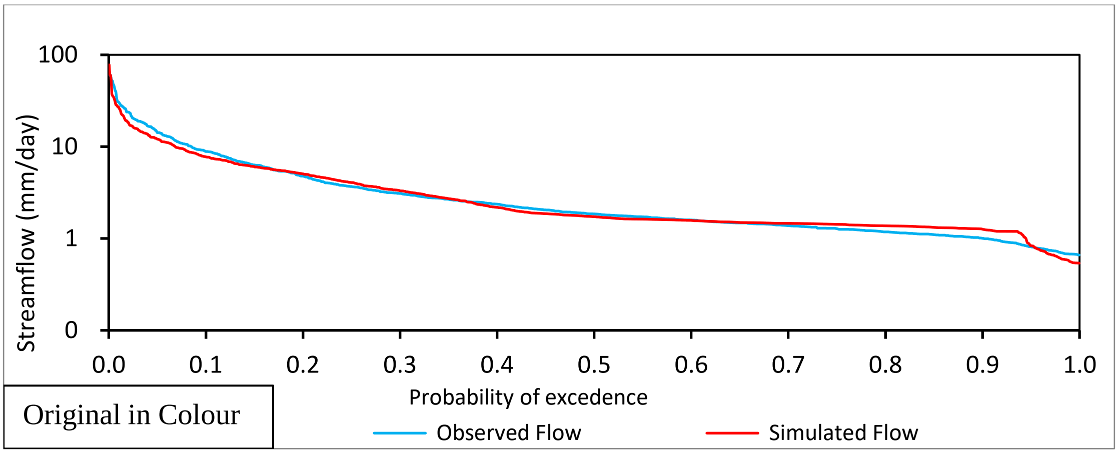



Figure 5-11 Hydrograph match for the calibration period of Ellagaw watershed

The flow duration curve matching of the observed and estimated streamflow by model for the calibration phase indicated a reasonable fit. The model calibrated with the MRAE value of 0.222 for high flows, 0.056 for medium flows, and 0.149 for low flows respectively.

The flow duration curve matching for the calibration period of Ellagawa watershed is shown in Figure 5-12.




Original in Colour

Figure 5-12 Flow duration curve match for the calibration period of Ellagawa

### 5.5.3 Verification of the model for Ellagawa watershed

For the verification of the model for Ellagawa watershed, four years of rainfall, streamflow, and pan evaporation data on a daily basis from 2013/14 to 2016/17 were used. To verify the optimum parameters, the model fixed up with the obtained parameters in the calibration process and the verification datasets. The performance indicators of the model are given in Table 5-9 .

Table 5-9 Model performance during verification for Ellagawa watershed

| Model Performance Indicators | | Value |
|---|---|---|
| Observed Runoff Coefficient | | 0.39 |
| Simulated Runoff Coefficient | | 0.33 |
| Average Annual Water Balance Error | | 22.08% |
| MRAE | Overall | 0.452 |
| | High | 0.444 |
| | Medium | 0.198 |
| | Low | 0.196 |

The performance of the model in the verification process for Ellagawa watershed is roughly comparable with the calibration period. The MRAE value for the verification period obtained 0.452. Similarly, the annual average water balance indicated 22.08% errors for the verification period. The annual water balance errors for the verification period of Ellagawa watershed is given in Table 5-10.

Table 5-10  Annual water balance of Ellgawa watershed for the verification period

| Water Year | Thiessen Averaged Rainfall (mm) | Simulated Streamflow (mm) | Observed Streamflow (mm) | Observed Water Balance (mm) | Simulated Water Balance (mm) | Annual Water Balance Difference (%) |
|---|---|---|---|---|---|---|
| 2009/2010 | 4253.82 | 1253.76 | 1414.76 | 2839.06 | 3000.06 | 5.67 |
| 2010/2011 | 4231.31 | 1240.72 | 1423.96 | 2807.35 | 2990.59 | 6.53 |
| 2011/2012 | 3511.18 | 1599.06 | 2098.27 | 1412.90 | 1912.12 | 35.33 |
| 2012/2013 | 3693.08 | 1086.94 | 1842.00 | 1851.07 | 2606.14 | 40.79 |
| Average | 3922.35 | 1295.12 | 1694.75 | 2227.60 | 2627.23 | 22.08 |

The graphical representation of water balance errors for the verification phase of Ellagawa watershed is sown in Figure 5-13.

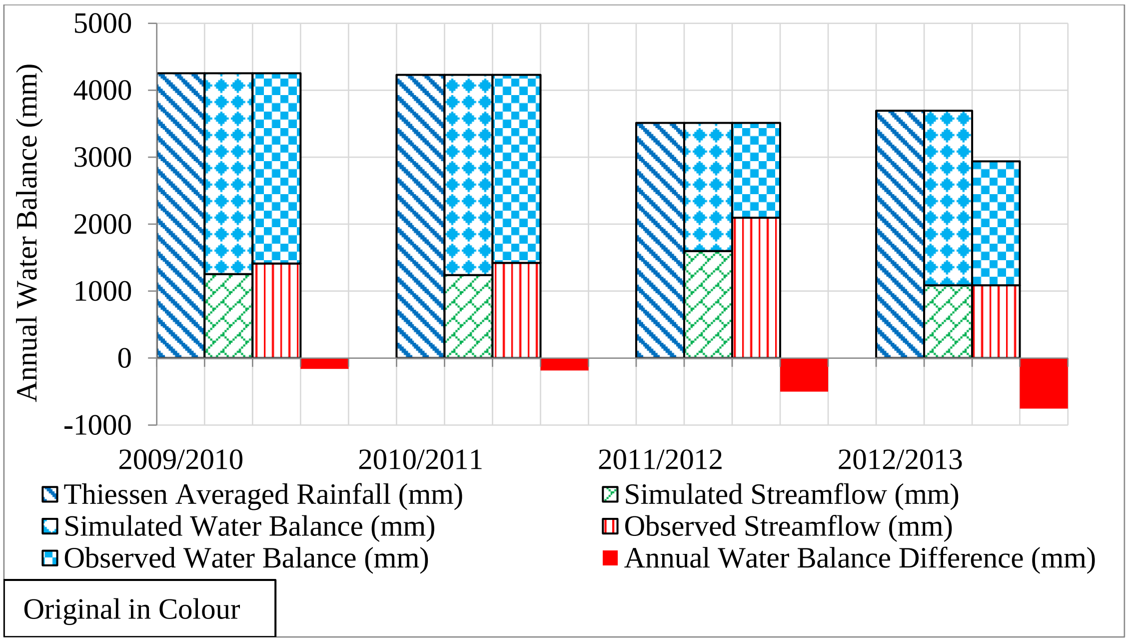



Figure 5-13 Annual water balance of Ellgawa watershed for the verification period

Hydrograph match for the verification period for Ellagaw watershed is shown in Figure 5-14.

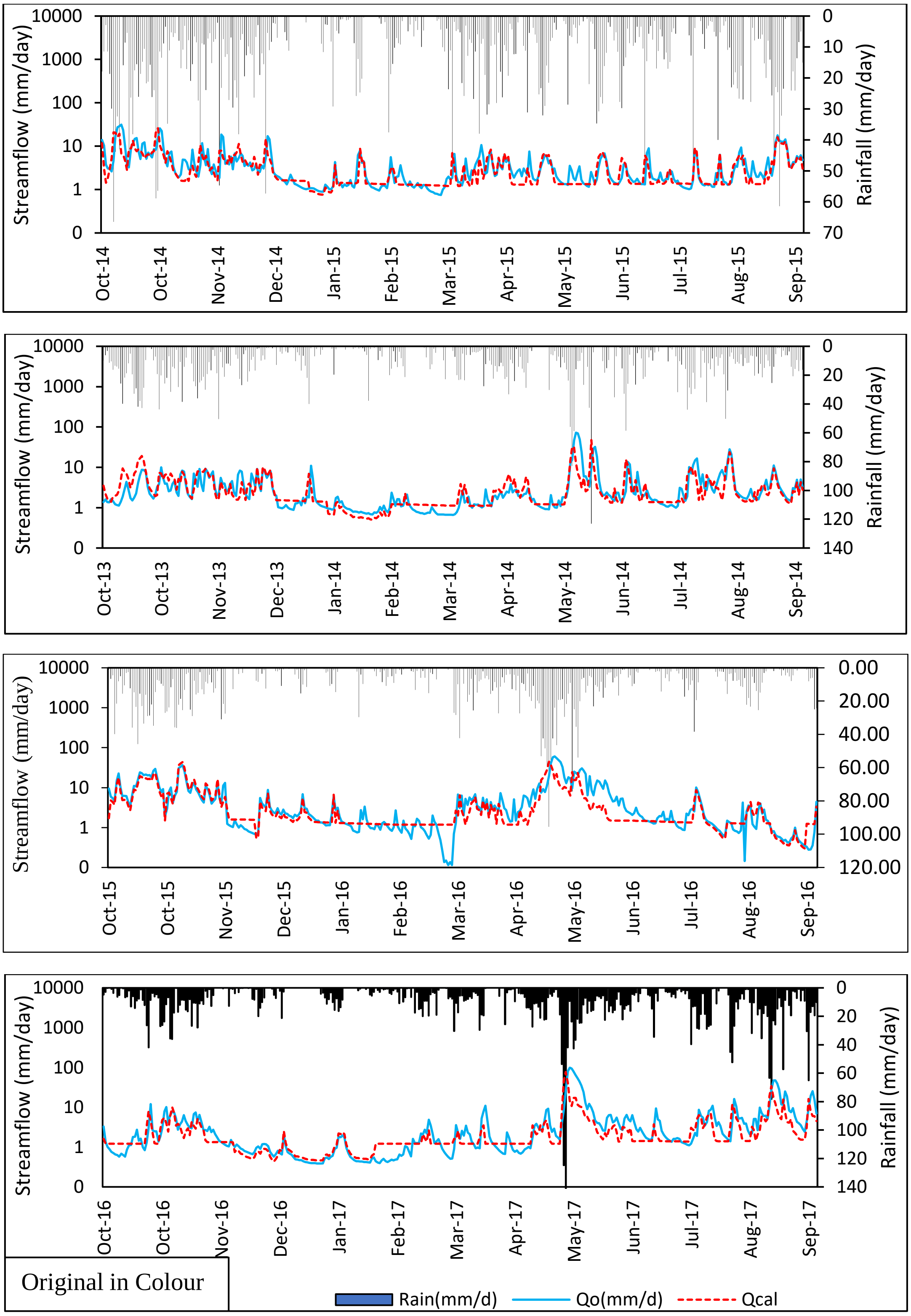



Figure 5-14 Hydrograph match for the verification period of Ellagaw watershed

The observed and estimated flow duration curves match for the verification period of Ellagawa watershed plotted. The optimized parameters of the calibration period reasonably performed well in all streamflow thresholds.  The model calibrated with the MRAE value of 0.444 for high flows, 0.156 for medium flows, and 0.158 for low flows respectively. The flow duration curve matching for the verification period of Ellagawa watershed is shown in Figure 5-15.

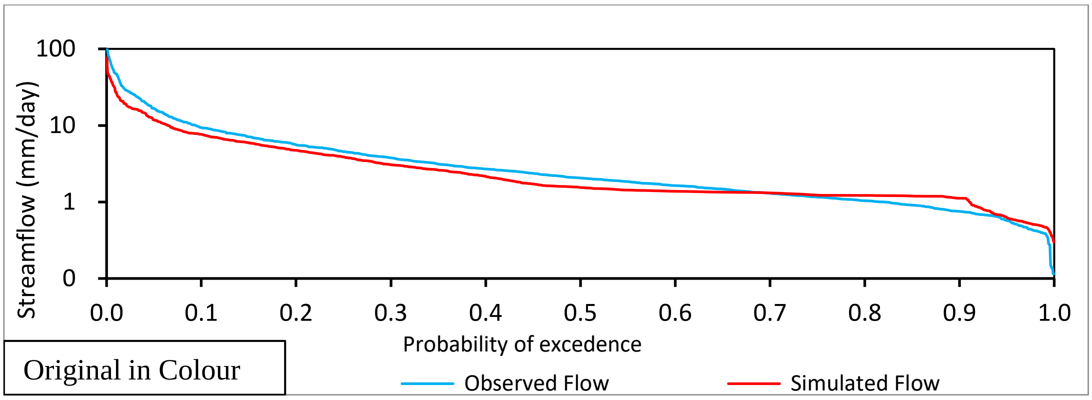



Figure 5-15 Flow duration curve match for the verification period of Ellagawa

### 5.5.4 Warm-Up Period of Model for Ratnapura Watershed

Prior to the optimization of model parameters, its crucial to identify the initial soil moisture condition and parameters of the model. The graphical representation of soil moisture behavior for Ratnapura watershed is shown in Figure 5-16.

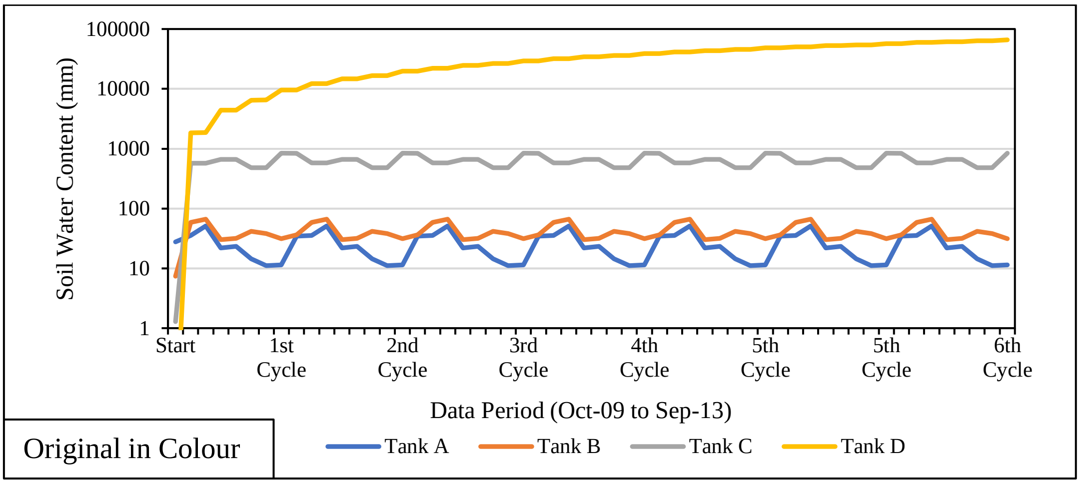



Figure 5-16 Behaviour of soil moisture content at Ratnapura watershed

Similar to Ellagawa, for the warm-up period of Ratnapura watershed as recommended in the literature, a periodic warm-up period of 6 cycles of 4 years datasets was used to obtained the representative soil moisture content of the watershed. first, second and third tank stabilize at first cycle while the fourth tank showed fluctuation up to the 6$^{th}$ cycle.

### 5.5.5 Calibration of the model for Ratnapura watershed

The calibration datasets include rainfall, streamflow, and pan evaporation on a daily basis. Considering the objective of the study, four years of data duration from 2009/2010-2012/2013 were used in the calibration process of the model. The solver tool of MS Excel was applied for the optimization of the model parameters. and performance of the model evaluated according to six criteria. According to these criteria performance of the model considering the water balance errors, hydrograph matching, overall MRAE, high, medium, and low flows were assessed. Model performance indicators for the calibration period are given in Table 5-11.

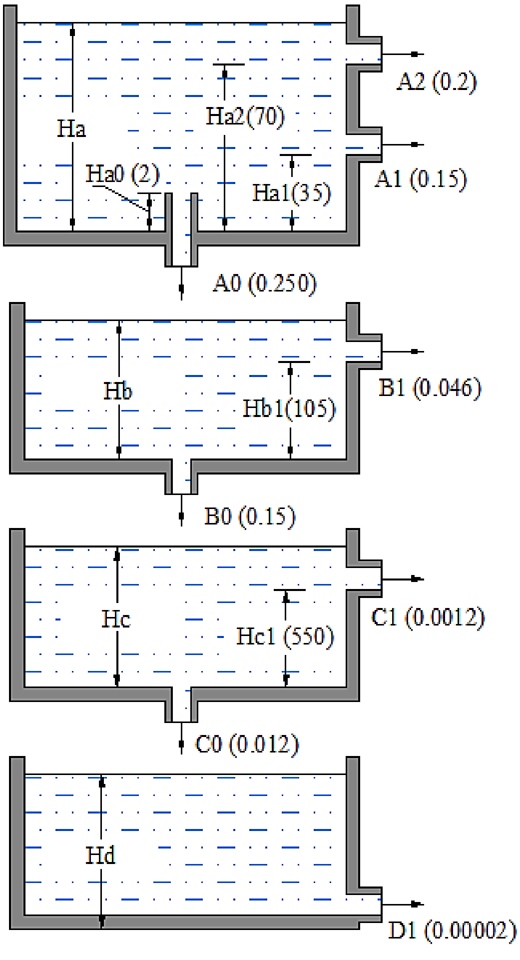



Table 5-11 Model performance indicators

| Model Performance Indicator | | Value |
|---|---|---|
| Observed Runoff Coefficient | | 0.400 |
| Simulated Runoff Coefficient | | 0.330 |
| Average Annual Water Balance Error(%) | | 14.060 |
| MRAE | Overall | 0.415 |
| | High | 0.387 |
| | Medium | 0.285 |
| | Low | 0.241 |

Figure 5-17 Model performance for the calibration period of Ratnapura watershed

The performance of the model indicated the overall MRAE value of 0.415 and accordingly, the annual average water balance indicated 14.06% errors. The annual water balance errors in the calibration process of Ratnapura watershed is given in Table 5-12.

Table 5-12 Annual water balance of Ratnapura watershed for the calibration period

| Water Year | Thiessen Averaged Rainfall (mm) | Simulated Streamflow (mm) | Observed Streamflow (mm) | Observed Water Balance (mm) | Simulated Water Balance (mm) | Annual Water Balance Error (mm) |
|---|---|---|---|---|---|---|
| 2009/2010 | 3721.82 | 1484.99 | 1768.80 | 1953.02 | 2236.83 | 14.53 |
| 2010/2011 | 3919.03 | 1362.42 | 1876.00 | 2043.03 | 2556.61 | 25.14 |
| 2011/2012 | 2980.18 | 791.28 | 880.93 | 2099.25 | 2188.90 | 4.27 |
| 2012/2013 | 5227.89 | 1588.07 | 1987.01 | 3240.88 | 3639.82 | 12.31 |
| Average | 3962.23 | 1306.69 | 1628.19 | 2334.04 | 2655.54 | 14.06 |

Water balance errors for the calibration period of Ratnapura watershed are shown in Figure 5-18.

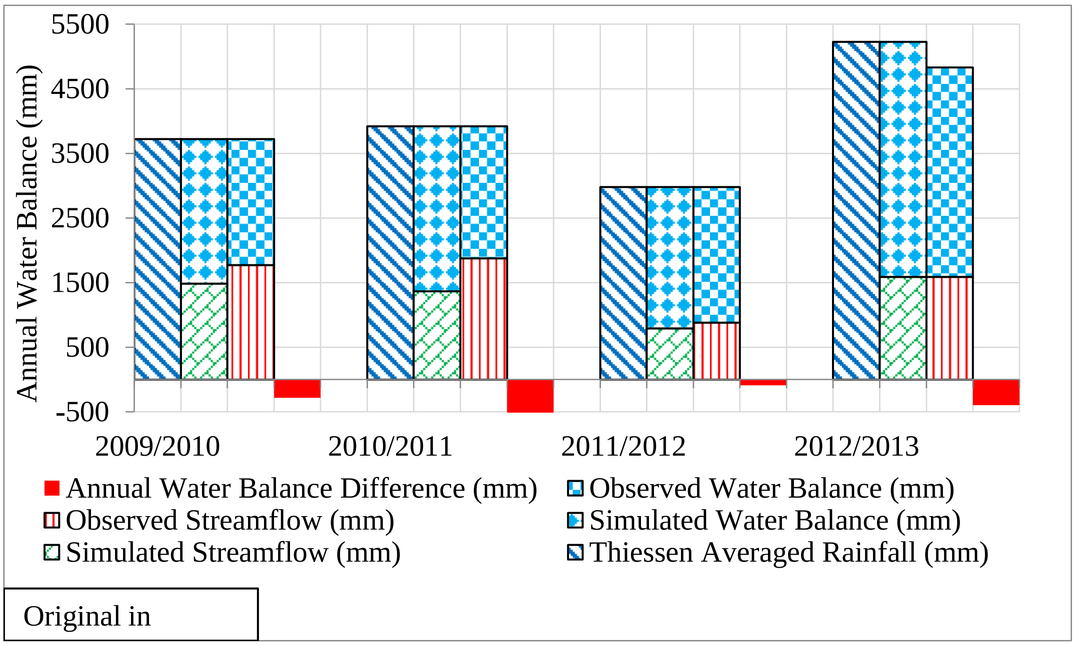



Figure 5-18 Annual water balance of Ratnapura watershed for the calibration period

The hydrograph match for the calibration period of Ratnapura watershed is shown in Figure 5-19.

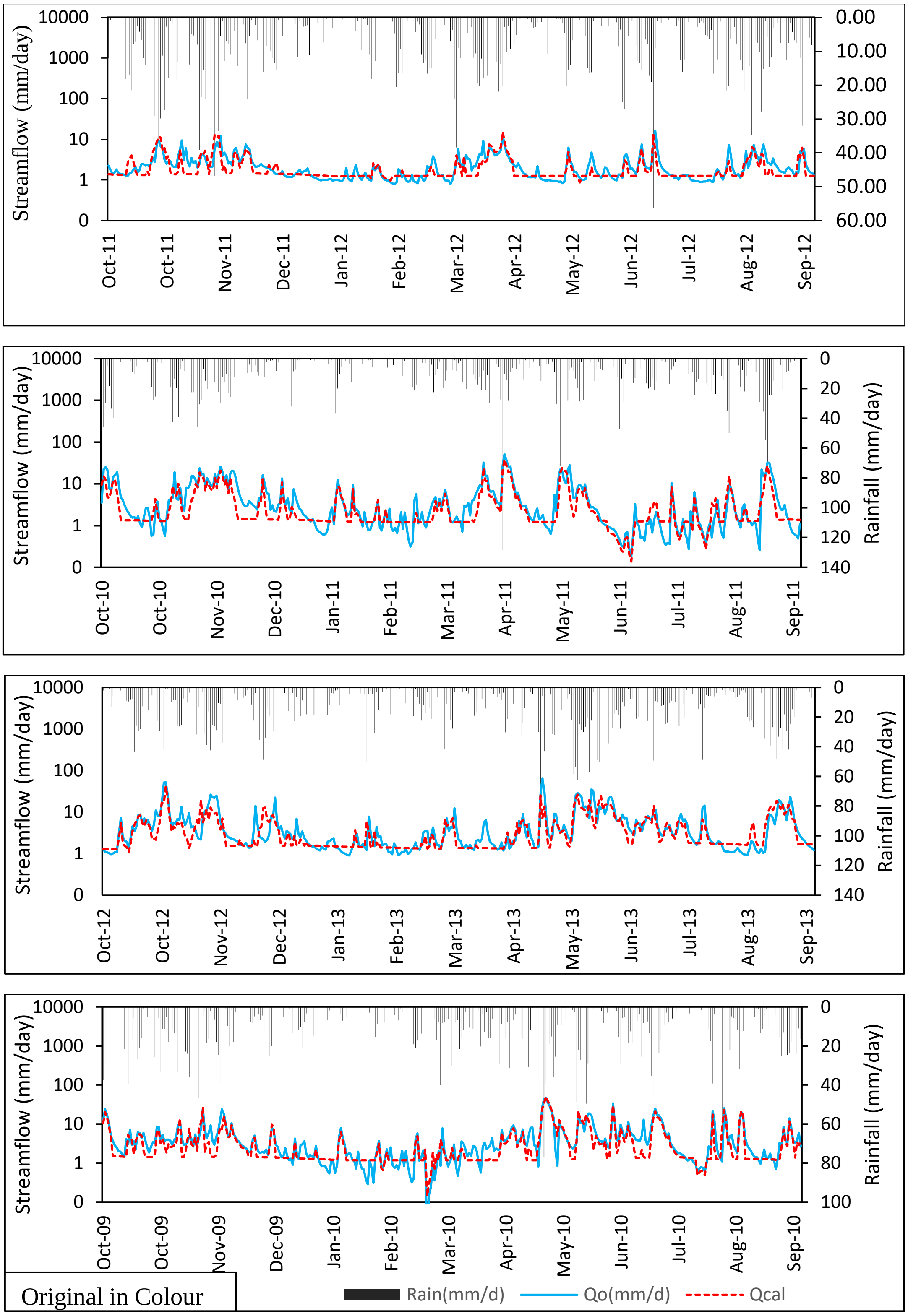



Figure 5-19 Hydrograph match for the calibration period of Ratnapura watershed

The simulated and observed flow duration curve for the calibration phase of the model were plotted to assess the performance of the model in flow thresholds. The model estimated the high, medium, and low flows with the MRAE values of 0.387, 0.285, and 0.241 respectively.

The flow duration curve matching for the calibration period of Ratnapura watershed is shown in Figure 5-20.

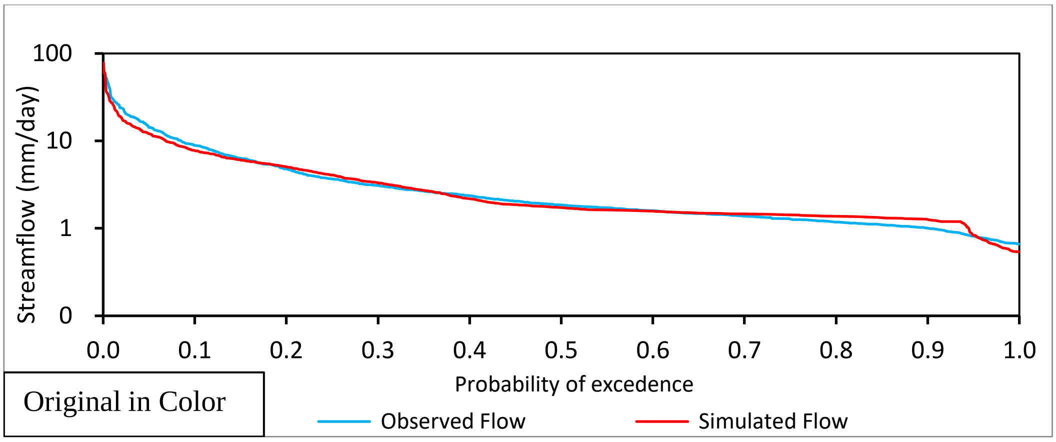



Figure 5-20 Flow duration curve match for the calibration period of Ratnapura

### 5.5.6 Verification of the model for Ratnapura watershed

For the verification of the model for Ratnapura watershed, four years of rainfall, streamflow, and pan evaporation data on a daily basis from 2013/14 to 2016/17 were used. To verify the optimum parameters, the model fixed up with the obtained parameters in the calibration process and the verification datasets. The performance indicators of the model are given in Table 5-13

Table 5-13 Model performance during verification for Ratnapura watershed

| **Model Performance Indicators** | | **Tank Model** |
|---|---|---|
| Observed Runoff Coefficient | | 0.4 |
| Simulated Runoff Coefficient | | 0.33 |
| Average Annual Water Balance Error (%) | | 13.94 |
| MRAE | Overall | 0.361 |
| | High | 0.384 |
| | Medium | 0.266 |
| | Low | 0.268 |

The model performance for the verification phase of Ratnapura watershed performed well with respect to the calibration period. The MRAE value for the verification period obtained 0.361. Similarly, the annual average water balance errors also showed a decline in the verification period indicated 13.94% errors for the verification period. The annual water balance errors for the verification period of Ratnapura watershed is given in Table 5-14.

Table 5-14 Annual water balance of Ratnapura watershed for the verification period

| Water Year | Thiessen Averaged Rainfall (mm) | Simulated Streamflow (mm) | Observed Streamflow (mm) | Observed Water Balance (mm) | Simulated Water Balance (mm) | Annual Water Balance Error (%) |
|---|---|---|---|---|---|---|
| 2009/2010 | 4168.61 | 1091.08 | 1326.86 | 2841.75 | 3077.53 | 8.30 |
| 2010/2011 | 4506.72 | 1905.66 | 2380.81 | 2125.91 | 2601.06 | 22.35 |
| 2011/2012 | 3451.99 | 1102.97 | 1494.20 | 1957.79 | 2349.02 | 19.98 |
| 2012/2013 | 3950.07 | 1189.46 | 1323.89 | 2626.18 | 2760.61 | 5.12 |
| Average | 4019.35 | 1322.29 | 1631.44 | 2387.91 | 2697.06 | 13.94 |

The graphical representation of water balance errors for the verification period of Ratnapura watershed is shown in Figure 5-21.

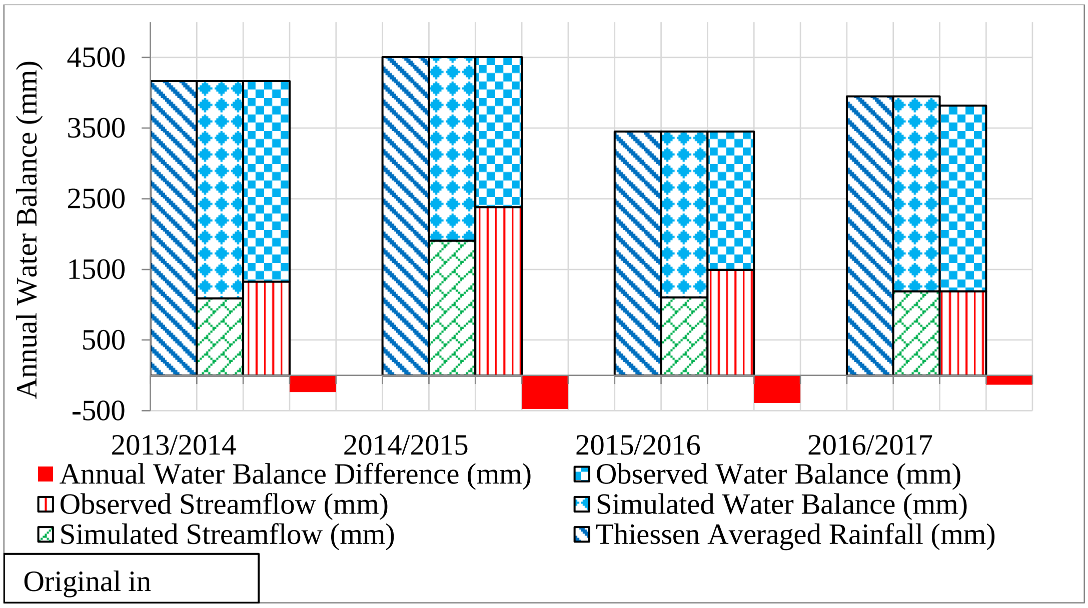



Figure 5-21 Annual water balance of Ratnapura watershed for the verification period

The hydrograph match for the verification period of Ratnapura watershed is shown in Figure 5-22.

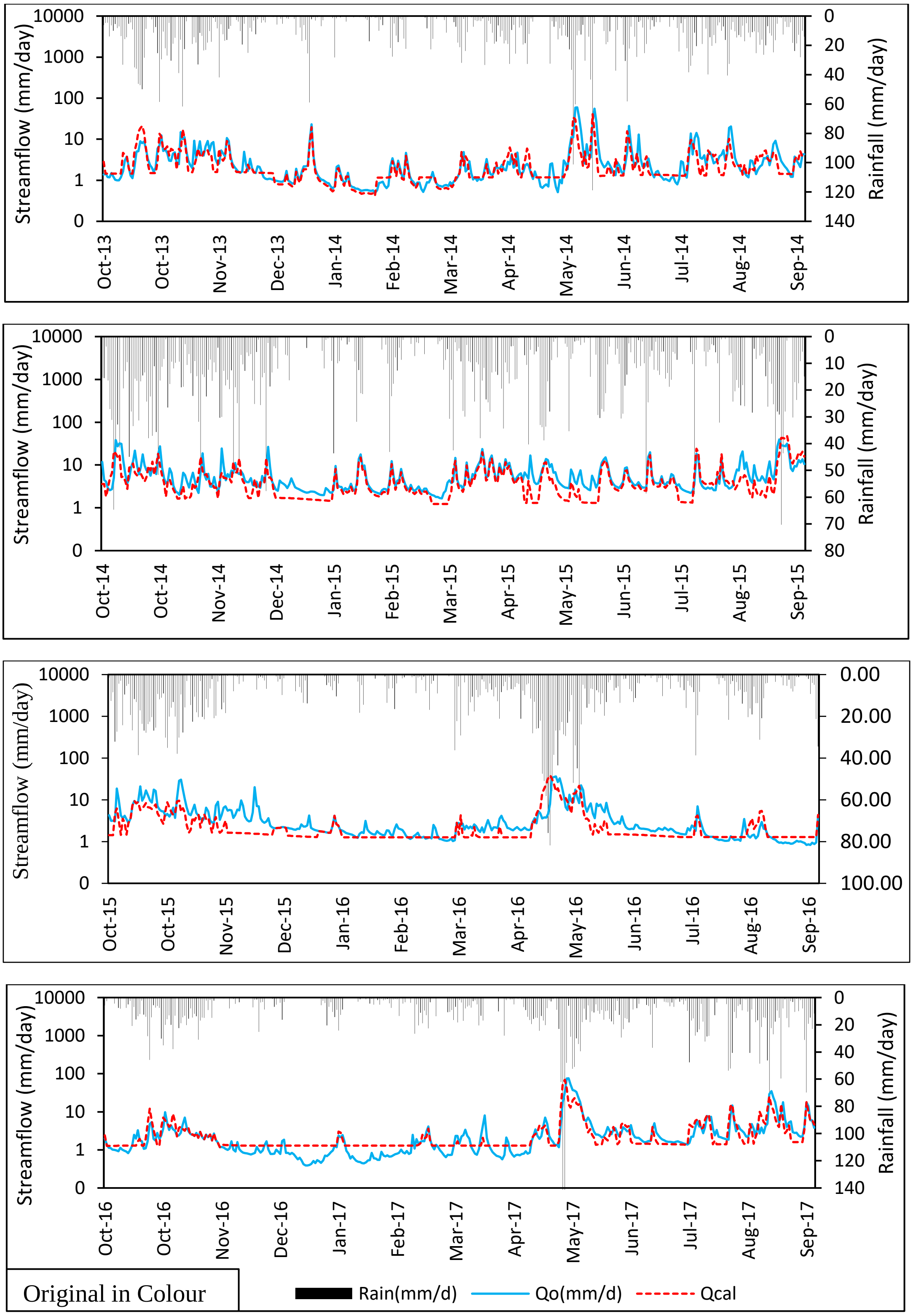
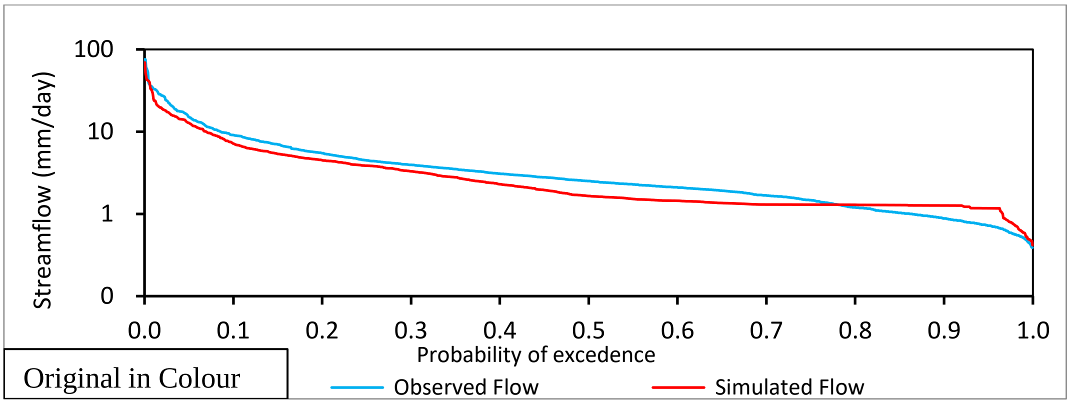



Figure 5-22 Hydrograph match for the verification period of Ratnapura watershed

The estimated flow duration curve matched with observed flow duration for the verification phase of the model indicated the MRAE value of 0.384 for high flows, 0.266 for medium flows, and 0.268 for low flows threshold. Flow duration curves for the verification phase of Ratnapura watershed are shown in Figure 5-20.




Original in Colour

Figure 5-23 Flow duration curve match for the verification period of Ratnapura

## 5.6 Transfer of Model Parameters

### 5.6.1 Transfer of model Parameters from Ellagawa to Ratnaupura

Review of the literature showed that different methods such as spatial proximity, global averages, and regression can be used for parameter transfer. Considering the spatial behavior of the model and study area spatial proximity method was used in this study. In this method, the whole set of calibrated parameters of Ellagawa was transferred to Ratnapura watershed. The underlying assumption here is that subwatershed should behave comparable to the main watershed because of similar physical and hydrologic characteristics. The model was then run and the simulated streamflow was compared to the observed streamflow of the subwatershed. Performance indicators of the model are given in Table 5-15

Table 5-15 Model performance for parameters transfer from Ellagawa to Ratnapura

| Model Performance Indicators | | Value |
|---|---|---|
| Observed Runoff Coefficient | | 0.4 |
| Simulated Runoff Coefficient | | 0.33 |
| Average Annual Water Balance Error (%) | | 11.9 |
| MRAE | Overall | 0.445 |
| | High | 0.174 |
| | Medium | 0.153 |
| | Low | 0.373 |

The model performance when parameter transfer from Ellagawa to Ratnapura the transfer parameters simulated the Ratnapura streamflow with a reasonable MRAE value of 0.445. The annual average water balance showed 11.9% errors for the parameter transfer. The annual water balance errors for the parameters transfer are given in Table 5-16.

Table 5-16 Annual water balance error for parameter transfer to Ratnapura

| Water Year | Thiessen Averaged Rainfall (mm) | Simulated Streamflow (mm) | Observed Streamflow (mm) | Observed Water Balance (mm) | Simulated Water Balance (mm) | Annual water balance Error (%) |
|---|---|---|---|---|---|---|
| 2009/2010 | 3721.75 | 1283.25 | 1768.91 | 1952.84 | 2438.50 | 24.87 |
| 2010/2011 | 3919.06 | 1371.66 | 1876.09 | 2042.97 | 2547.40 | 24.69 |
| 2011/2012 | 2980.22 | 835.61 | 880.95 | 2099.27 | 2144.61 | 2.16 |
| 2012/2013 | 5227.86 | 1744.70 | 1987.05 | 3240.81 | 3483.16 | 7.48 |
| 2013/2014 | 4168.61 | 1278.97 | 1326.86 | 2841.75 | 2889.64 | 1.69 |
| 2014/2015 | 4506.72 | 1779.77 | 2380.81 | 2125.91 | 2726.95 | 28.27 |
| 2015/2016 | 3451.99 | 1377.09 | 1494.20 | 1957.79 | 2074.90 | 5.98 |
| 2016/2017 | 3950.07 | 1328.42 | 1323.89 | 2626.18 | 2621.65 | 0.17 |
| Average | 3990.79 | 1374.93 | 1629.85 | 2360.94 | 2615.85 | 11.91 |

Annual water balance difference for parameter transfer from Ellagawa to Ratnapura watershed graphically shown in Figure 5-24.

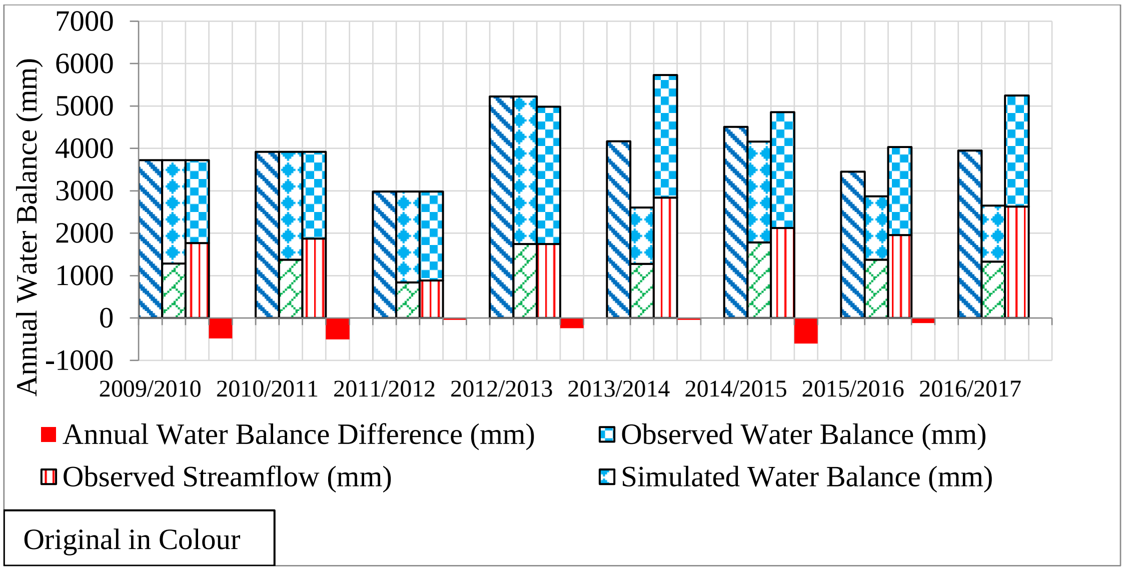



Figure 5-24 Annual water balance error for parameter transfer to Ratnapura

Hydrograph match for the water years from 2009/10 to 2012/13 of the parameter transfer from Ellagawa to Ratnapura watershed is shown in Figure 5-25.

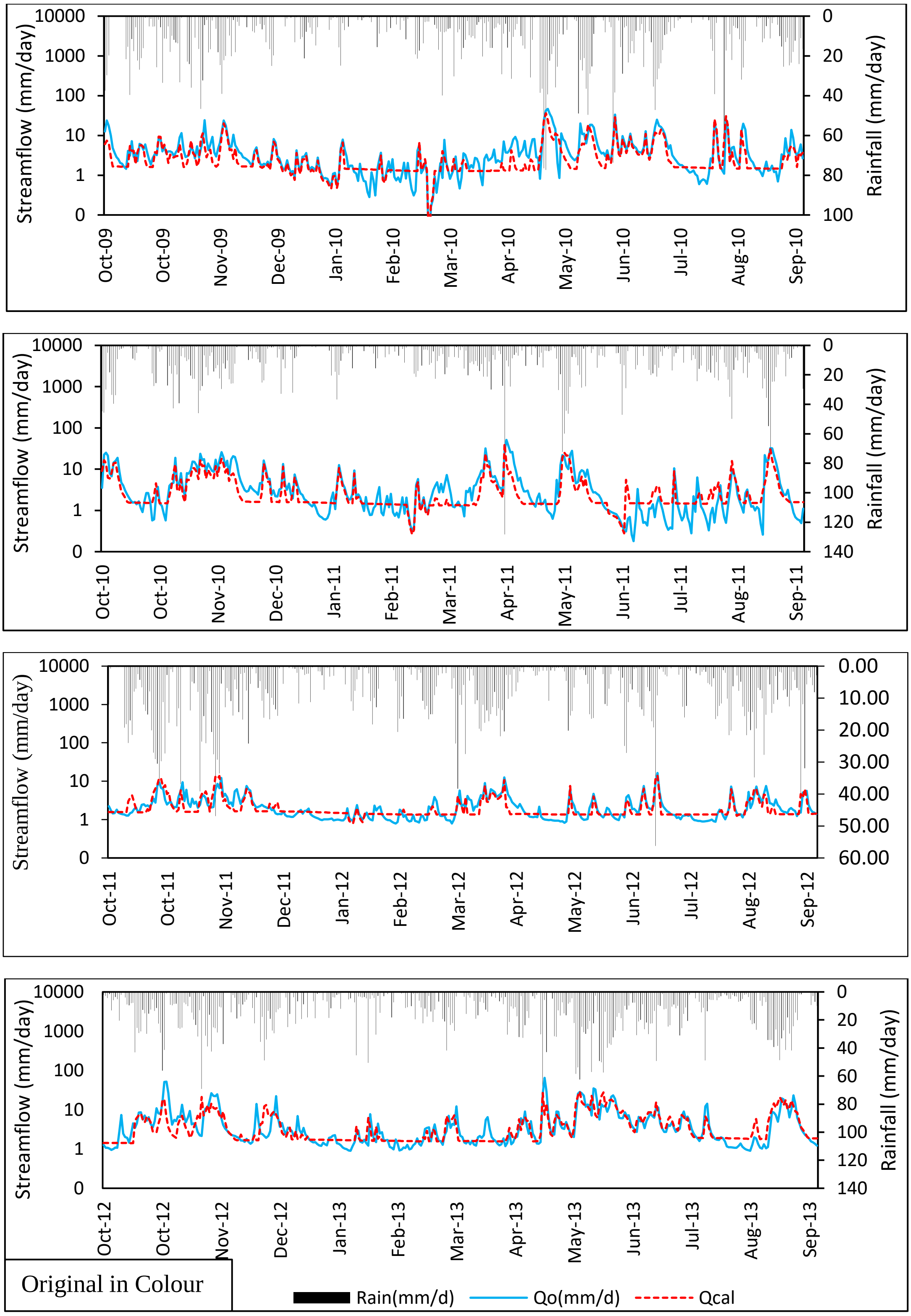



Figure 5-25 Hydrographs match for parameter transfer from Ellagawa to Ratnapura

Hydrograph match for the water years from 2013/14 to 2016/17 of the parameter transfer from Ellagawa to Ratnapura watershed is given in Figure 5-26.

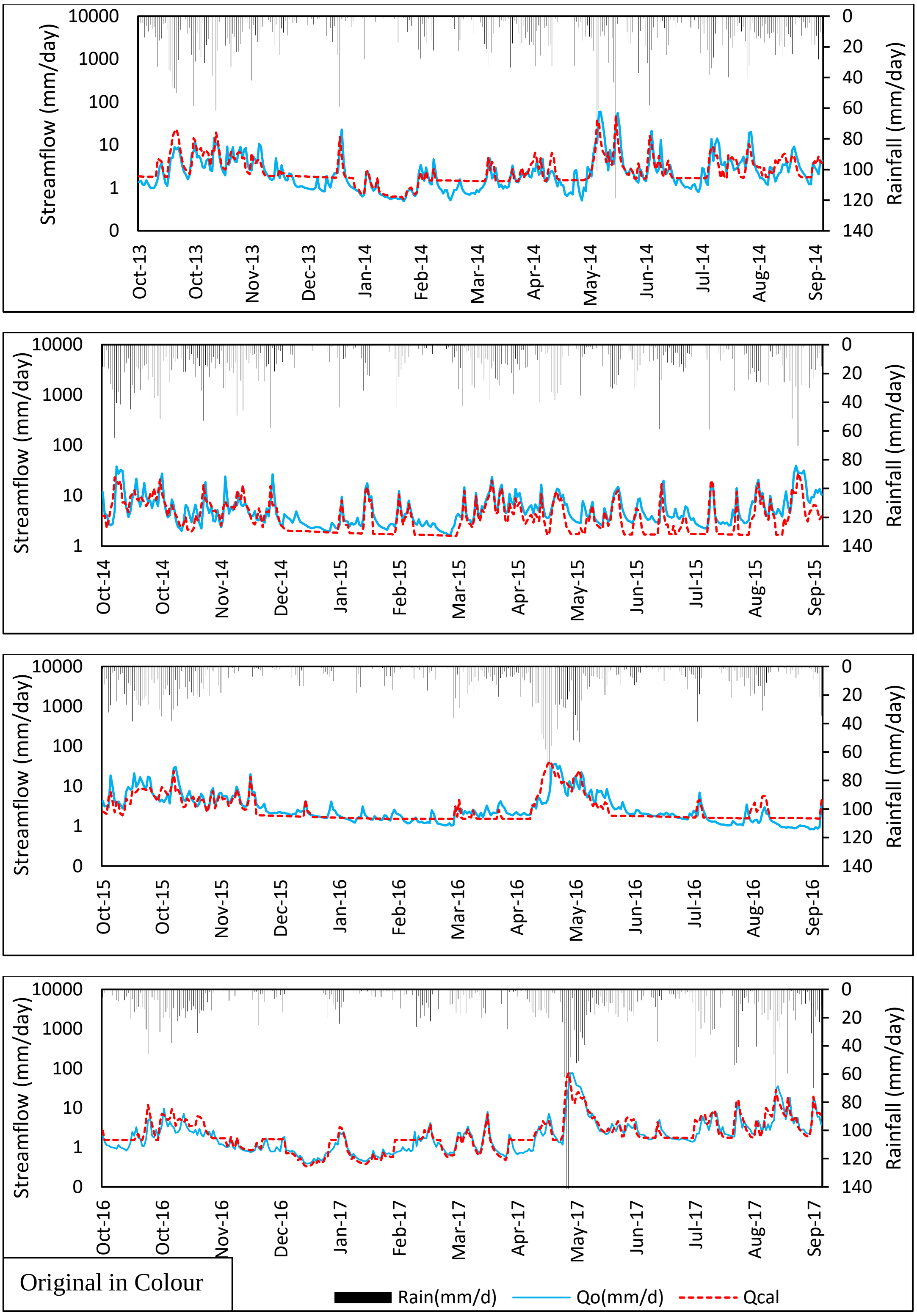
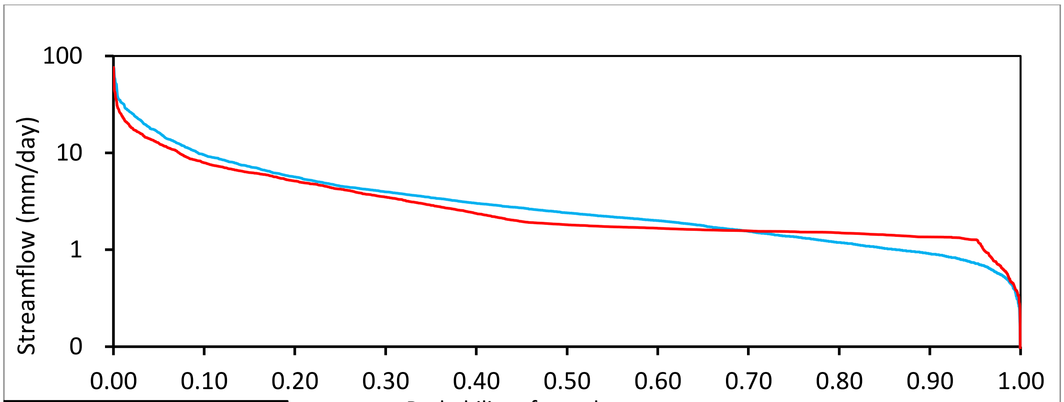



Figure 5-26 Hydrographs match for parameter transfer from Ellagawa to Ratnapura

The simulated and observed flow duration curve for parameter transfer to Ratnapura watershed were plotted and matched to assess the model performance in streamflow thresholds. The MRAE values of 0.174 for high flows, 0.153 for medium flows, and 0.373 for low flows were obtained. The flow duration curve matching for parameters transfer to Ratnapura watershed is shown in Figure 5-20.




Original in Colour

Figure 5-27 Flow duration curve matching for parameter transfer to Ratnapura

### 5.6.2 Transfer of model parameters from Ratnapura to Ellagawa

Similarly, the whole set of calibrated parameters for Ratnapura watershed was transferred to Ellagawa watershed. The underlying assumption here is that the main watershed should behave similarly to the subwatershed because of similar hydrologic characteristics. The subwatershed calibrated and the parameters were transferred to the main watershed. Then the model run and the performance of the model evaluated. Model performance indicators are given in Table 5-17.

Table 5-17 Model performance for parameters transfer from Ellagawa to Ratnapura

| Model Performance Indicators | | Value |
|---|---|---|
| Observed Runoff Coefficient | | 0.34 |
| Simulated Runoff Coefficient | | 0.3 |
| Average Annual Water Balance Error (%) | | 21.87 |
| MRAE | Overall | 0.511 |
| | High | 0.277 |
| | Medium | 0.133 |
| | Low | 0.370 |

Performance of the model when parameters transfer from Ratnapura to Ellagawa, the transfer parameters estimated the Ellagawa response with a reasonable overall MRAE value of 0.511. The annual average water balance indicated 21.87% errors. Annual water balance errors for the parameters transfer are given in Table 5-18.

Table 5-18Annual water balance error for parameter transfer to Ellagawa watershed

| Water Year | Thiessen Averaged Rainfall (mm) | Simulated Streamflow (mm) | Observed Streamflo w (mm) | Observed Water Balance (mm) | Simulate d Water Balance (mm) | Annual water balance Error (%) |
|---|---|---|---|---|---|---|
| 2009/2010 | 3667.36 | 1104.49 | 1600.16 | 2067.20 | 2562.88 | 23.98 |
| 2010/2011 | 4045.01 | 1164.44 | 1746.87 | 2298.14 | 2880.57 | 25.34 |
| 2011/2012 | 3537.54 | 913.47 | 738.71 | 2798.83 | 2624.07 | 6.24 |
| 2012/2013 | 5696.14 | 1719.42 | 1738.12 | 3958.02 | 3976.72 | 0.47 |
| 2013/2014 | 4253.82 | 1186.45 | 1414.76 | 2839.06 | 3067.37 | 8.04 |
| 2014/2015 | 4231.31 | 1215.21 | 1423.96 | 2807.35 | 3016.09 | 7.44 |
| 2015/2016 | 3511.18 | 1195.59 | 2098.27 | 1412.90 | 2315.59 | 63.89 |
| 2016/2017 | 3693.08 | 1109.29 | 1842.00 | 1851.07 | 2583.78 | 39.58 |
| Average | 4079.43 | 1201.05 | 1575.36 | 2504.07 | 2878.38 | 21.87 |

Annual water balance errors for parameter transfer from Ratnapura to Ellagawa watershed graphically represented in Figure 5-28.

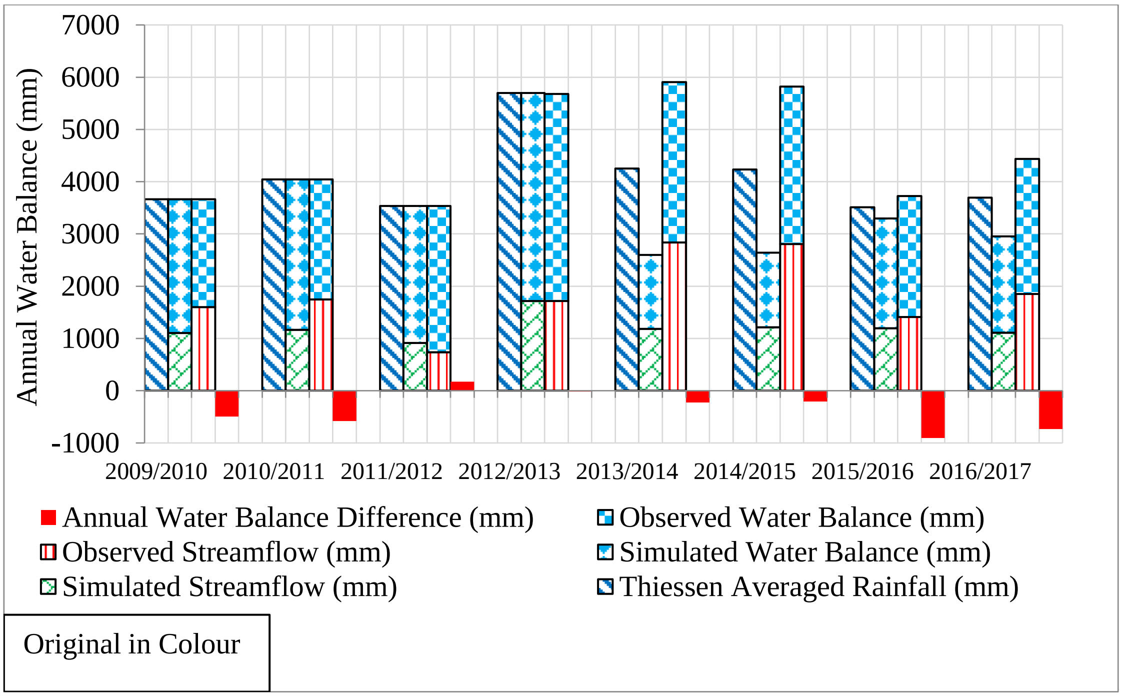



Figure 5-28 Annual water balance when parameter transfer to Ellagawa watershed

Hydrograph match for the water years from 2009/10 to 2012/13 of the parameter transfer from Ratnapura to Ellagawa watershed is given in Figure 5-29.

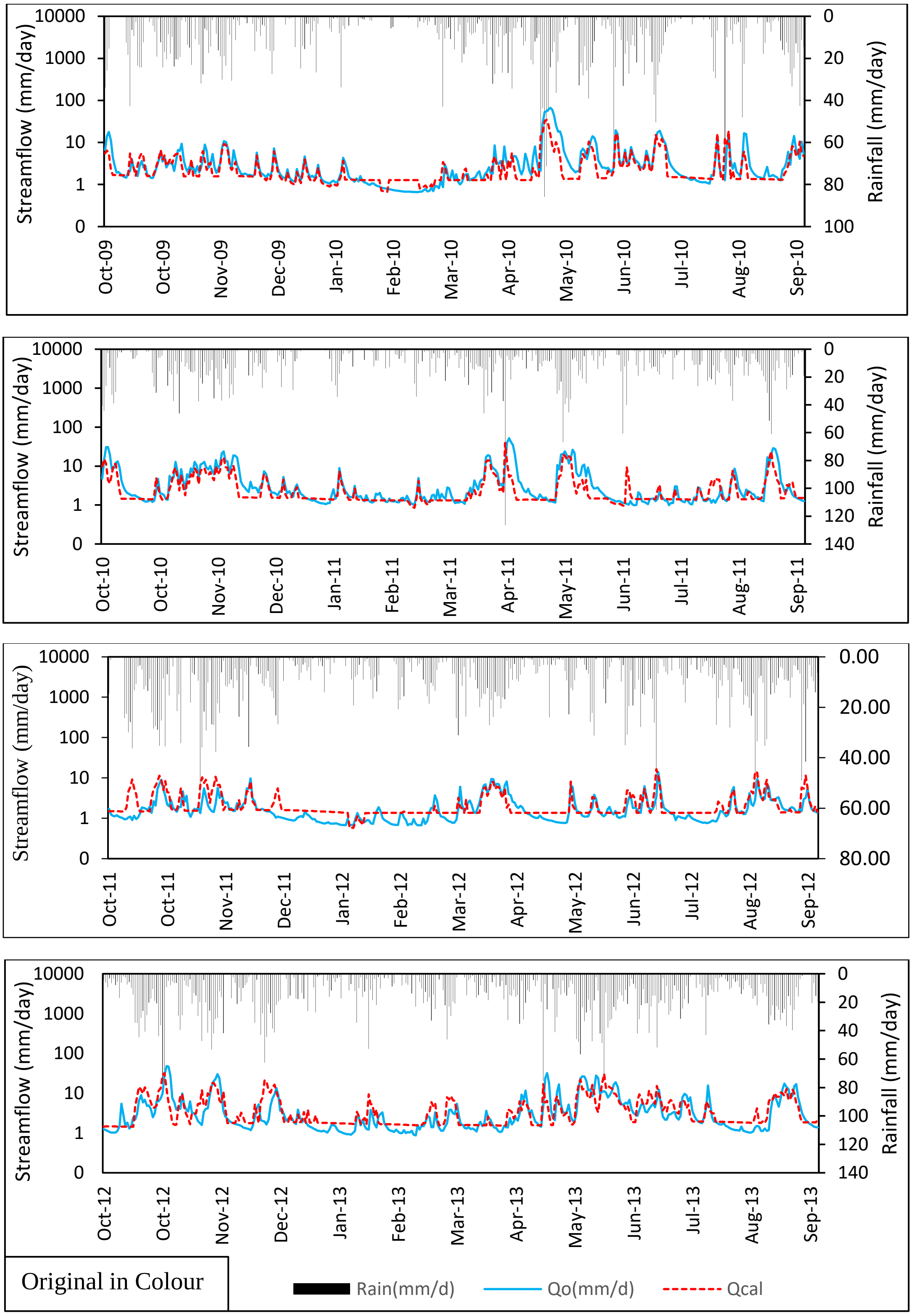



Figure 5-29 Hydrographs match for parameter transfer from Ratnapura to Ellagawa

Hydrograph match for the water years from 2013/14 to 2014/17 of the parameter transfer from Ratnapura to Ellagawa watershed is shown in Figure 5-30.

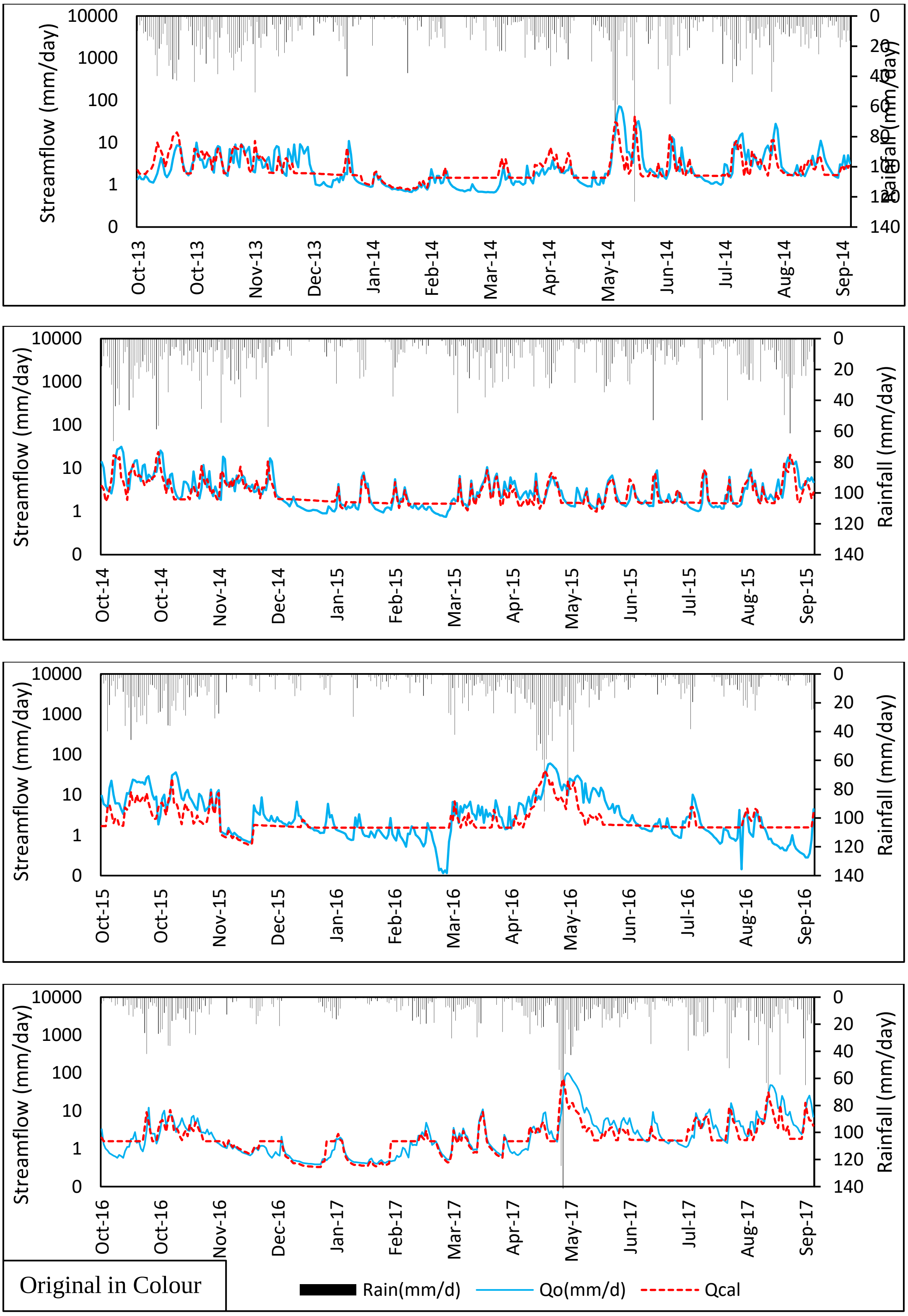
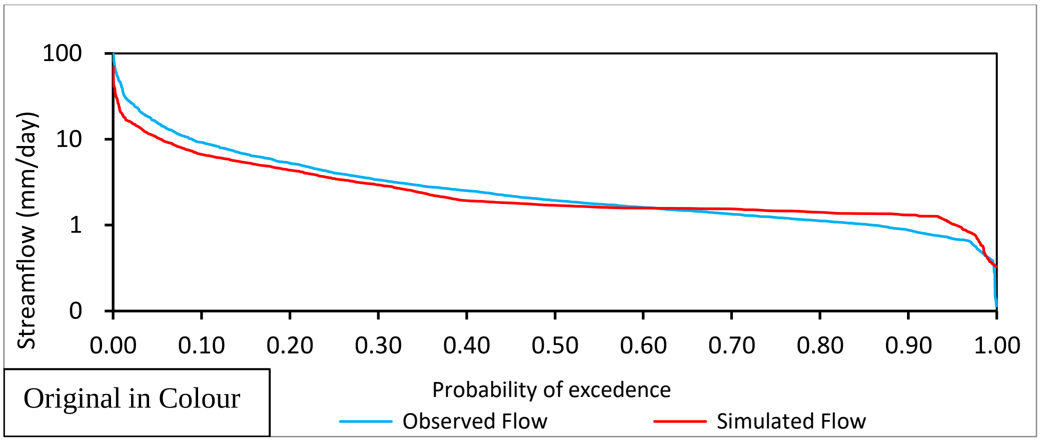



Figure 5-30 Hydrographs match for parameter transfer from Ratnapura to Ellagawa

The estimated and observed flow duration curves for parameter transfer to Ellagawa watershed plotted and also matched. The MRAE value of 0.277 for high flows, 0.133 for medium flows, and 0.370 for low flows were obtained. The flow duration curve matching for parameter transfer from Ratnapura to Ellagawa watershed is shown in Figure 5-20.




Original in Colour

Figure 5-31 Flow duration curve matching for parameter transfer to Ellagawa

# 6 RESULTS AND DISCUSSION

## 6.1 Model Modification

Tank Model was originally developed by Sugawara in 1967 keeping in mind the hydrological condition of Japan. In Japan evapotranspiration is comparatively not very much high, basins are small in size, river gradients are steep and time of concentration is small. So, the original model developed included three tanks that laid vertically in a series. Later on, Sugawara suggested m x n structure of the model for non-humid basins. According to the climate and characteristics of watershed components, special consideration and correction are requires for the application of the Tank model (Hong et al., 2015).

Precipitation and evapotranspiration are the main Input to the model. Outputs from each zone tank are carried forward as input to the next zone. Water in all four tanks from top moves to both horizontally and vertically. Discharge through the bottom outlet of the top tank is the inflow to the second tank. Similarly discharges through the bottom outlets of second and third tanks are the inflows to the third and fourth tanks respectively (Sugawara, 1961).

In this study, the standard Tank model suggested by Sugawara in (1974) which comprises four tanks for the humid regions applied for the simulation of Ellagawa and Ratnapura watersheds responses to Thiessen rainfall. Only for the consideration of the time delay in the infiltration process from the first tank, height as a parameter added to the bottom outlet of the first Tank. Interval for the newly added parameter assigned between equal or greater than zero, and having less height from the height of the first outlet of the first tank.

## 6.2 Identification and Comparison of the Initial Condition of the Model

Model identification requires a suitable initial soil moisture content prior to run the model for simulation. Considering the review of the literature, a periodic warm-up of 6 cycles was applied to obtain the representative value of the initial soil moisture content of the watersheds. During warming up of the model, it's observed that one cycle with four years data set is acceptable for obtaining the initial soil moisture content of the first three tanks of the model. While the soil moisture of the fourth tank of the model showed fluctuation up to the 6$^{th}$ cycle.

The initial soil moisture of each tank of the Tank model for Ellagawa and Ratnapura watershed is given in Table 6-1 for comparison.

Table 6-1 Comparison of Initial soil moisture of Ellagawa and Ratnapura watersheds

| Watershed | Tank A Initial storage (mm) | Tank B Initial storage (mm) | Tank C Initial storage (mm) | Tank D Initial storage (mm) |
|---|---|---|---|---|
| Ellagawa | 28.22 | 71.13 | 975.06 | 67529.97 |
| Ratnapura | 11.44 | 31.43 | 841.06 | 65951.05 |

From Table 6-1 it can be noticed that the soil moisture of the first, second, and third tank of Ellagawa watershed showing almost double-fold increase from Ratnapura watershed. While the soil moisture of the lowermost tank is comparable for Ellagawa and Ratnapura watershed.  Increase in the soil moisture of the first, second, and third tank can be linked to the location of Ratnapura watershed in the upstream and variation of land use and soil types of these two watersheds. In addition, the soil moisture behavior for the calibration period of the model for Ellagawa and Ratnapura watershed is given Annex D – Analysis.

### 6.3 Identification and Comparison of the Streamflow Thresholds

To evaluate the model performance for specific engineering applications such as water resources planning and management, drought, and flood management, the daily flow duration curves were prepared for Ellagawa and Ratnapura watershed. In order to separate streamflow regions at first, the intermediate flow period was demarcated on the "Probability of Exceedance" axis by combining the flow magnitude and slope variability information. The step type behavior of the slope curves demonstrates the consistency of each order of magnitude with the length of each step (having the same slope value). Accordingly, with the evidence from the Slope-of-FDC curves, the onset of the consistent flow period was determined by first selecting the appropriate step and then selecting the probability of exceedance which is closer to the high flow region. Once the onset was identified then the intermediate flow region could be visualized with slowly decreasing flow magnitudes reflected by the gradual decrease in the slope of FDC. The watershed low flow period commences with the end of the gradual decrease. As such, the tail end of the intermediate flow region was first selected by capturing the appropriate step and then selecting the probability of exceedance value corresponding to the low flow end of the step for Ellagawa and Ratnapura watershed.

Comparison of the streamflow thresholds of Ellagawa and Ratnapura watershed is given in Table 6-2.

Table 6-2 Identification and comparison of streamflow thresholds

| **Flow Type** | **Percentage exceedance** | |
|---|---|---|
| | **Ellagawa** | **Ratnapura** |
| High | < 0.18 | < 0.18 |
| Medium | > 0.18& < 0.78 | > 0.18& < 0.78 |
| Low | > 0.78 | > 0.78 |

Usually, streamflow regions of watersheds with comparable physical and hydrological characteristics tend to have comparable flow regimes. Accordingly, comparison of the watershed properties of Ellagawa and Ratnapura watershed revealed that both watersheds have a high degree of similarity. Therefore, the demarcation of the flow threshold boundaries revealed that the Ellagawa and Ratnapura subwatershed of Ellagawa has a similar flow regime. The probability of exceedance from 0 to 18% estimated and marked as high flows, from 18 to 78% marked as medium and, from 78% to 100% marked as a low flow region.

## 6.4 Parameters Optimization and Evaluation Criteria of the Tank Model

For many years, calibration of the tank model with snowpack components was carried out by a trial and error method. Recently an automatic calibration method was developed to determine the runoff and infiltration coefficient. Then, the semi-automatic procedure was developed to determine the parameters of the soil moisture structure, the parameter of the side outlets position, and finally parameters of the snow model. Considering a large number of parameters and structure of the Tank model which involve several discrete functions, a semi-automatic method was applied for the optimization of the Tank model parameters.

In the optimization process of a model, identification of a suitable initial condition is crucial for obtaining the optimum value of parameters. Therefore, the recommended

initial values of the model parameters in the guideline were introduced to the model. Initially, a sensitivity analysis was carried out to find out the most sensitive parameters of the model. The result of the analysis revealed that the parameters controlling the infiltration of the first tank (A0), sub-surface flow (A1) of the model, and parameter controlling the baseflow were found the most sensitive parameters respectively. Besides, the review and assessment of the objective functions revealed that the Mean Ratio of Absolute Errors is the most suitable choice for the optimization of the model parameters. Therefore, the MRAE was used to evaluate model performance.
Initially, considering the sensitivity level of the parameters the trial and error method was used to optimized the model parameters. 30 trials were performed and for each trial, the performance of the model was evaluated according to 6 criteria. These 6 criteria included the overall MRAE, MRAE for low flows, MRAE for medium flows, MRAE for high flows, hydrograph match, water balance errors, and flow duration curve match of the observed and simulated flows. To improve the quality of manual optimization, the solver tools of Microsoft Excel was applied for the automation of the process. The goal of minimizing the MRAE value and constraints of the parameters were introduced to the solver tool. To include the speed of GRG nonlinear and robustness of the Evolutionary algorithm tools the GRG Nonlinear Multistart was used as a suitable method of solution. Manual optimization supporting by automatic procedure showed a satisfactory result in the optimization of the Tank model parameters. Therefore, this study recommends and emphasizes that the trial and error procedure carried out under the subjective and synthetic judgments is the most important and effective method of the parameter optimization of the Tank model and automatic or semi-automatic are only supporting methods.

## 6.5 Identification of the Suitable Option for Parameter Transferability

To select a suitable method of parameter transfer, four most frequently used methods (e.g., Regression, Global Average, Spatial Proximity, and Kriging) were reviewed and assessed according to the criteria considering the strength and limitation of the method.

Regression is the most popular method of the parameter transferability of hydrologic models. In this method, the parameters are linked to the hydrological and physical characteristics of a gauged watershed. Hereafter, the obtained coefficient of regression with respect to the characteristics of the gauged watershed is used to estimate the parameters of the ungauged watershed. The Regression approach for parameter transfer is based on two assumptions. The first assumption considering that there is a strong link of the watershed characteristics and parameters of the model, however, most hydrologic models do not have a single set of model parameters to estimate the best fit of the model. Indeed, the optimum set of parameters is dependent on the quality of input data, and the period of calibration. The second assumption in the approach assumes that the characteristics of gauged watershed selected for regression deliver a similar result in the ungauged watershed. while in practice the spatial variation of watershed characteristics hindering the viability of this approach.

The second option for parameter transfer reviewed and assessed was the Global Average approach. In this approach the average of calibrated parameters of the gauged watershed transfer to the receiver watershed. The review of the literature revealed that the approach reduces the level of uncertainty in the modeling process. however, the approach is not considering the heterogeneity of donor and receiver watershed and most of the time leads to the unsatisfactory result of the modeling.

The third option for parameter transfer is the Spatial Proximity method. In this approach, the calibrated parameters of the geographically neighboring gauged watershed transfer to the ungauged watershed. The approach is based on the concept that the closest watershed should response comparable because of having comparable physical and hydrologic characteristics. For the successful application of the approach, it's essential to make sure that the donor and receiver watershed have similar hydrologic and physical characteristics. In this method, the whole set of calibrated parameters transferred to the receiver watershed.

The fourth option is Kriging method of interpolation. In this approach, the observed values are given a weightage, and respect to the weightage of observed values the simulated values of the receiver watershed are obtained. These weights are given based on the distance between the gauged and ungauged point locations. This approach considers the nested nature of a watershed, geometric arrangement, and structure of the hydrographic network and area of the watershed. However, the successful application of the approach depends on the availability of a spatially well-organized dataset of the donor watershed.

Table 6-3 Strength and limitations of the options for parameter transferability

| No | Option for transferability | Strength | Limitation |
|---|---|---|---|
| 1 | Regression | ➢ Indicate the significant relationship between variables.<br>➢ Compare the effects of variables. | ➢ Not considering heterogeneity between watersheds.<br>➢ Easily affected by outliers in data. |
| 2 | Global Average | ➢ Reduces the level of uncertainty. | ➢ Not considering heterogeneity between watersheds. |
| 3 | Spatial Proximity | ➢ Considering heterogeneity between watersheds.<br>➢ Easy to apply.<br>➢ High accuracy. | ➢ Required reasonably similar hydrologic and physical characteristics of the watershed. |
| 4 | Kriging method | ➢ Considers the nested nature of a watershed.<br>➢ Consider the geometric arrangement and structure of the hydrographic network. | ➢ Not considering. heterogeneity between watersheds.<br>➢ Required spatially well-organized datasets. |

Comparison of the selected methods revealed that the Regression, Global Average, and Kriging methods are based on the assumptions that strongly criticized by the recent studies and do not fulfill the selected criteria for the assessment. While, the spatial proximity, is by far the most reliable approach for parameter transfer. Therefore, this study recommends the application of the Spatial Proximity approach for the transferability of model parameters.

## 6.6 Comparison of the Parameters for Ellagawa and Ratnapura Watersheds

The Ellagawa main watershed has similar physical characteristics to Ratnapura subwatershed. Both watersheds are located in the same ecoregion therefore, it was expected that the estimated characteristics of the Ellagawa and Ratnapura watershed would well estimate the characteristics of each other. The results of the study supported this hypothesis. The parameters of Ellagawa for the calibration period applied to the model of the Ratnapura watershed to simulate discharge at the gage of Ratnapura form October 1, 2009, to September 30, 2017. Similarly, the optimum parameters of the Ratnapura watershed transferred to the Ellagawa model. The rainfall station's weights were changed considering the boundary of Ratnapura so that the subwatershed model would use an input that better represent precipitation specifically in the subwatershed. Table 5-1 and Table 5-2 shows Thiessen weightage of these weather stations. Visually, Comparison of the parameters of the Tank model for Ellagawa and Ratnapura watershed is given in the following sections.

### 6.6.1 Comparison of the parameters controlling surface and subsurface flows

Multiplicative and height of the side outlets of the first tank governing the surface and subsurface runoff of a watershed. These four parameters of the first tank (A1, Ha1, A2, Ha2) are mainly responsible for the peaks in a hydrograph. Soil types, land use, the elevation of drainage area, vegetation, and slope of the watershed are the main factors altering the pattern and amount of surface runoff of a watershed. Hence the analysis of these factors for both watersheds was carried out and a comparison of these factors is made for Ellagawa and Rantnaura watershed.

According to the soil map from Survey Department, Figure 5-5 Red-Yellow podzolic soils, hilly and rolling te, and steeply dissected is the dominant soil type for both watersheds covering 86.5% and 90.0%, area of Ellagwa and Ratnapura watershed respectively. Furthermore, Analysis of elevation map using GIS tools showed the elevation of Ellagawa and Ratnapura is comparable and ranging from 7m to 2149m for Ellagawa and 10m to 2149 m, MSL, for Ratnapura watershed.

Furthermore, Neighbourhood Methods was used to calculate the average slope for both watersheds. The slope and its classification are shown in Figure 5-4. The gradient of both watersheds at the upper region is steep while in the downstream area following a mild gradient.

Considering the analysis of land use in Figure 5-6 of the study area, cultivation is the dominant vegetation type for both main and subwatershed. The non-permeable and semi-permeable area altogether covers almost 19% of Ellagawa and Ratnapura watershed. On the other hand, the drainage area of Ellagawa watershed is significantly varied from Ratnapura watershed. This variation is almost more than double-fold for both watersheds.

In the meantime, considering the parameters responsible for surface and subsurface flows in the model are comparable. Multiplicative of the first outlet and height of the outlet are similar for both watersheds. While considering the second outlet and height of the outlet, there is a variation of 0.05 in A2 and 5mm for Ha2 for Ellagawa and Ratnapura watershed respectively. This variation of parameters can be linked to the location of the huge flood-prone area in the downstream of Ellagawa watershed and variation of the land use and soil properties of these two watersheds. Comparison of the parameters controlling surface and subsurface flows are given in Table 6-4.

Table 6-4 Comparison of parameters controlling surface and subsurface flow

| Tank | No | Parameter | Initial Parameter | Ellagawa Watershed | Ratnapura Watershed |
|---|---|---|---|---|---|
| Tank A | 1 | A1 | 0.232 | 0.15 | 0.15 |
| | 2 | Ha1 | 14.280 | 35.00 | 35.00 |
| | 3 | A2 | 0.168 | 0.25 | 0.20 |
| | 4 | Ha2 | 41.380 | 75.00 | 70.00 |

### 6.6.2 Comparison of the Parameters Controlling Intermediate Flow

Hight and multiplicative of the side outlet of the second tank are controlling the intermediate flow of a watershed. Considering the fact that the variation in land use and soil type causing variation in intermediate flow, the parameters B1 and Hb1 for Ellagawa and Ratnapura watershed has 0.001 and 5mm variation respectively. These variations are given in Table 6-5. Therefore when the parameter transferred the variation of the parameters didn't influence the overall hydrograph of the watershed significantly.

Table 6-5 Comparison of parameters controlling the intermediate flow

| Tank | No | Parameter | Initial Parameter | Ellagawa Watershed | Ratnapura Watershed |
|---|---|---|---|---|---|
| Tank B | 1 | B1 | 0.065 | 0.045 | 0.046 |
| | 2 | Hb1 | 24.750 | 100.00 | 105.00 |

### 6.6.3 Comparison of the parameters controlling sub-base and base Flow

Sub-base and baseflows are the crucial components of the water resources available in a watershed. The base and sub base flow components influence by the land cover, geological conditions, precipitation, soil moisture, and thermal condition of the area. The height of the outlets and multiplicative of third and fourth tank is responsible for sub-base and base flow. The optimized values for these parameters are given in Table 6-6. Multiplicative and height of the outlets for the third tank has a small variation of 0.002 for multiplicative and 50 mm variation between the height of outlets. While the multiplicative of the fourth tank is similar for both watersheds.

Table 6-6 Comparison of parameters controlling the sub base and base flow

| Tank | No | Parameter | Initial Parameter | Ellagawa Watershed | Ratnapura Watershed |
|---|---|---|---|---|---|
| Tank C | 1 | C1 | 0.008 | 0.001 | 0.0012 |
| | 2 | Hc1 | 0.000 | 500.00 | 550.00 |
| Tank D | 3 | D1 | 0.001 | 0.00002 | 0.00002 |

### 6.6.4 Comparison of the Parameters Controlling Infiltration

Parameter of the bottom outlet of each tank of the Tank model is responsible for the infiltration process. The process of infiltration is influencing by soil type (texture, structure, and hydrodynamic properties of soil). As discussed in the previous section the soil types for both watersheds are comparable. Vegetation coverage is another dominant factor affect the process. It has a positive impact on the process by increasing the time of water infiltration. Parameters responsible for infiltration are given in Table 6-7. Comparison of the parameters showing a decreasing pattern from top to bottom for both watersheds. Multiplicative and height of the first outlet are similar for Ellagawa and Ratnapura watershed. While comparison of the second and third tank of infiltration parmaters showed variation of 0.05 and 0.002 in parameter vaalues respectively.

Table 6-7 Comparison of parameters controlling the process of infiltration

| Tank | No | Parameter | Initial Parameter | Ellagawa Watershed | Ratnapura Watershed |
|---|---|---|---|---|---|
| Tank A | 1 | A0 | 0.133 | 0.25 | 0.25 |
| | 2 | Ha0 | 5.000 | 2.00 | 2.00 |
| Tank B | 7 | B0 | 0.044 | 0.10 | 0.15 |
| Tank C | 10 | C0 | 0.017 | 0.010 | 0.012 |

From the Comparison of optimum parameters for both watersheds, it can be observed that the values of the parameters are not significantly varied for Ellagawa main and Ratnapura subwatershed.

## 6.7 Comparison of the Water Balance Errors for Parameters Transfer

### 6.7.1 Transfer of optimized parameters from Ellagawa to Ratnapura

Although for both cases when parameters optimized for watershed itself and when transferred optimized parameters from Ellagawa to Ratnapura, the annual water balance error is comparable, the model underestimated the streamflow in both cases. Errors in the annual water balance are given in Table 6-6. From the comparison of errors, it revealed that the water balance errors decrease by 3% while the parameters transferred from main to subwatershed. The results showed that the efficiency of the model increased when the parameters transferred from main to subwatershed. The most crucial factor that might be contributed to the improvement of model performance is the scale and rainfall station density impact on the representative rainfall of watershed.

Considering the spatial and temporal variation of rainfall, a high density of rain gauge stations is crucial for the accurate estimation of representative rainfall of the watershed. Obviously, the larger the sampling density the accurate representative rainfall can be estimated for hydrologic analysis (Skoien, et al., 2003). Hence, an increased number of rainfall stations at Ellagawa watershed might leads to the accurate estimation of the representative rainfall and accordingly obtaining the optimum parameters of the model which could simulate the watershed response accurately compared to the Ratnapura model.

In addition, the elevation map of Ellagawa and Ratnapura watersheds showed that most of the high-altitude areas include in Ratnapura subwatershed. And as a matter of fact, the precipitation is a lot more common where there are higher elevations. And the reason is that the cooler weather and atmosphere cannot hold in as much condensation. Although, high altitude areas surrounded by Ratnapura, the estimated representative annual average rainfall of Ratnapura watershed is less than Ellgawa watershed.

Comparison of water balance errors for parameter transfer to Ratnapura watershed is given in Table 6-8.

Table 6-8 Comparison of water balance errors for parameter transfer to Ratnapura

| Water Year | Observed Streamflow (mm) | Simulated Streamflow (Optimized Parameters) (mm) | Simulated Streamflow (Transfer Parameter) (mm) | Annual water balance Errors (Optimized Parameters) (%) | Annual water balance Errors (Parameters Transfer) (%) |
|---|---|---|---|---|---|
| 2009/2010 | 1768.91 | 1484.97 | 1283.25 | 14.54 | 24.87 |
| 2010/2011 | 1876.09 | 1362.41 | 1371.66 | 25.14 | 24.69 |
| 2011/2012 | 880.95 | 791.28 | 835.61 | 4.27 | 2.16 |
| 2012/2013 | 1987.05 | 1588.08 | 1744.70 | 12.31 | 7.48 |
| 2013/2014 | 1326.86 | 1097.82 | 1278.97 | 8.06 | 1.69 |
| 2014/2015 | 2380.81 | 1905.66 | 1779.77 | 22.35 | 28.27 |
| 2015/2016 | 1494.20 | 1102.97 | 1377.09 | 19.98 | 5.98 |
| 2016/2017 | 1323.89 | 1189.46 | 1328.42 | 5.12 | 0.17 |
| Average | 1629.85 | 1315.33 | 1374.93 | 13.97 | 11.91 |

Comparison of water balance errors for the parameters transfer from Ellagawa main watershed and when the parameters optimized for the watershed shown in Figure 6-1 for each water year.

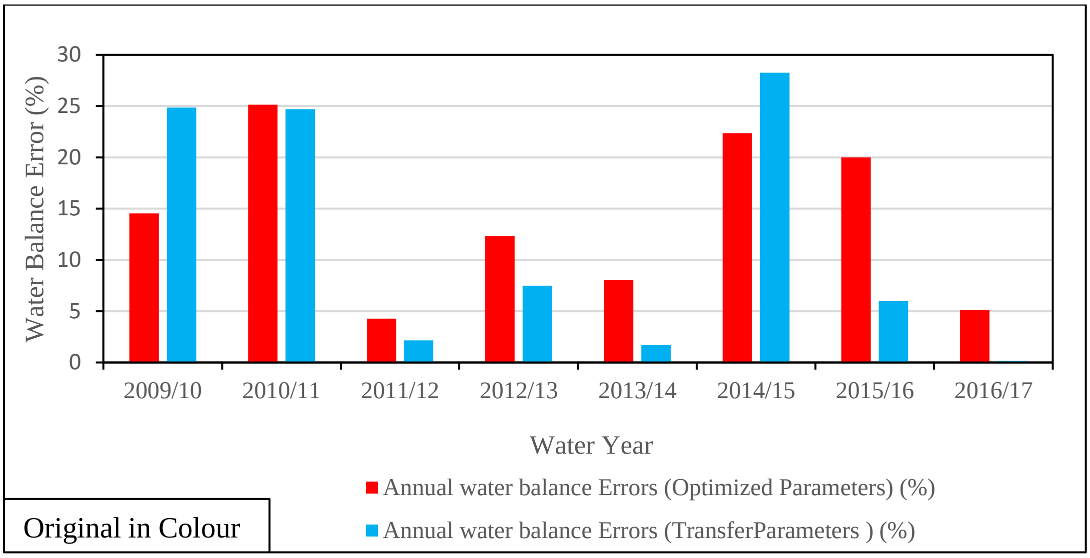



Figure 6-1 Comparison of water balance errors for parameter transfer to Ratnapura

The comparison of water balance errors concluded that that the parameters transfer from Ellagawa to Rantnapura watershed decreased the water balance errors in simulation. And the main reason might be the optimization of Ellagawa parameters by means of accurate representative rainfall with compare to the representative rainfall of Ratanpura watershed.

### 6.7.2 Transfer of optimized parameters from Ratnapura to Ellagawa

When the optimized parameters of the Ratnapura watershed transferred to the Ellagawa watershed, the performance of the model decline. The water balance errors increased by 6.15%. The model underestimated the streamflow for parameter transfer. Only for the two consecutive water years 2011/2012 and 2012/2013 the model overestimated the streamflow. As discussed in section 6.4.1 of this chapter the model efficiency decrease over the scale and the main and perhaps the most critical factor that may contribute is the scale impact on the estimation of representative rainfall of the watershed.

Comparison of the annual water balance errors for parameters transfer to Ellagawa watershed is given in Table 6-9.

Table 6-9 Comparison of annual water balance errors transfer to Ellagawa

| Water Year | Observed Streamflow (mm) | Simulated Streamflow (Optimized Parameters) (mm) | Simulated Streamflow (Transfer Parameter) (mm) | Annual water balance Errors (Optimized Parameters) (%) | Annual water balance Errors (Parameters Transfer) (%) |
|---|---|---|---|---|---|
| 2009/2010 | 1600.16 | 1135.92 | 1104.49 | 22.46 | 23.98 |
| 2010/2011 | 1746.87 | 1564.40 | 1164.44 | 7.94 | 25.34 |
| 2011/2012 | 738.71 | 844.47 | 913.47 | 3.78 | 6.24 |
| 2012/2013 | 1738.12 | 1866.12 | 1719.42 | 3.23 | 0.47 |
| 2013/2014 | 1414.76 | 1253.76 | 1186.45 | 5.67 | 8.04 |
| 2014/2015 | 1423.96 | 1240.72 | 1215.21 | 6.53 | 7.44 |
| 2015/2016 | 2098.27 | 1599.06 | 1195.59 | 35.33 | 63.89 |
| 2016/2017 | 1842.00 | 1086.94 | 1109.29 | 40.79 | 39.58 |
| Average | 1575.36 | 1323.92 | 1201.05 | 15.72 | 21.87 |

Comparison of water balance errors for the parameters transfer from Ratnapura sub watershed and when parameters optimized for the watershed shown in Figure 6-2 for each water year.

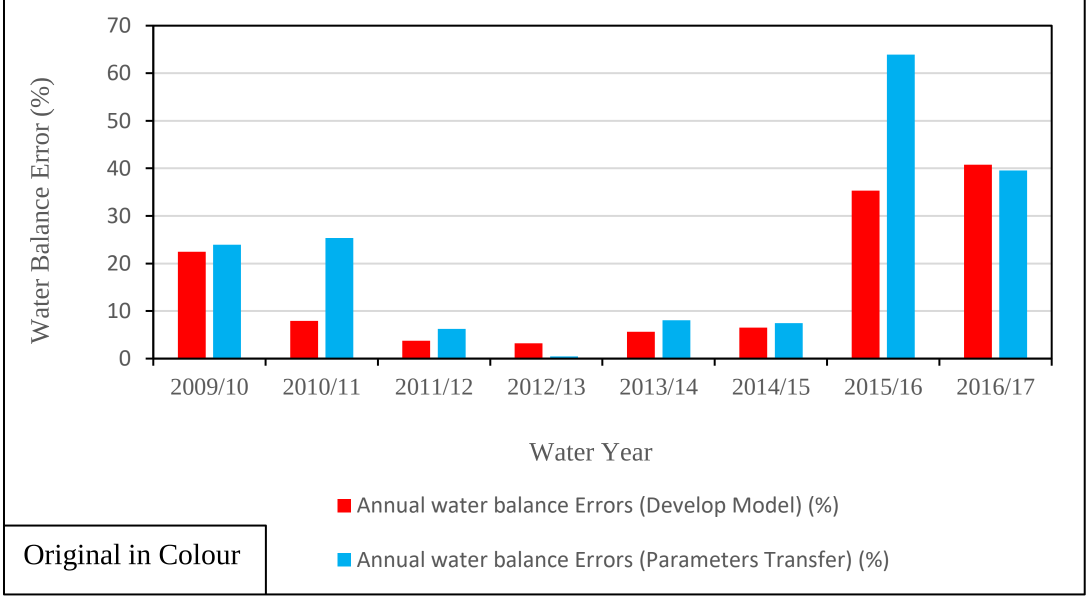



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Figure 6-2 Comparison of water balance errors for parameter transfer Ellagawa

## 6.8 Comparison of the Runoff Coefficient for Parameters Transfer

### 6.8.1 Transfer of Optimized Parameters from Ellagawa to Ratnapura

Overall comparison of the runoff coefficient for both cases (optimizing the model parameters and transfer the optimized parameters from the main watershed) showed that the model underestimated the streamflow. While considering the water years 2012/2013 and 2013/2014 where the observed runoff coefficient showed comparatively very low value, the transfer of optimized parameters to the subwatershed, overestimated the streamflow. The reason for an overestimation in these two years might be the data errors where the streamflow is not responding well to the Thiessen average rainfall.

Comparison of the runoff coefficient for observed, parameters optimized for the Ratnapura watershed and when the optimized parameters transfer from Ellagawa to Ratnapura watershed are given in Table 6-10.

Table 6-10 Comparison of runoff coefficients for parameter transfer to Ratnapura

| Water Year | Observed Runoff Coefficient | Simulated Runoff Coefficient (Optimizing Parameters) | Simulated Runoff Coefficient (Transfer parameters) |
|---|---|---|---|
| 2009/2010 | 0.48 | 0.40 | 0.34 |
| 2010/2011 | 0.48 | 0.35 | 0.35 |
| 2011/2012 | 0.30 | 0.27 | 0.28 |
| 2012/2013 | 0.30 | 0.30 | 0.33 |
| 2013/2014 | 0.26 | 0.26 | 0.31 |
| 2014/2015 | 0.42 | 0.42 | 0.39 |
| 2015/2016 | 0.32 | 0.32 | 0.40 |
| 2016/2017 | 0.30 | 0.30 | 0.34 |
| Average | 0.39 | 0.33 | 0.33 |

Graphical representation of the comparison for all three cases discussed previously is given in Figure 6-3.

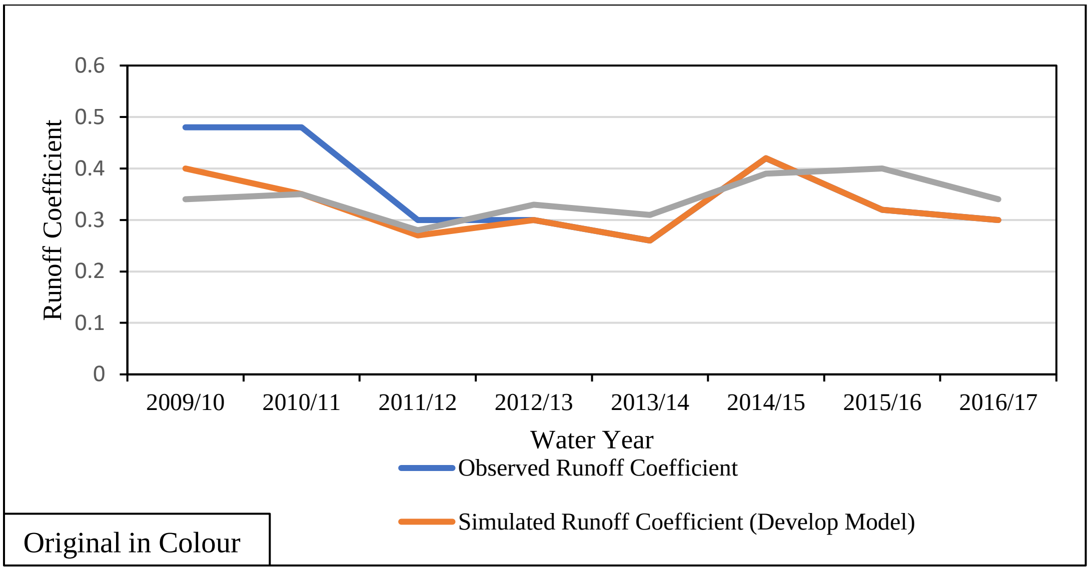


Figure 6-3 Comparison of runoff coefficients for parameter transfer to Ratnapura

### 6.8.2 Transfer of optimized parameters from Ratnapura to Ellagawa

Comparison of the runoff coefficient for both cases (when optimized the model parameters and transfer the optimized parameters from sub watershed to Ellgawa watershed) implying that the model underestimated the streamflow. Comparison of the runoff coefficient for observed, parameters transfer, and when optimizing parameters for Ratnapura watershed are given in Table 6-11.

Table 6-11 Comparison of runoff coefficient for parameter transfer to Ellagawa

| Water Year | Observed Runoff Coefficient | Simulated Runoff Coefficient (Optimizing Parameters) | Simulated Runoff Coefficient (Transfer parameters) |
|---|---|---|---|
| 2009/10 | 0.44 | 0.31 | 0.30 |
| 2010/11 | 0.43 | 0.39 | 0.29 |
| 2011/12 | 0.21 | 0.24 | 0.26 |
| 2012/13 | 0.30 | 0.33 | 0.30 |
| 2013/14 | 0.28 | 0.29 | 0.28 |
| 2014/15 | 0.29 | 0.29 | 0.29 |
| 2015/16 | 0.34 | 0.46 | 0.34 |
| 2016/17 | 0.30 | 0.29 | 0.30 |
| Average | 0.34 | 0.32 | 0.29 |

Graphical representation of the comparison for all three cases discussed previously is given in Figure 6-4.

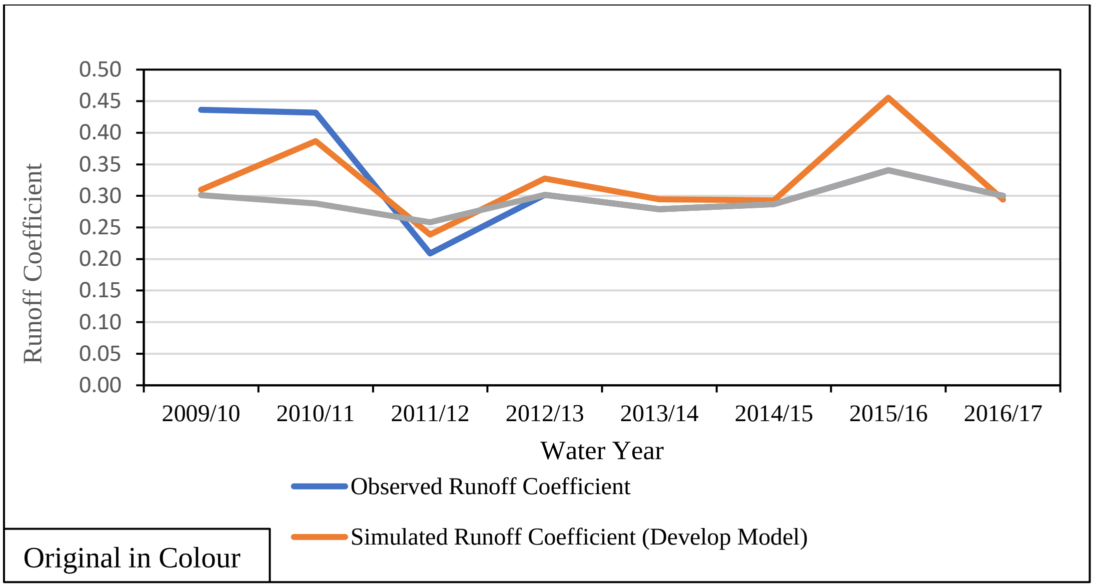


Figure 6-4 Comparison of runoff coefficient for parameter transfer to Ellagawa

## 6.9 Comparison of the Model Performance Considering the flow thresholds

### 6.9.1 Transfer of Optimized Parameters from Ellgawa to Ratnapura

Generally, the comparison of the model performance for optimization and transfer of the parameters showing that the model performance for both cases is comparable. The parameters of the model optimized for the Ratnapura watershed with significant MRAE value 0.416, while transferred the optimized parameters to the entire data sets of Ratnapura watershed presented the overall MRAE value of 0.445, which showed 7% decline in the water balance errors. Considering the flow threshold, the parameters transfer of the model outperformed optimization of the parameters for the watershed in high and medium flows. The model performance when the parameters optimized for the watershed showed the MRAE values of 0.2 and 0.243 for high and Medium flows respectively. While for parameters transfer the model showed significant improvement in the performance of the model with the MRAE values of 0.174 and 0.153 for high and medium flows respectively. On the other hand, the model performance in low flows for parameter transfer showed a significant decline with the MRAE value of 0.373, compared to the optimization of the parameters with MRAE values of 0.302.

Comparison of the model implies that the Ellagawa watershed parameters adequately estimate the physical characteristics of the Ratnapura watershed. Comparison of the model performance considering the flow threshold is given in Table 6-12.

Table 6-12 Comparison of model performance considering flow threshold

| Objective Function | Flow Threshold | Model Develop for Catchment | Transferring the parameters to catchment |
|---|---|---|---|
| MRAE | Overall | 0.416 | 0.445 |
| | High | 0.200 | 0.174 |
| | Medium | 0.243 | 0.153 |
| | Low | 0.302 | 0.373 |

### 6.9.2 Transfer of optimized parameters from Ratnapura to Ellagawa

The overall MRAE value for the parameter transfer from sub to the main watershed showed a decline in the model performance. The parameters of the model optimized for Ellagawa watershed with a significant MRAE value of 0.451, while transferred the optimized parameters of Ratnapura watershed to Ellagawa, the overall MRAE showed a significant decline with MRAE value of 0.551. Considering the flow threshold, the parameters optimized for the watershed outperformed the transferred of the optimized parameters from Ratnapura to Ellagaw.

Comparison of the model performance considering the flow threshold for parameter transfer and optimized for the catchment itself is given in Table 6-13.

Table 6-13 Comparison of model performance considering flow threshold

| Objective Function | Flow Threshold | Optimizing Parameters | Transferring parameters |
|---|---|---|---|
| MRAE | Overall | 0.451 | 0.511 |
| | High | 0.174 | 0.277 |
| | Medium | 0.087 | 0.133 |
| | Low | 0.198 | 0.370 |

# 7 CONCLUSIONS

1. The Tank hydrologic model and the spatial proximity method for parameter transfer were found the most suitable options for spatial transferability of the lumped model parameters for streamflow estimation.
2. The Tank model demonstrated the capability to estimate the daily streamflow to a satisfactory level of accuracy. The model successfully calibrated with the MRAE values of 0.450 and 0.415 and verified with the MRAE values of 0.452 and 0.361 for Ellagawa and Ratnapura watershed respectively.
3. Parameters of the model controlling the infiltration process (A0), subsurface flow (A1), and baseflow (D1) were found the most sensitive parameters respectively.
4. Parameters controlling surface flow (A2, and Ha2), infiltration of the first tank (A0 and Ha0), and baseflow (D1) were similar for both watersheds. However, the parameters controlling subsurface flow showed a variation of 0.05 for A1, and 5mm for Ha1, parameters controlling the intermediate flows showed a variation of 0.001 for B1, and 5m for Hb1 and parameters controlling sub-base flows showed a variation of 0.002 and 50 mm for C1 and Hc1 respectively.
5. The optimized parameters of Ellagawa estimated the overall streamflow of Ratnapura with reasonable accuracy with the MRAE value of 0.445 and 2.06% decrease in water balance errors demonstrated the improvement in model performance. However, the transferred parameters to Ellagawa showed a significant decline in the model performance with the MRAE value of 0.551 and a 6.15% increase in water balance errors.
6. Considering the engineering application, the transferred parameters to Ratnapura, estimated the high and medium flows of the watershed with a high level of accuracy demonstrated the MRAE value of 0.174 and 0.153 respectively. However, the model underestimated the low flows with the MRAE value of 0.373. Similarly, the transferred parameters to Ellagawa underestimated the low flows with the MRAE value of 0.370, while simulation accuracy of high and medium flows was comparatively high and demonstrated the MRAE values of 0.277 and 0.133 respectively.

# 8 RECOMMENDATIONS

1. Transferring the optimized parameters of a lumped model from gauged to an ungauged watershed for streamflow estimation of a watershed should be used only in the case of donor and receiver watershed having a similar hydrologic and physical characteristic.
2. In this study, only the spatial proximity method of parameter transfer was analyzed. Other methods of parameter transfer such as kriging, global averages, and regression methods can be analyzed.
3. In order to find out the range of a watersheds variation that hinders the transferability of the parameters across the scale, the model should be applied to various watersheds having different ranges of variation in terms of hydrological, climatological, and physical characteristics.

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# ANNEX A – DATA

Table A-1 Thiessen average rainfall data – Ellagawa watershed

| Water Year | Monthly rainfall (mm/month) | | | Annual rainfall (mm/year) |
|---|---|---|---|---|
| | Min | Mean | Max | |
| 2009/2010 | 71.69 | 305.61 | 600.64 | 4645.30 |
| 2010/2011 | 115.63 | 337.08 | 513.11 | 5010.83 |
| 2011/2012 | 88.60 | 294.80 | 457.45 | 4378.39 |
| 2012/2013 | 244.90 | 474.68 | 766.08 | 7181.80 |
| 2013/2014 | 116.72 | 354.49 | 653.76 | 5378.79 |
| 2014/2015 | 94.47 | 352.61 | 757.44 | 5435.83 |
| 2015/2016 | 73.21 | 292.60 | 962.99 | 4839.98 |
| 2016/2017 | 37.44 | 307.76 | 757.65 | 4795.93 |

Table A-2 Streamflow data – Ellagawa watershed

| Water Year | Monthly streamflow (mm/month) | | | Annual rainfall (mm/year) |
|---|---|---|---|---|
| | Min | Mean | Max | |
| 2009/2010 | 29.63 | 133.35 | 516.38 | 2279.51 |
| 2010/2011 | 44.91 | 145.57 | 255.94 | 2193.29 |
| 2011/2012 | 27.62 | 61.56 | 125.42 | 953.31 |
| 2012/2013 | 47.31 | 144.84 | 360.79 | 2291.07 |
| 2013/2014 | 26.08 | 117.90 | 431.20 | 1989.94 |
| 2014/2015 | 42.39 | 118.66 | 355.03 | 1940.04 |
| 2015/2016 | 29.77 | 174.86 | 632.62 | 2935.51 |
| 2016/2017 | 14.86 | 153.50 | 568.15 | 2578.52 |

Table A-3 Thiessen average rainfall Data – Ratnapura watershed

| Water Year | Monthly rainfall (mm/month) | | | Annual rainfall (mm/year) |
|---|---|---|---|---|
| | Min | Mean | Max | |
| 2009/2010 | 89.02 | 310.15 | 550.05 | 4671.04 |
| 2010/2011 | 113.02 | 326.59 | 486.73 | 4845.36 |
| 2011/2012 | 64.15 | 248.35 | 412.31 | 3704.98 |
| 2012/2013 | 219.00 | 435.66 | 793.73 | 6676.28 |
| 2013/2014 | 100.74 | 347.39 | 665.90 | 5282.66 |
| 2014/2015 | 116.35 | 375.57 | 781.96 | 5780.72 |
| 2015/2016 | 57.62 | 287.67 | 997.83 | 4795.14 |
| 2016/2017 | 44.24 | 329.18 | 807.07 | 5130.61 |

Table A-4 Streamflow data – Ratnapura watershed

| Water Year | Monthly streamflow (mm/month) | | | Annual rainfall (mm/year) |
|---|---|---|---|---|
| | Min | Mean | Max | |
| 2009/2010 | 45.25 | 147.40 | 337.74 | 2299.20 |
| 2010/2011 | 40.78 | 156.33 | 270.81 | 2343.92 |
| 2011/2012 | 37.62 | 73.41 | 124.52 | 1116.48 |
| 2012/2013 | 54.03 | 165.58 | 396.91 | 2603.54 |
| 2013/2014 | 25.22 | 110.57 | 366.02 | 1828.71 |
| 2014/2015 | 25.11 | 87.28 | 372.79 | 1532.50 |
| 2015/2016 | 37.10 | 124.52 | 355.46 | 2011.35 |
| 2016/2017 | 18.91 | 110.32 | 410.27 | 1863.33 |

Table A-5 Pan evaporation data – Ratnapura watershed

| Water Year | Monthly Evaporation (mm/month) | | | Annual rainfall (mm/year) |
|---|---|---|---|---|
| | Min | Mean | Max | |
| 2009/2010 | 41.35 | 78.51 | 105.30 | 942.17 |
| 2010/2011 | 51.86 | 75.71 | 88.86 | 908.58 |
| 2011/2012 | 67.45 | 84.32 | 113.70 | 1011.83 |
| 2012/2013 | 54.81 | 74.99 | 98.43 | 899.90 |
| 2013/2014 | 58.27 | 76.89 | 107.35 | 922.66 |
| 2014/2015 | 52.73 | 75.59 | 96.47 | 907.09 |
| 2015/2016 | 51.04 | 71.97 | 94.75 | 863.67 |
| 2016/2017 | 58.69 | 74.93 | 92.00 | 899.18 |

# ANNEX B – DATA CHECKING

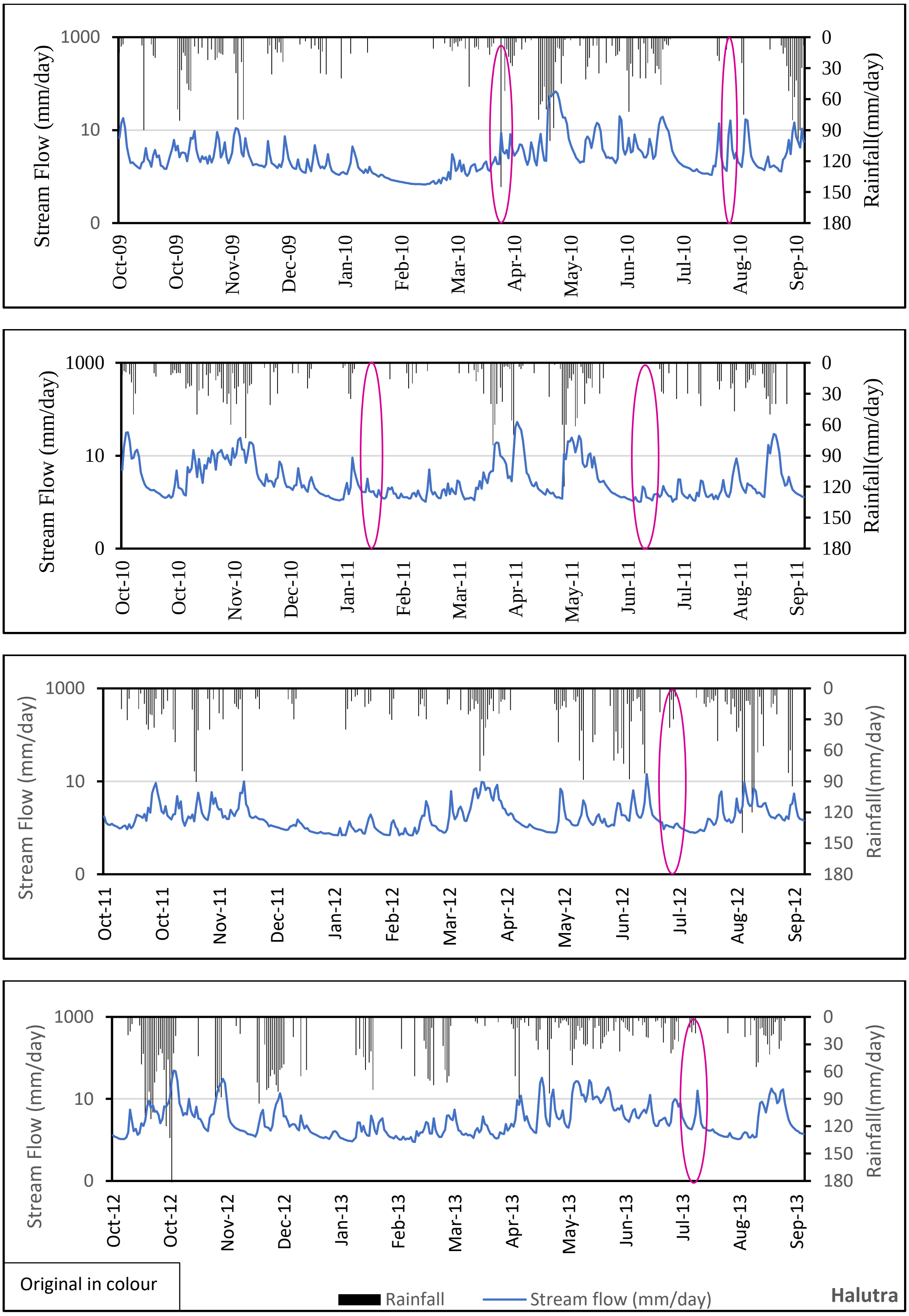



Figure B- 1 Semi-log plot of Ellagawa streamflow response to Halutra rainfall

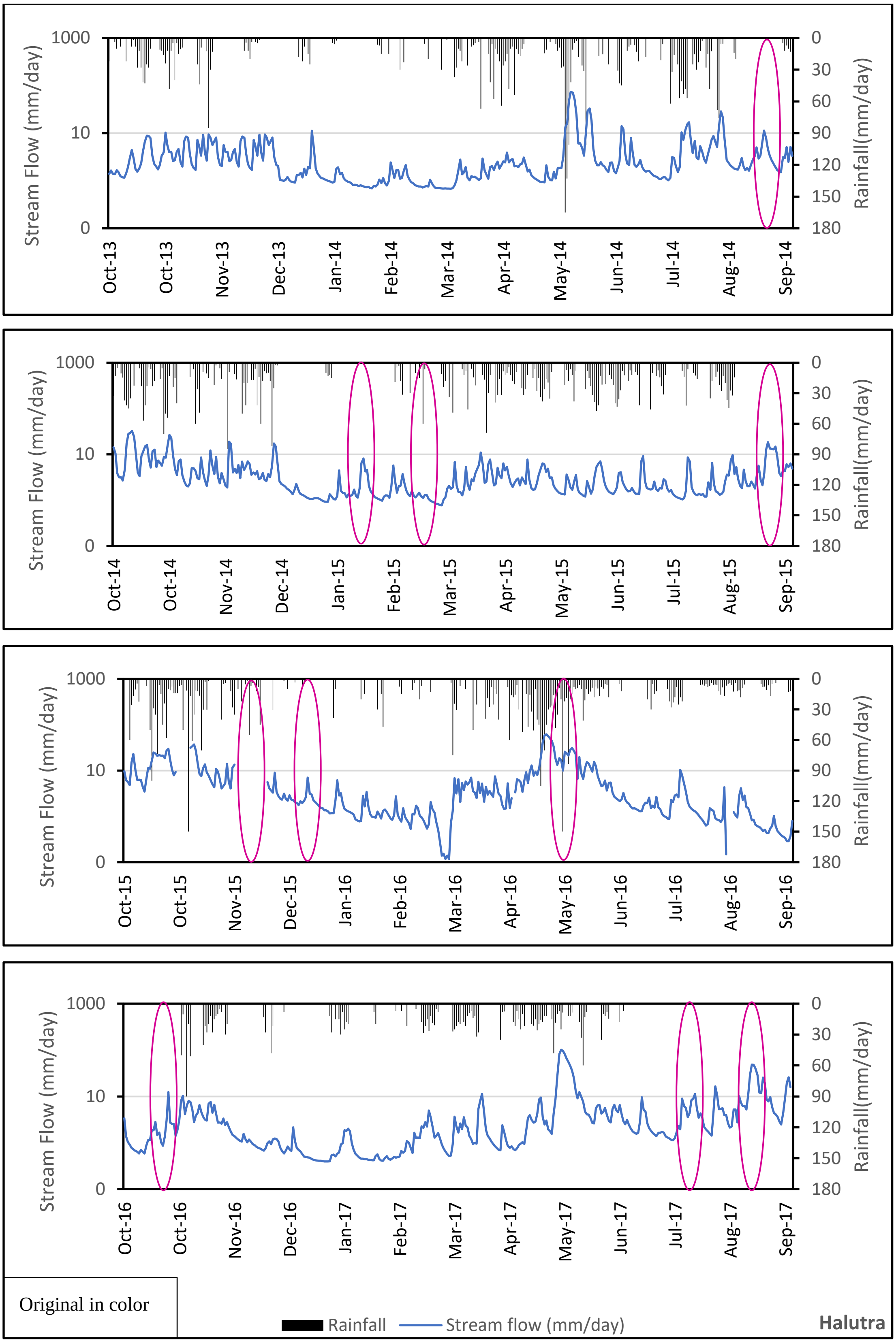



Figure B- 2 Semi-log plot of Ellagawa streamflow response to Halutra rainfall

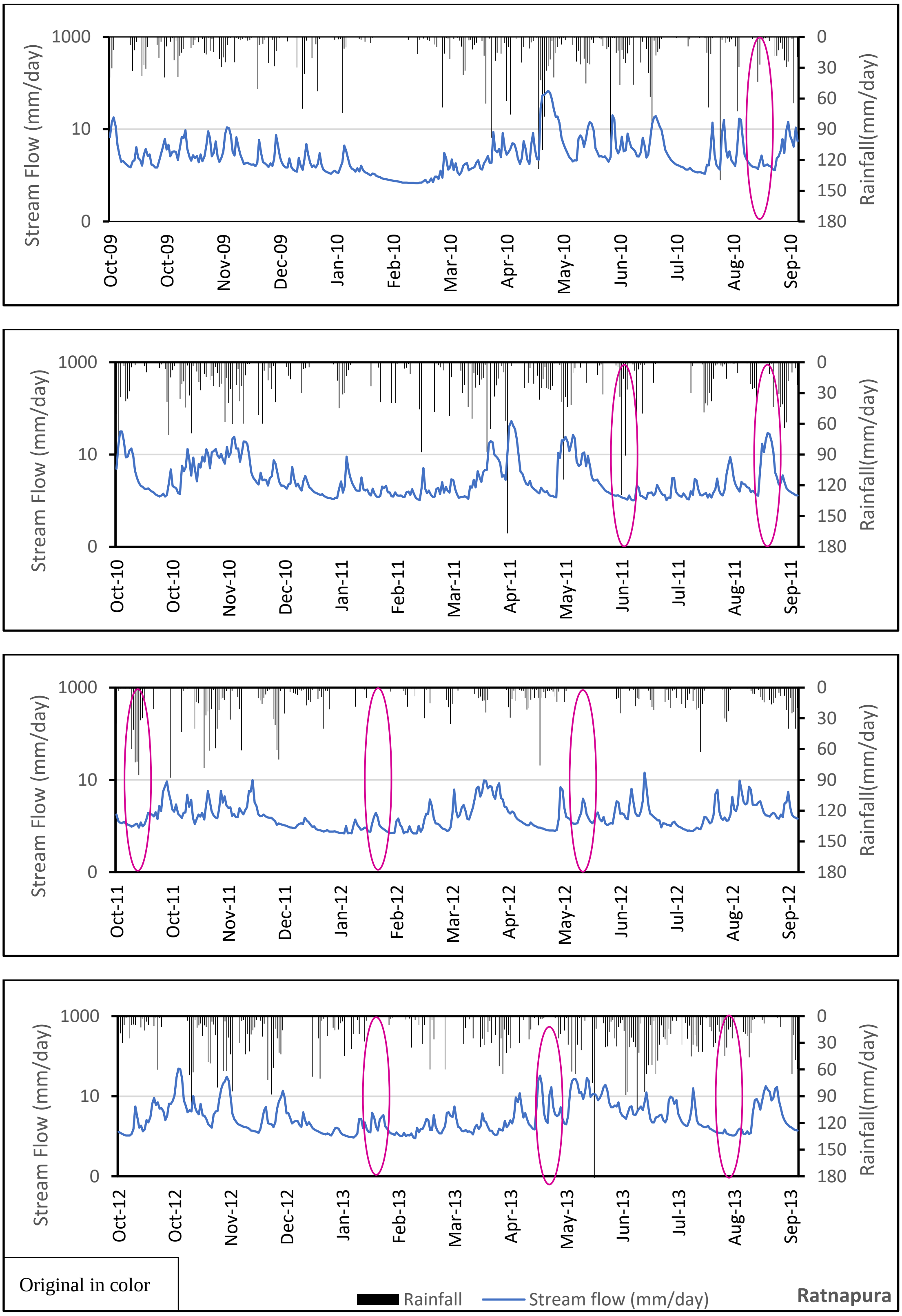



Figure B-3 Semi-log plot of Ellagawa streamflow response to Ratnapura rainfall

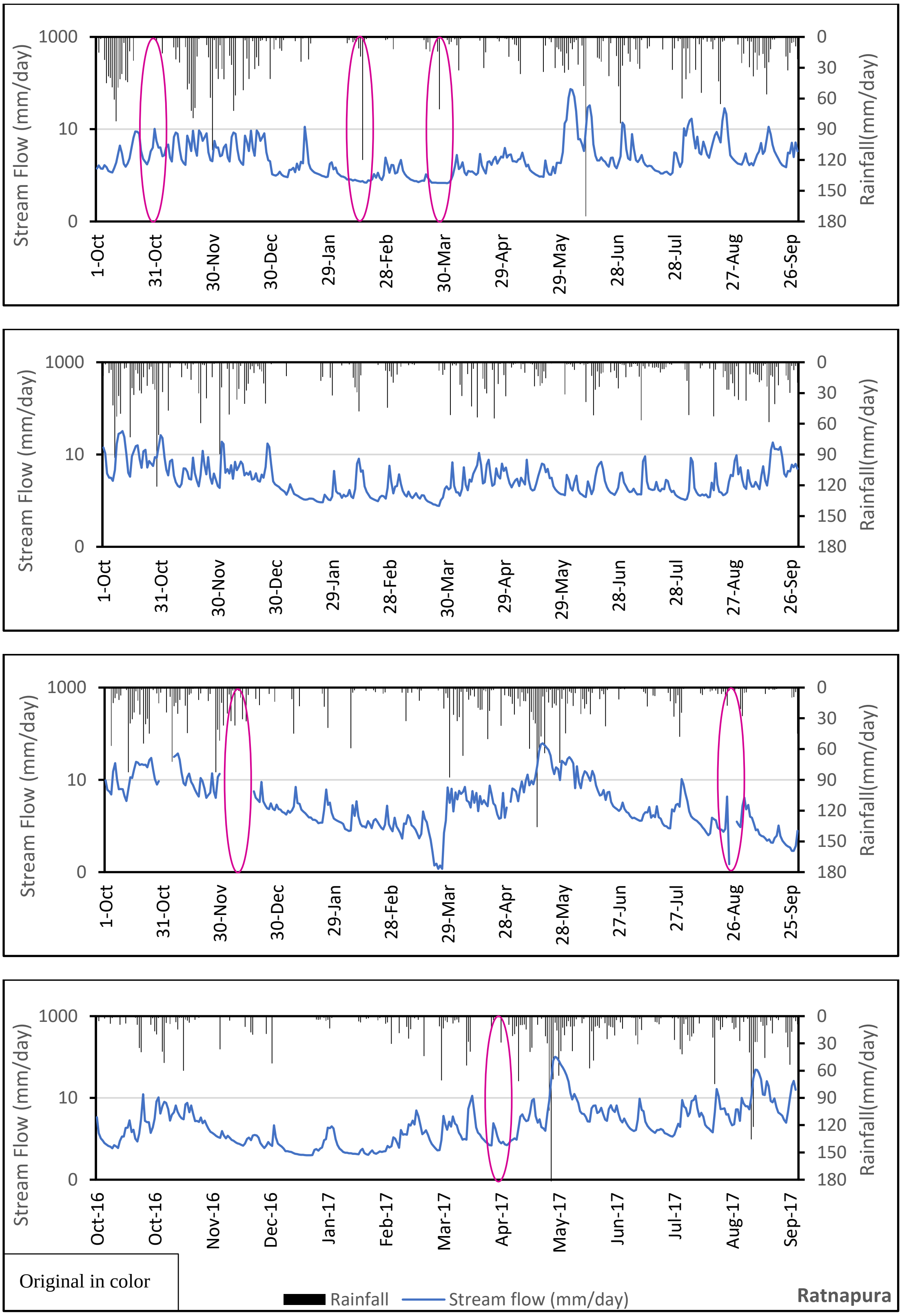



Figure B-4 Semi-log plot of Ellagawa Streamflow response to Ratnapura rainfall

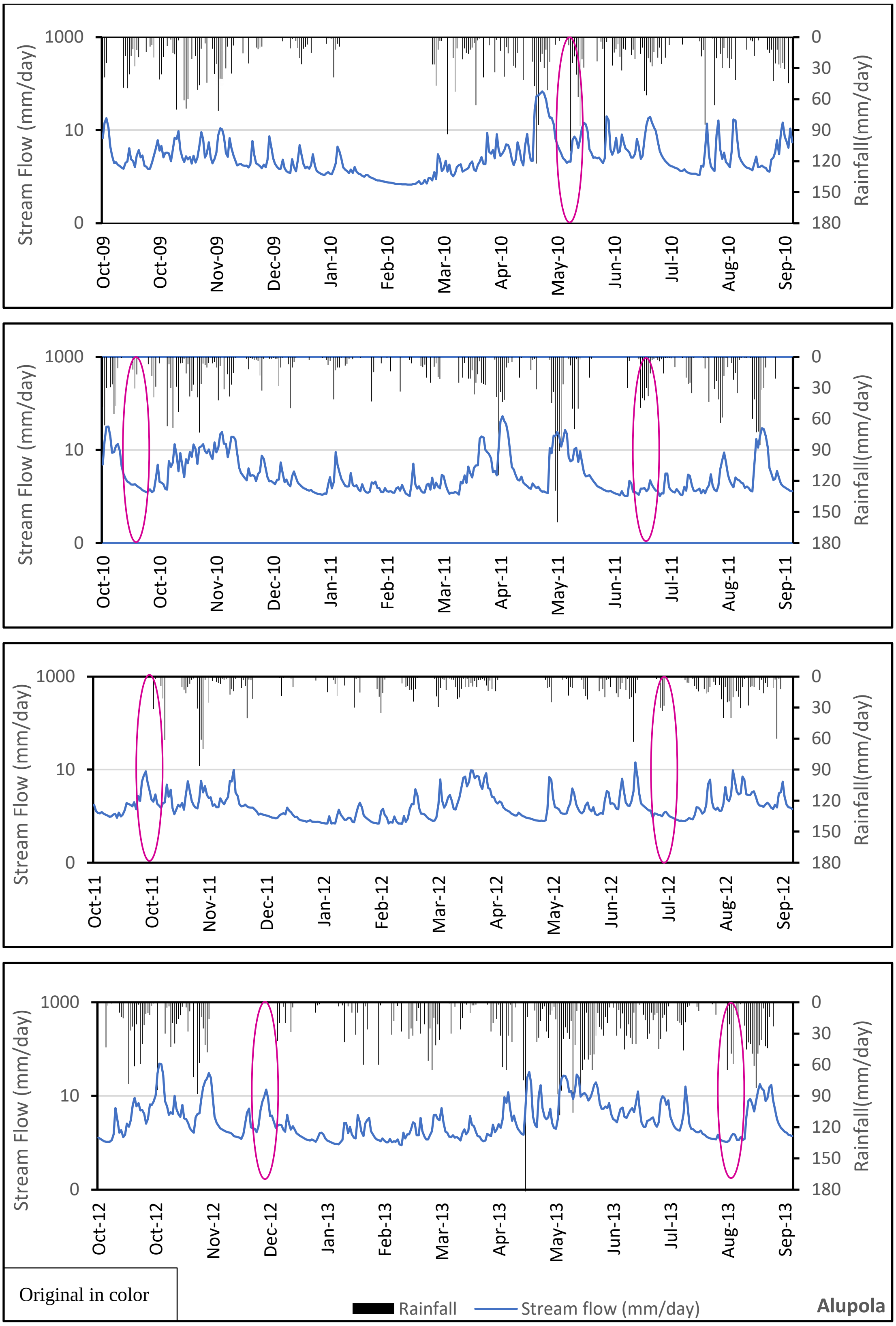



Figure B-5 Semi-log plot of Ellagawa Streamflow response to Alupola rainfall

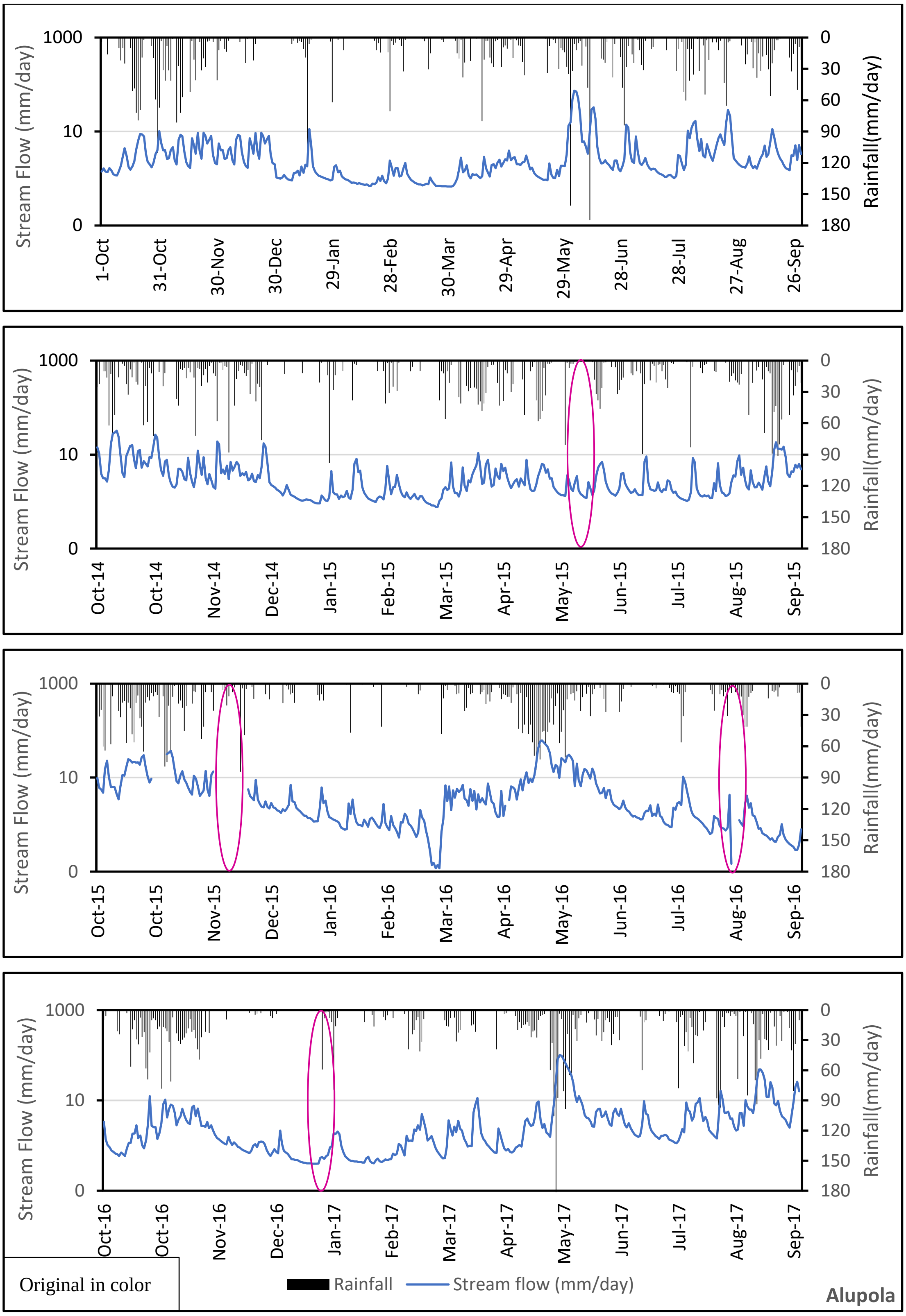



Figure B-6 Semi-log plot of Ellagawa streamflow response to Alupola rainfall

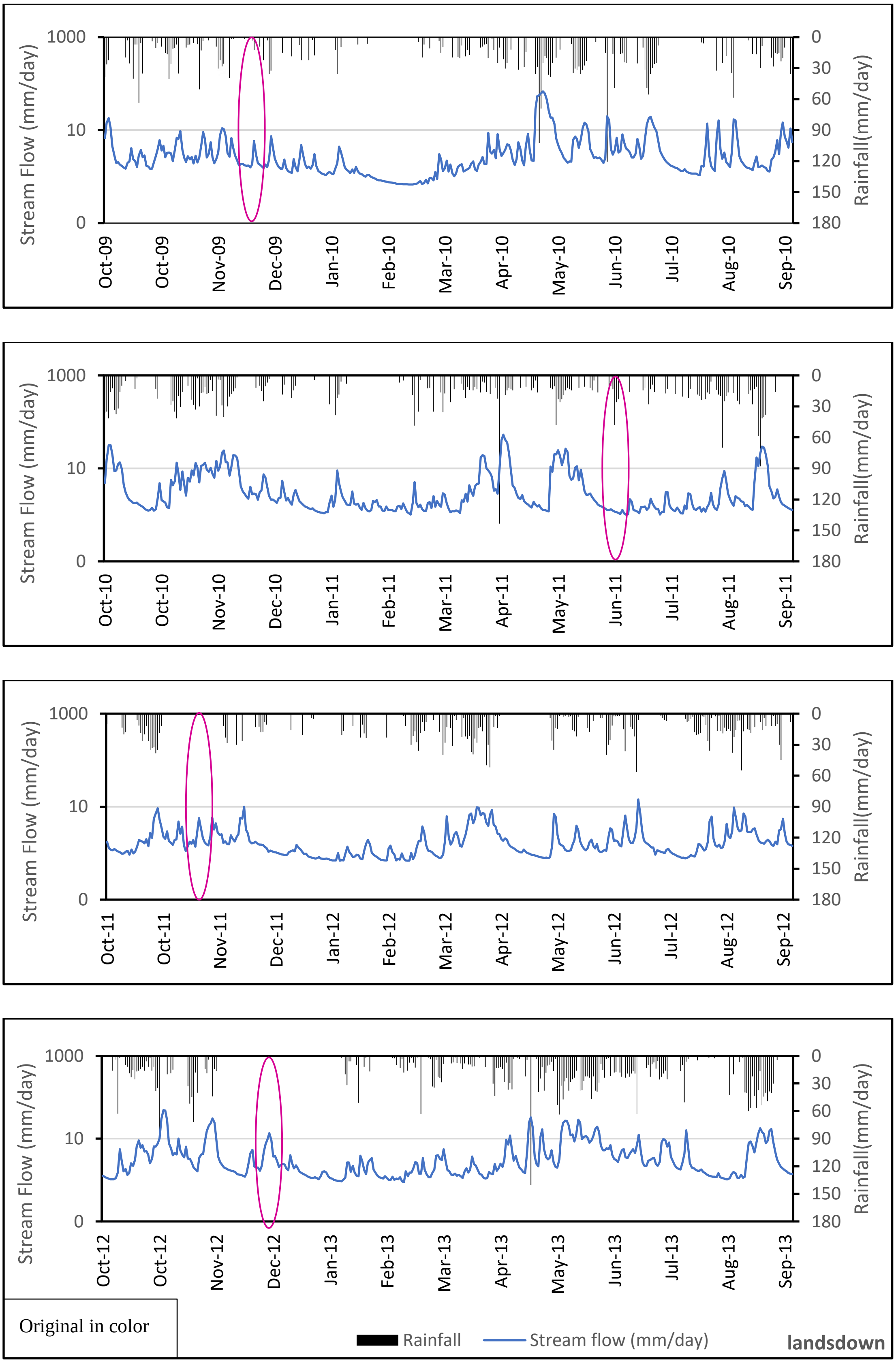



Figure B-7 Semi-log plot of Ellagawa streamflow response to Landsdown rainfall

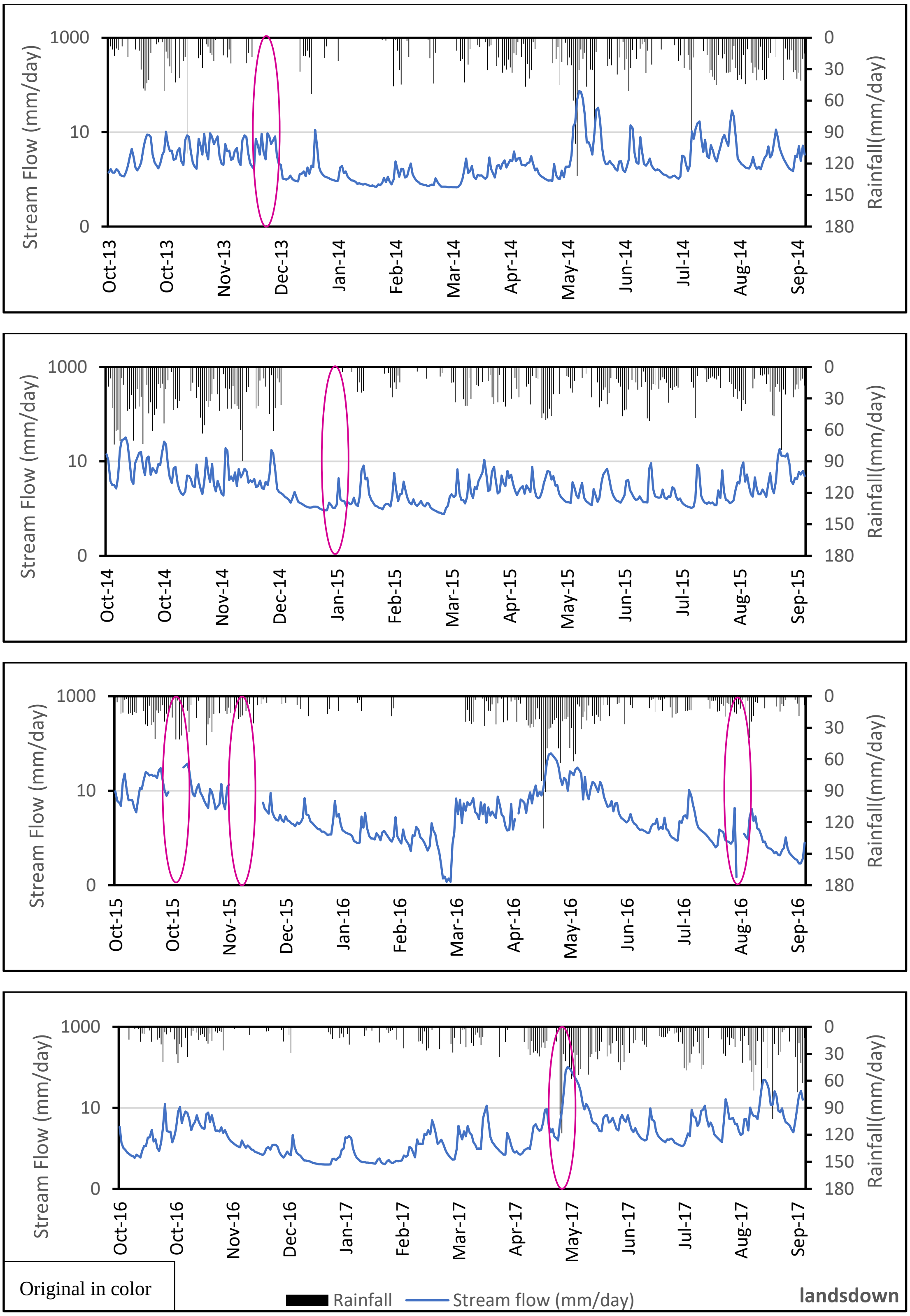



Figure B-8 Semi-log plot of Ellagawa streamflow response to Landsdown rainfall

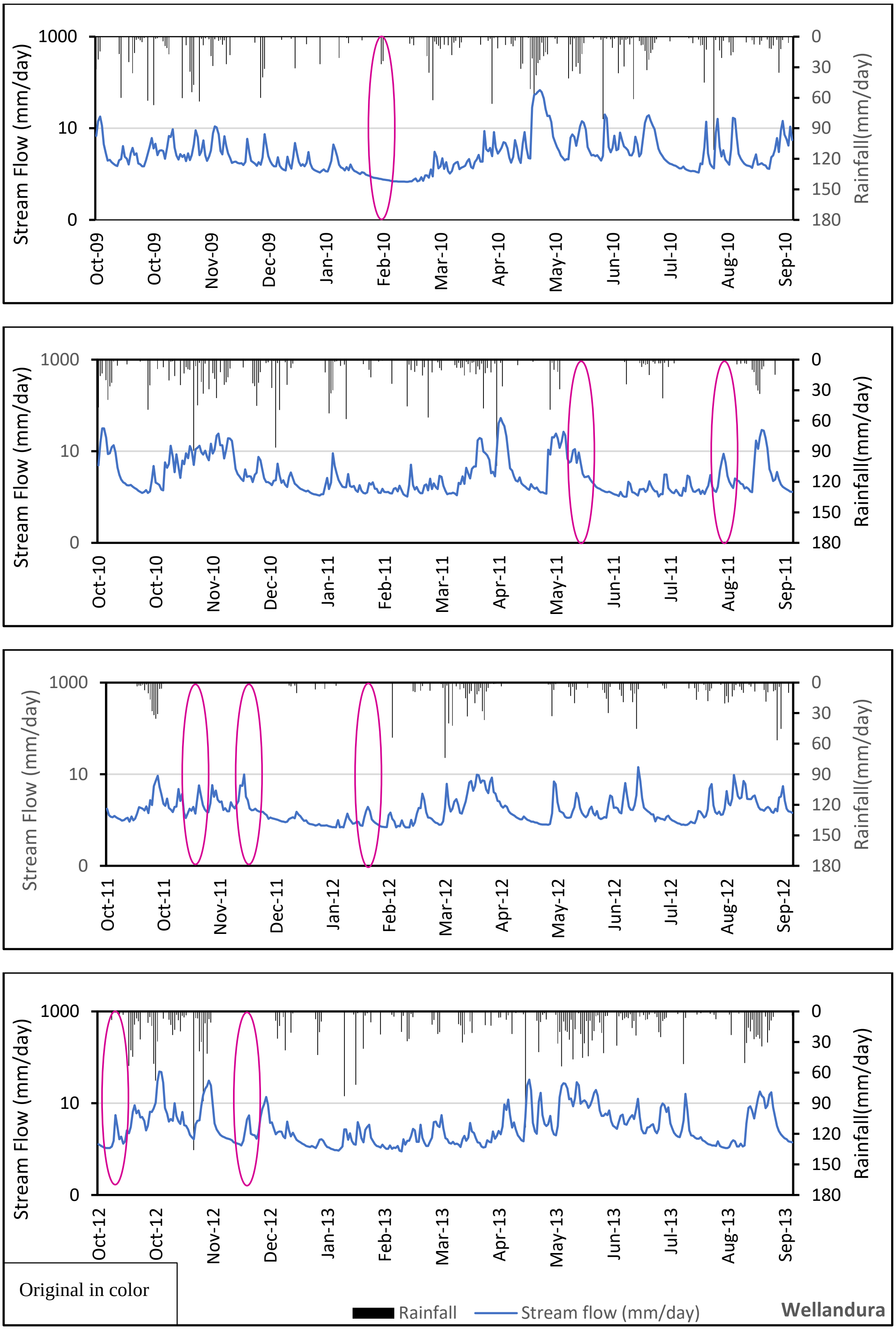



Figure B-9 Semi-log plot of Ellagawa streamflow response to Wellandura rainfall

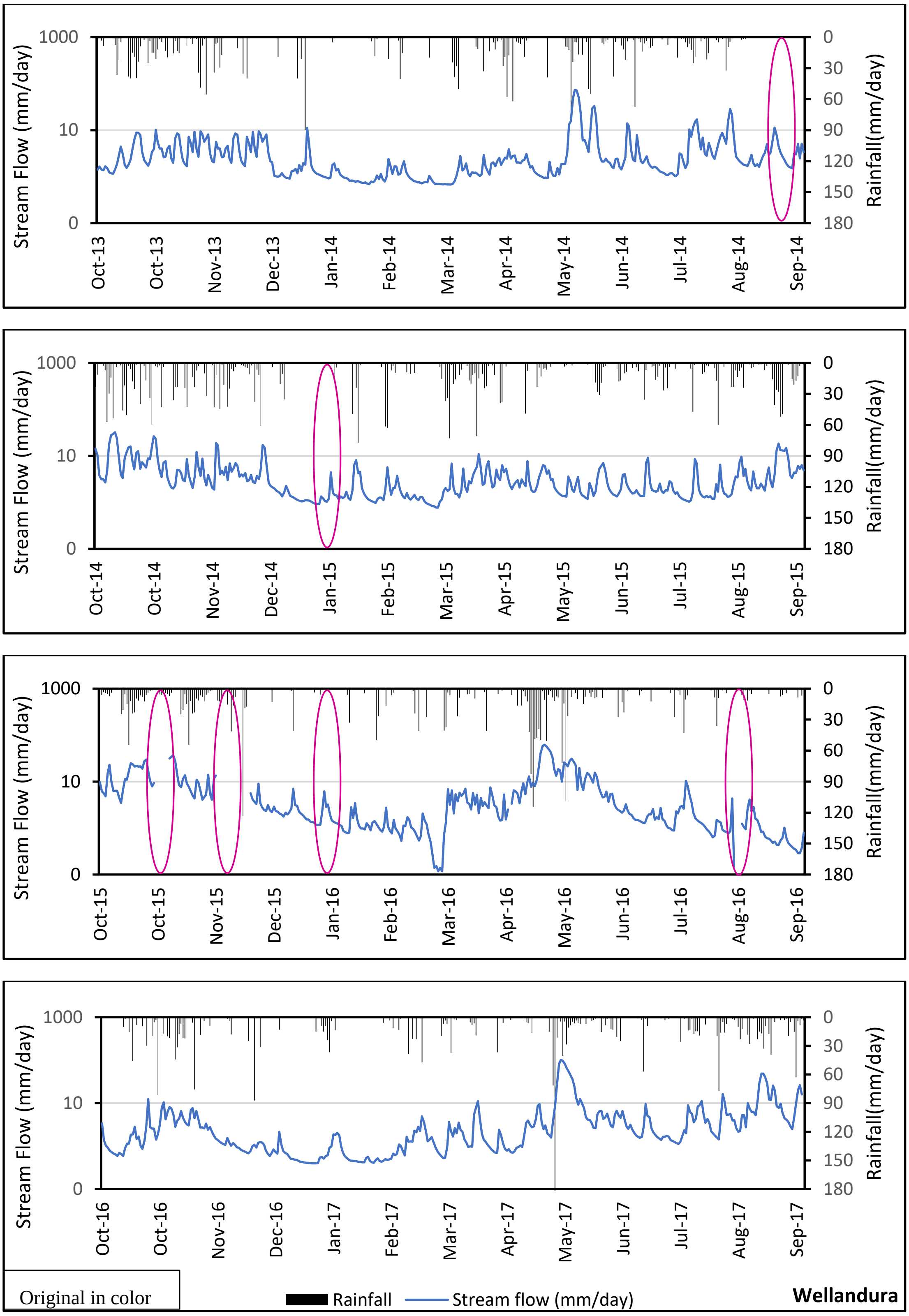



Figure B-10 Semi-log plot of Ellagawa streamflow response to Wellandura rainfall

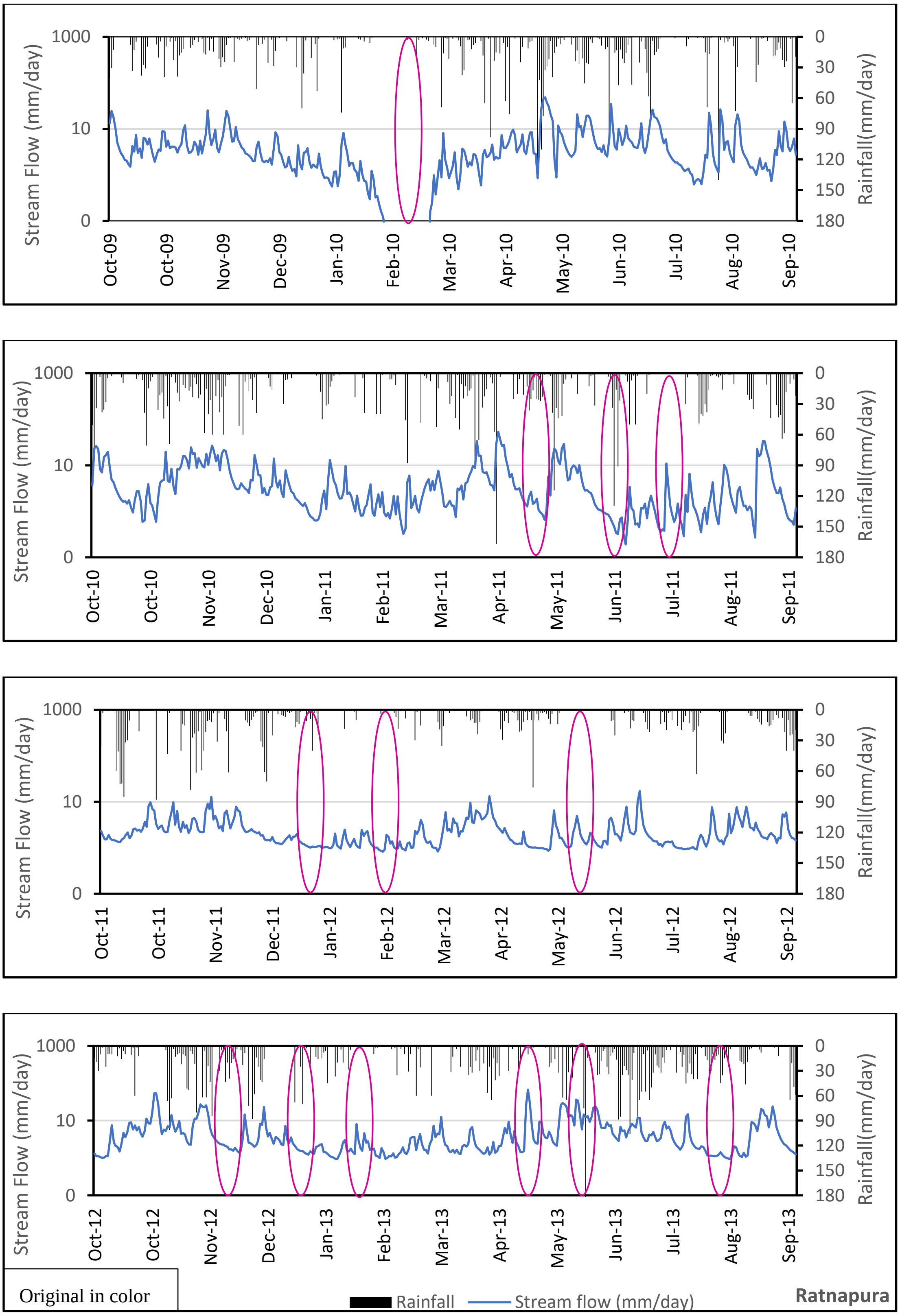



Figure B- 11 Semi-log plot of Ratnapura streamflow response to Ratnapura rainfall

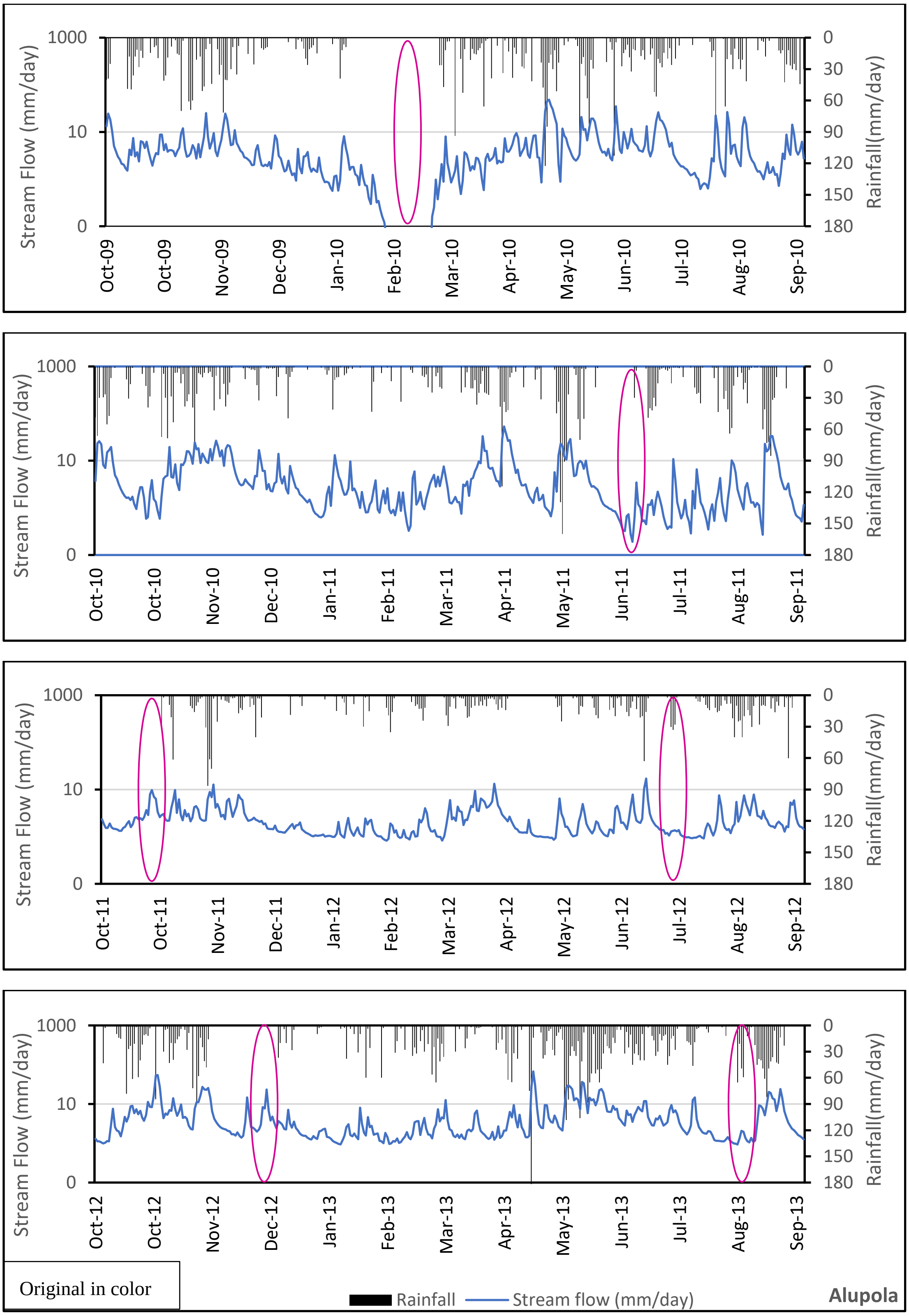



Figure B-12 Semi-log plot of Ratnapura streamflow response to Ratnapura rainfall

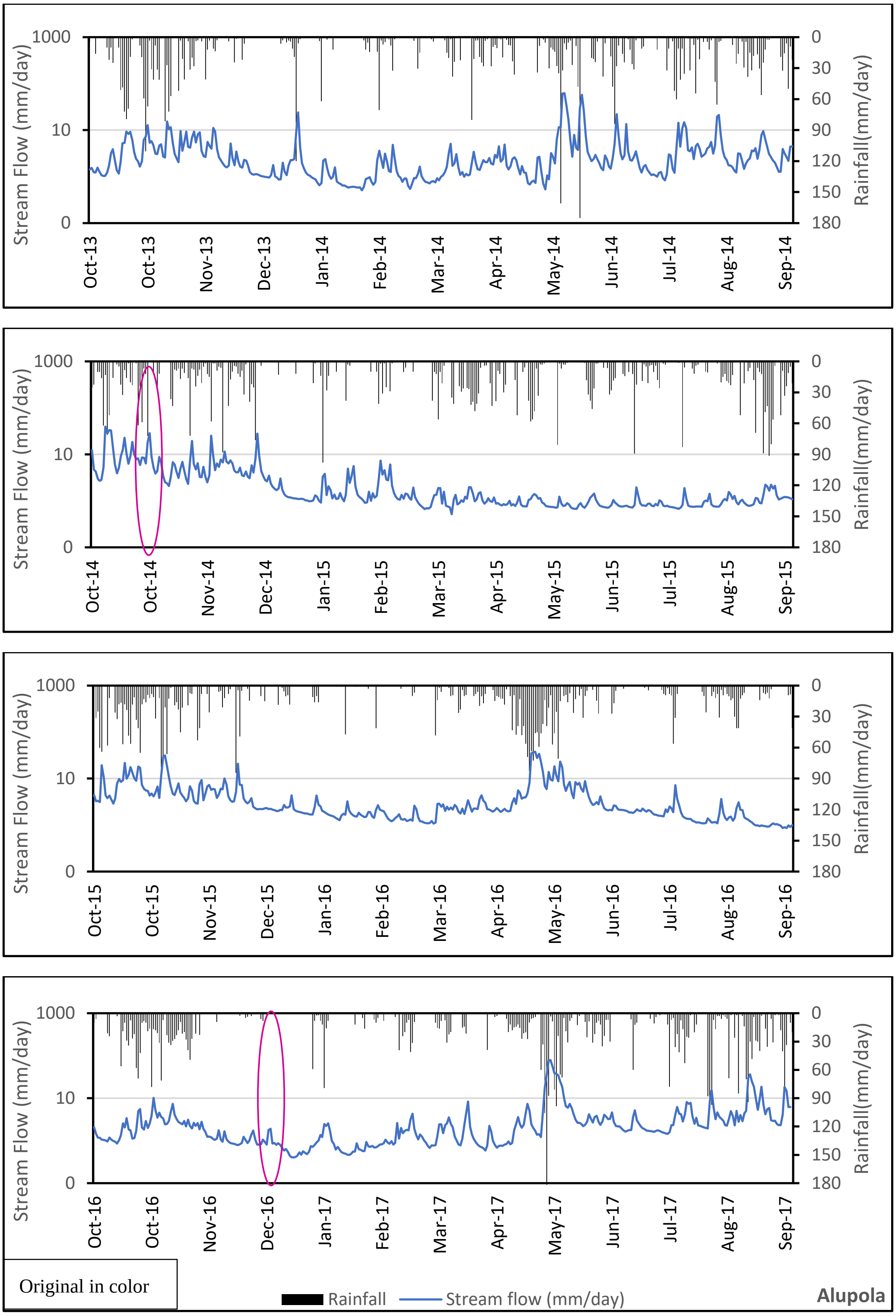



Figure B-13 Semi-log plot of Ratnapura streamflow response to Alupola rainfall

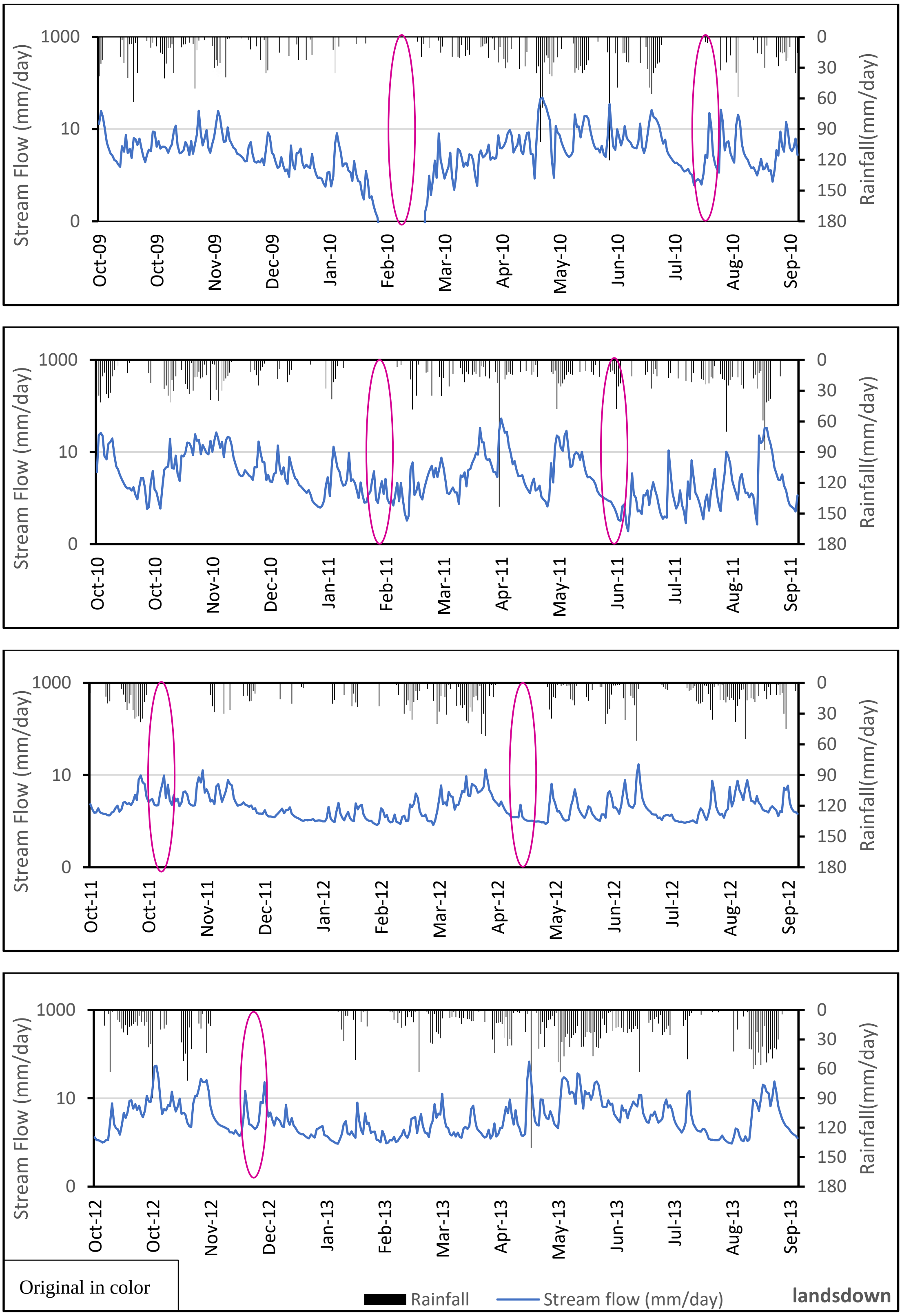



Figure B-14 Semi-log plot of Ratnapura streamflow response to Landsdown rainfall

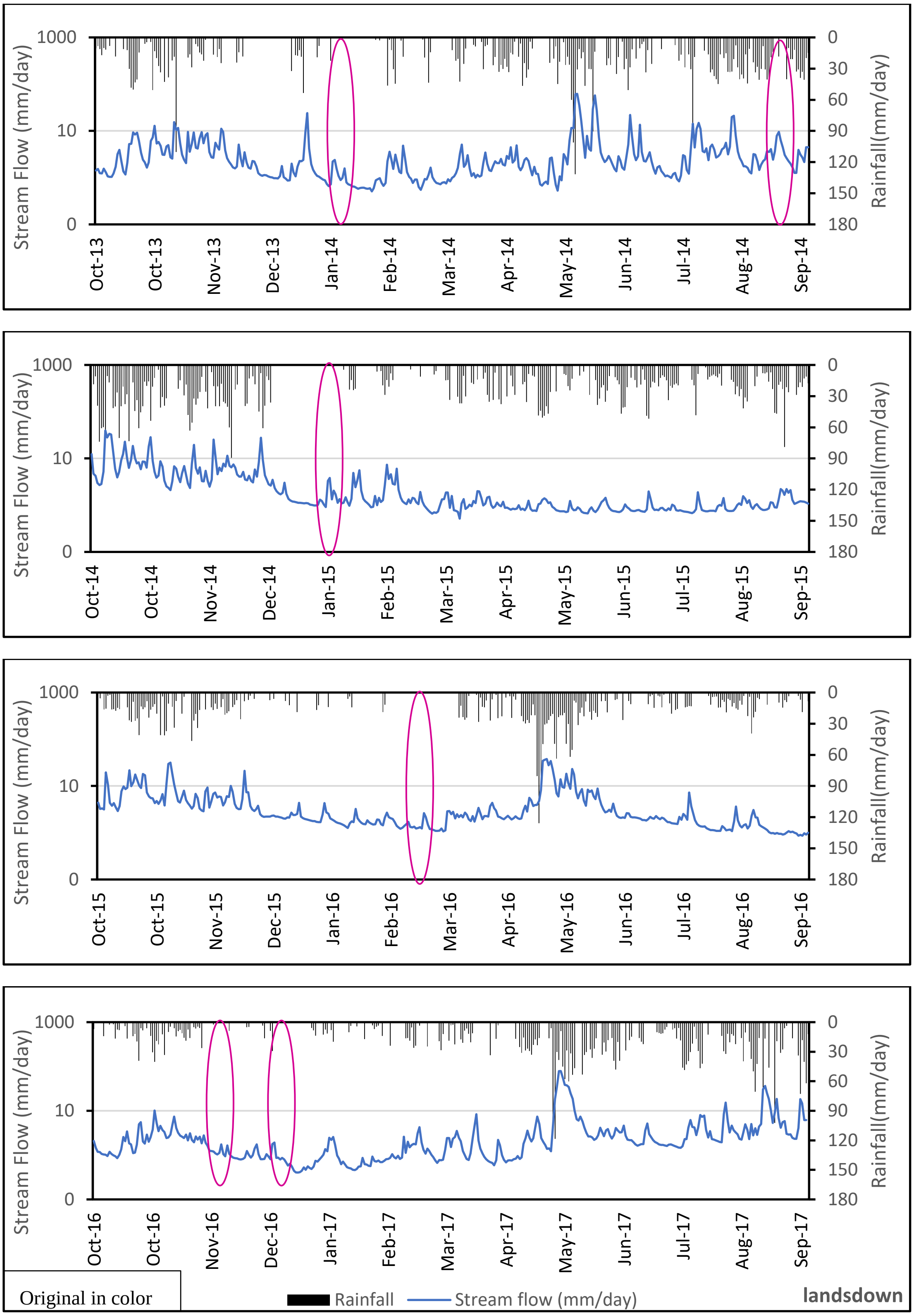



Figure B-15 Semi-log plot of Ratnapura streamflow response to Landsdown rainfall

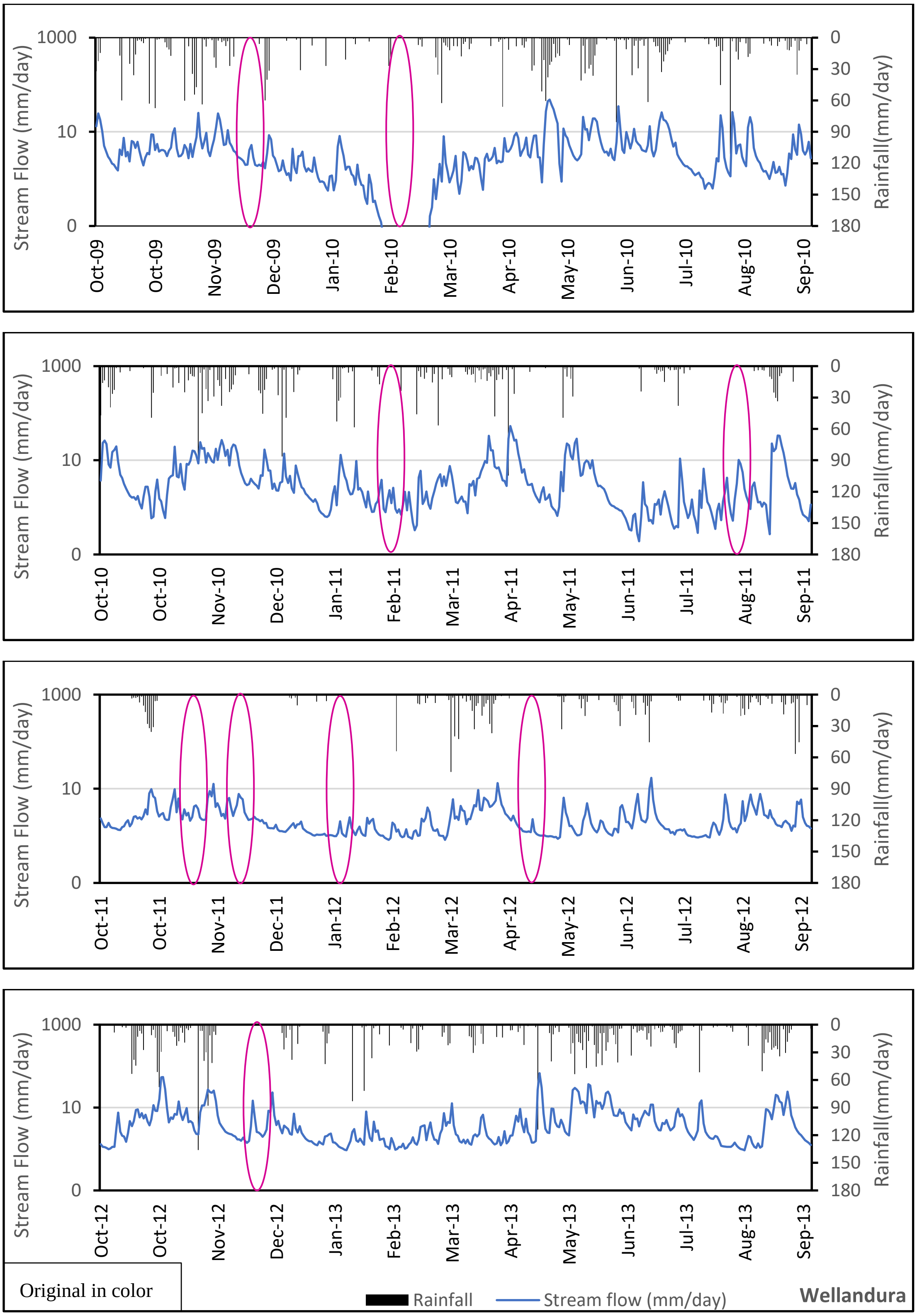



Figure B-16 Semi-log plot of Ratnapura streamflow response to Wellandura rainfall

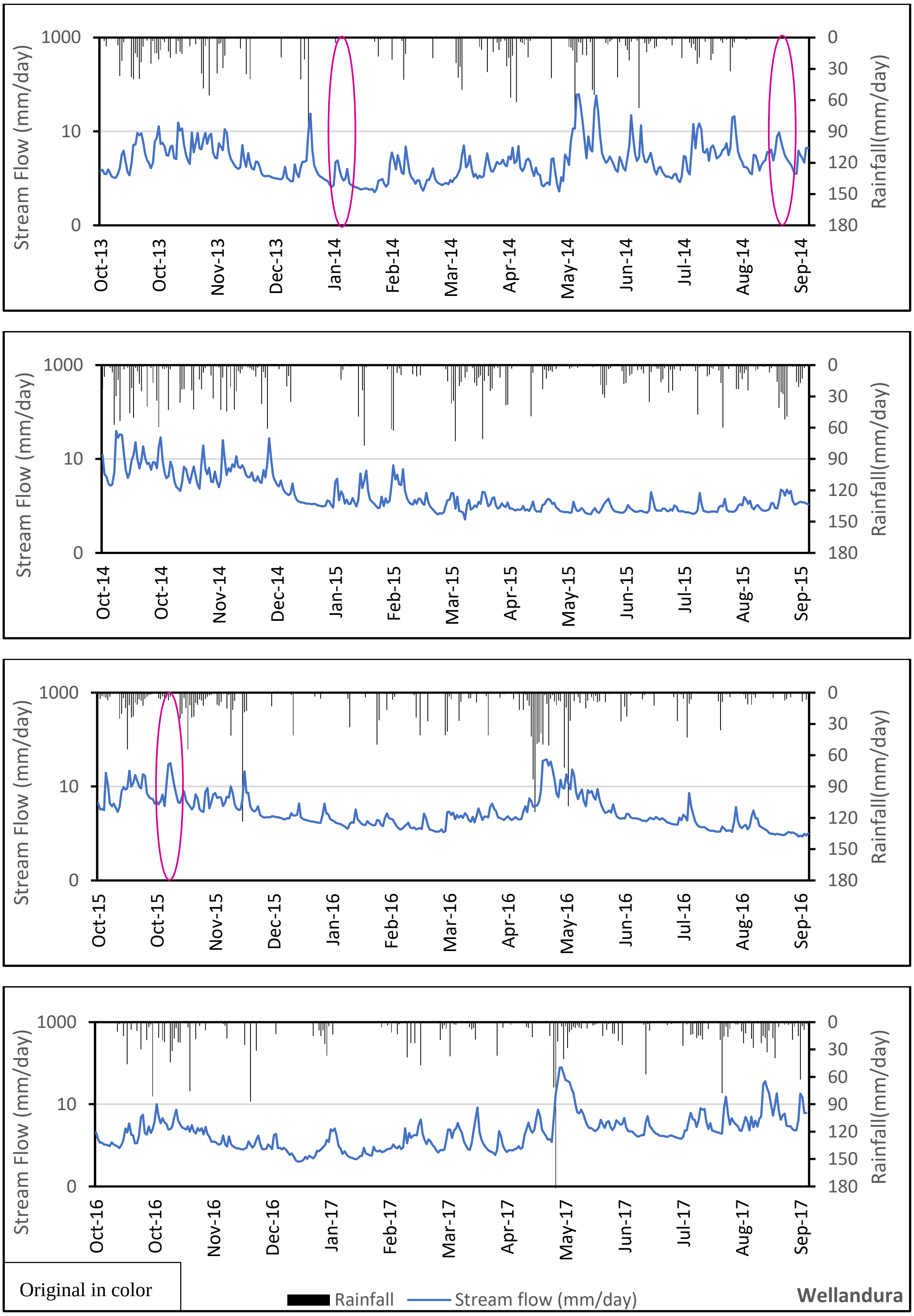



Figure B-17 Semi-log plot of Ratnapura streamflow response to Wellandura rainfall

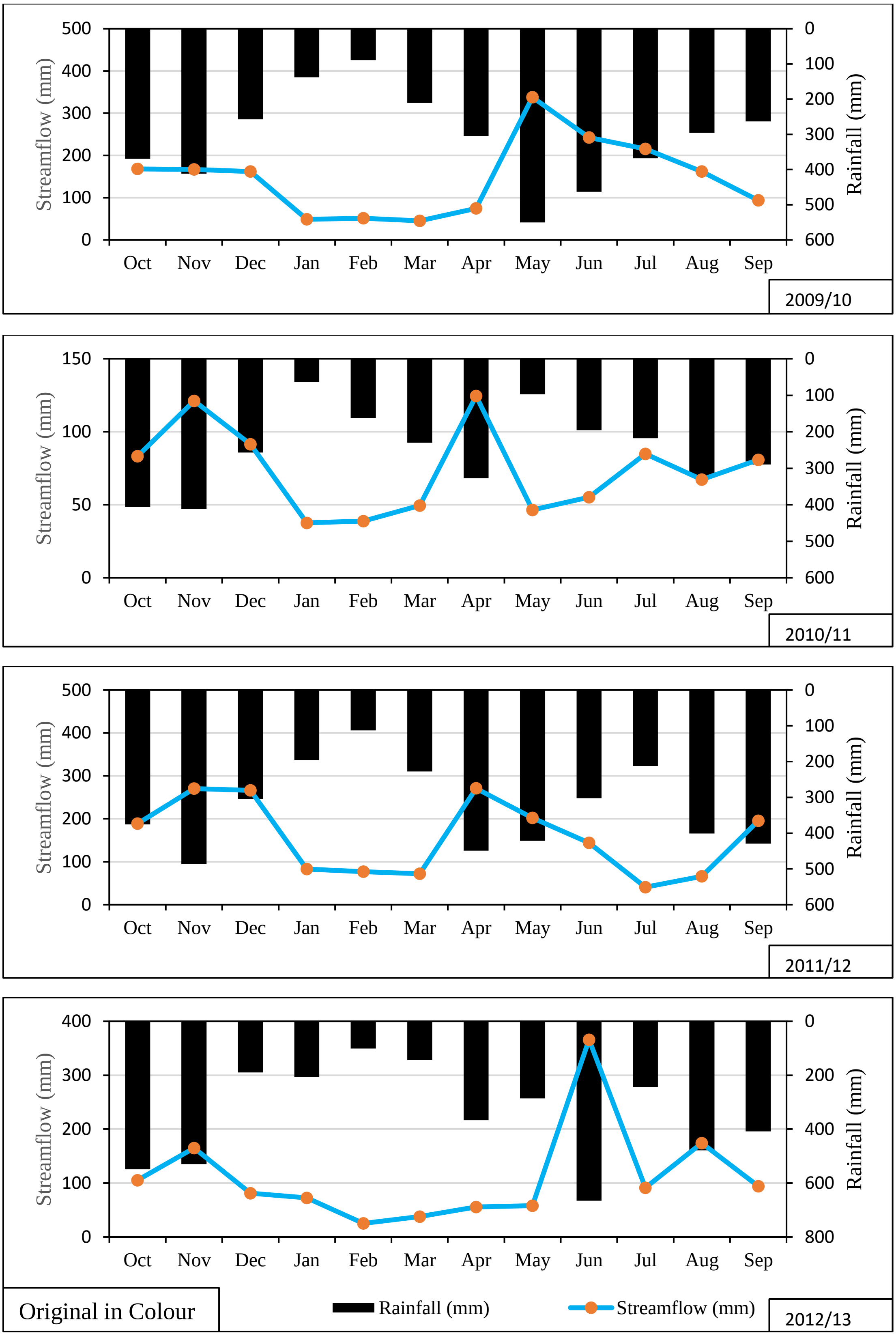



Figure B-18 Ellagawa monthly streamflow response to Thiessen rainfall

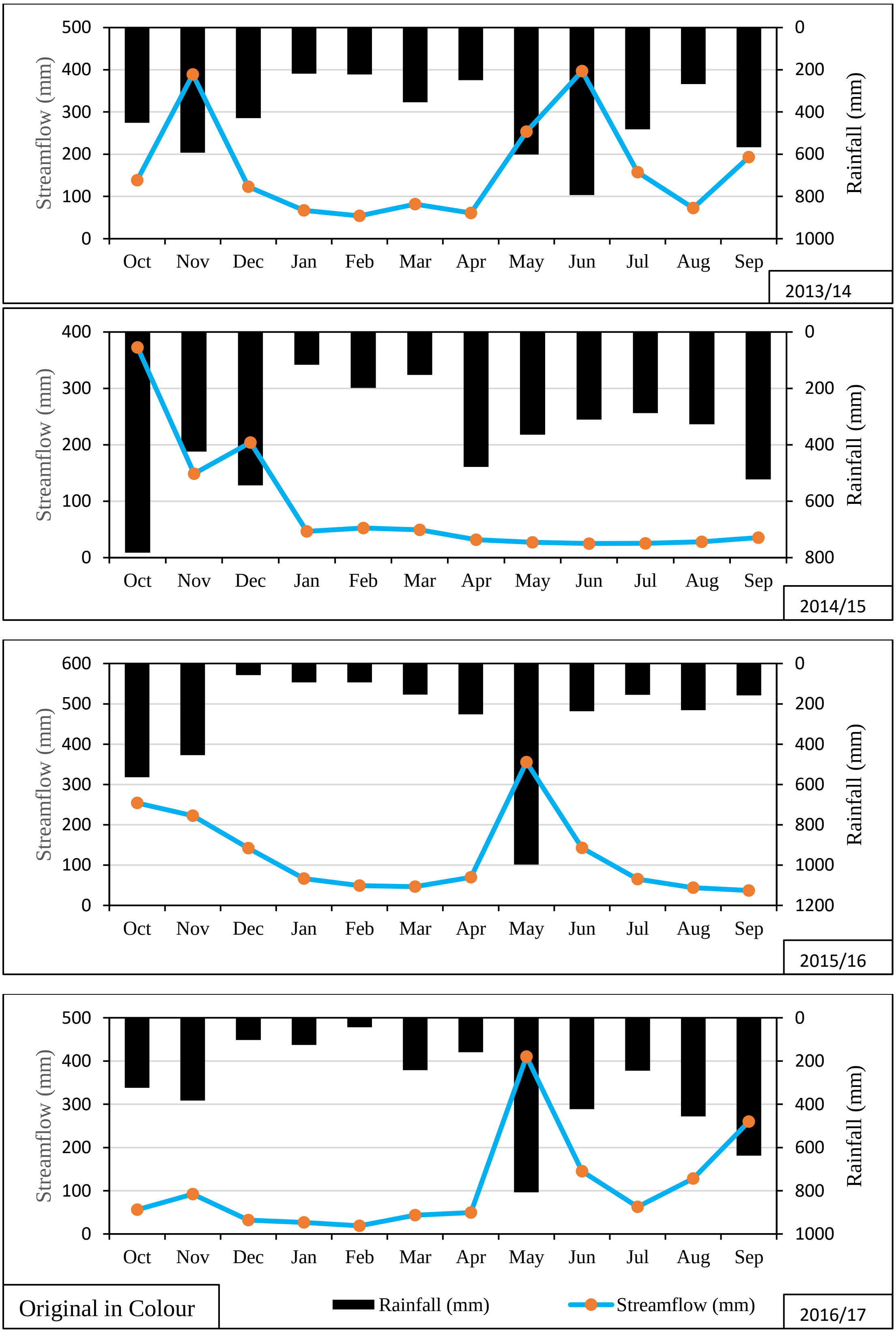



Figure B-19 Ellagaw monthly streamflow response to Thiessen rainfall

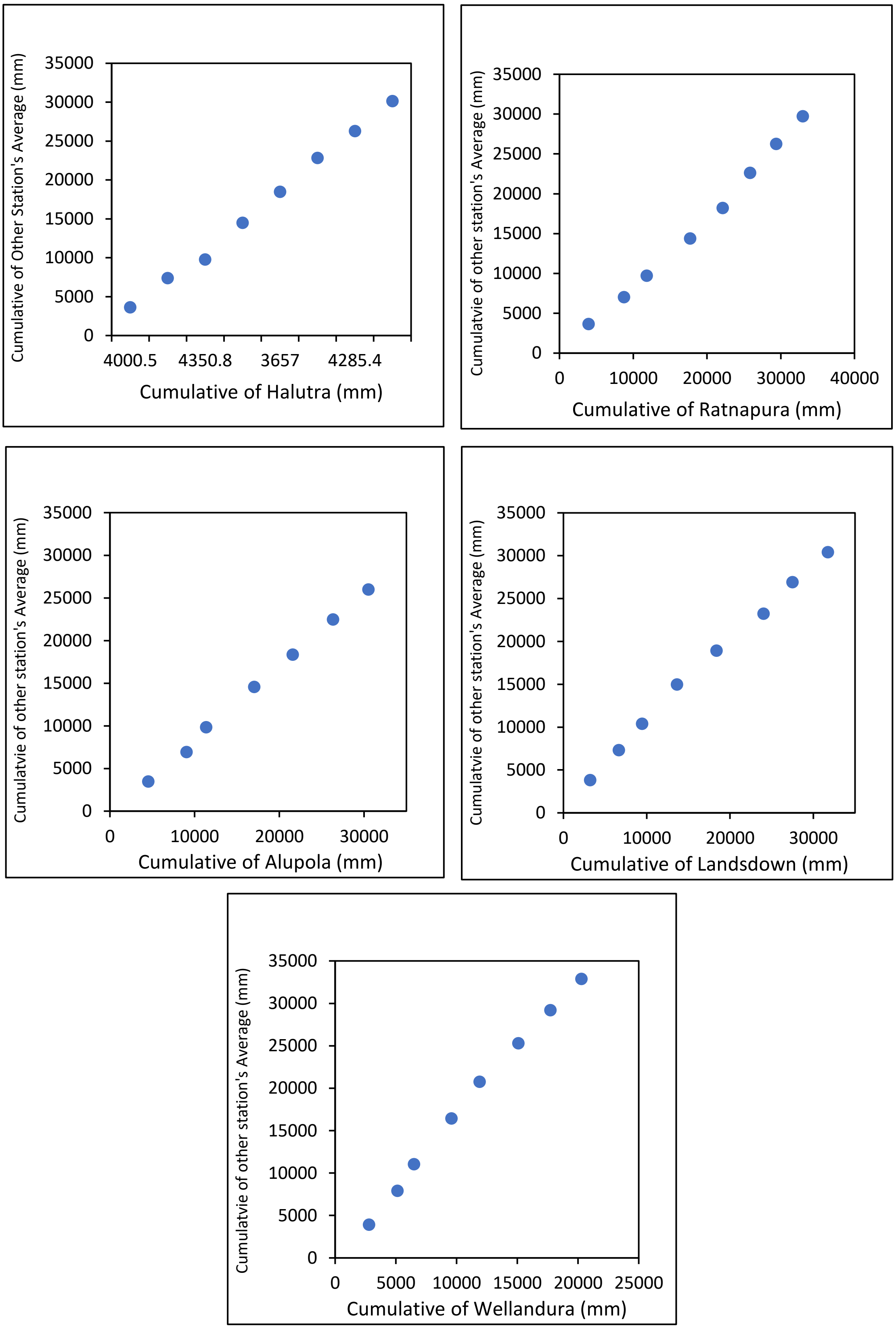



Figure B-20 Double mass curve for rainfall data – Ellagawa watershed

# ANNEX C – METHODOLOGY

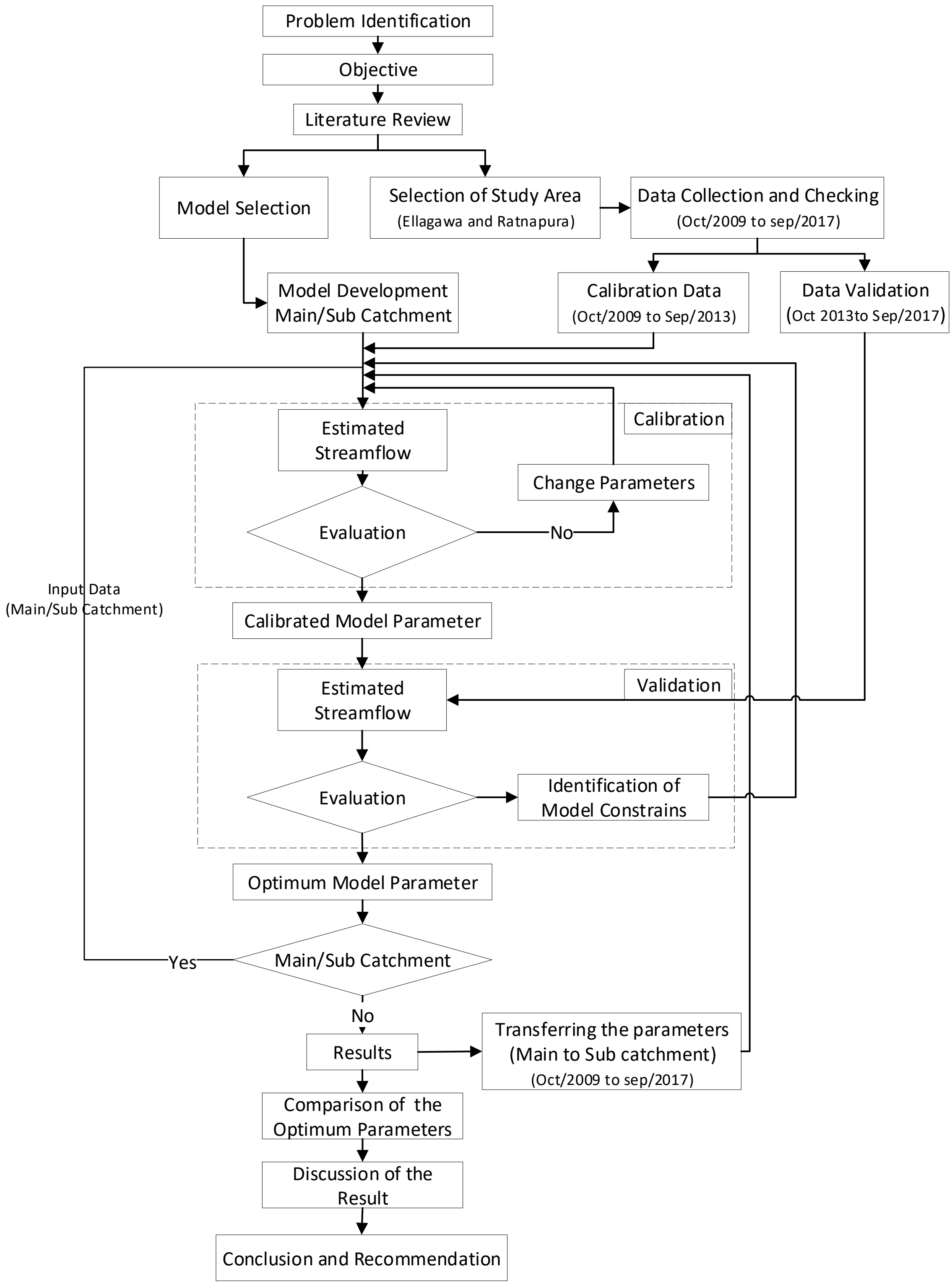



Figure C-1 Detailed methodology flowchart

# ANNEX D – ANALYSIS

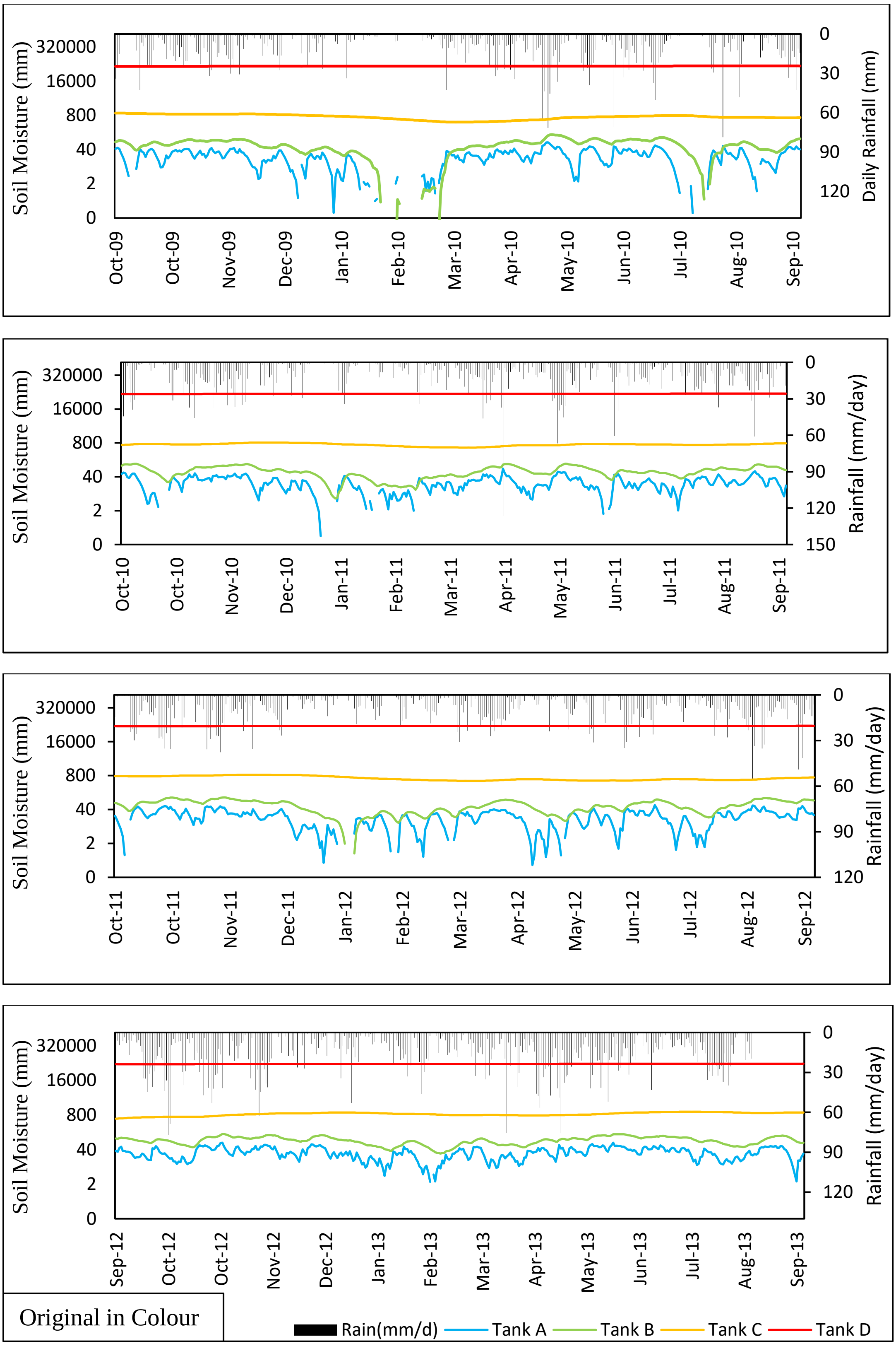



Figure D-1 Soil moisture behaviour of Tank model in calibration period- Ellagawa

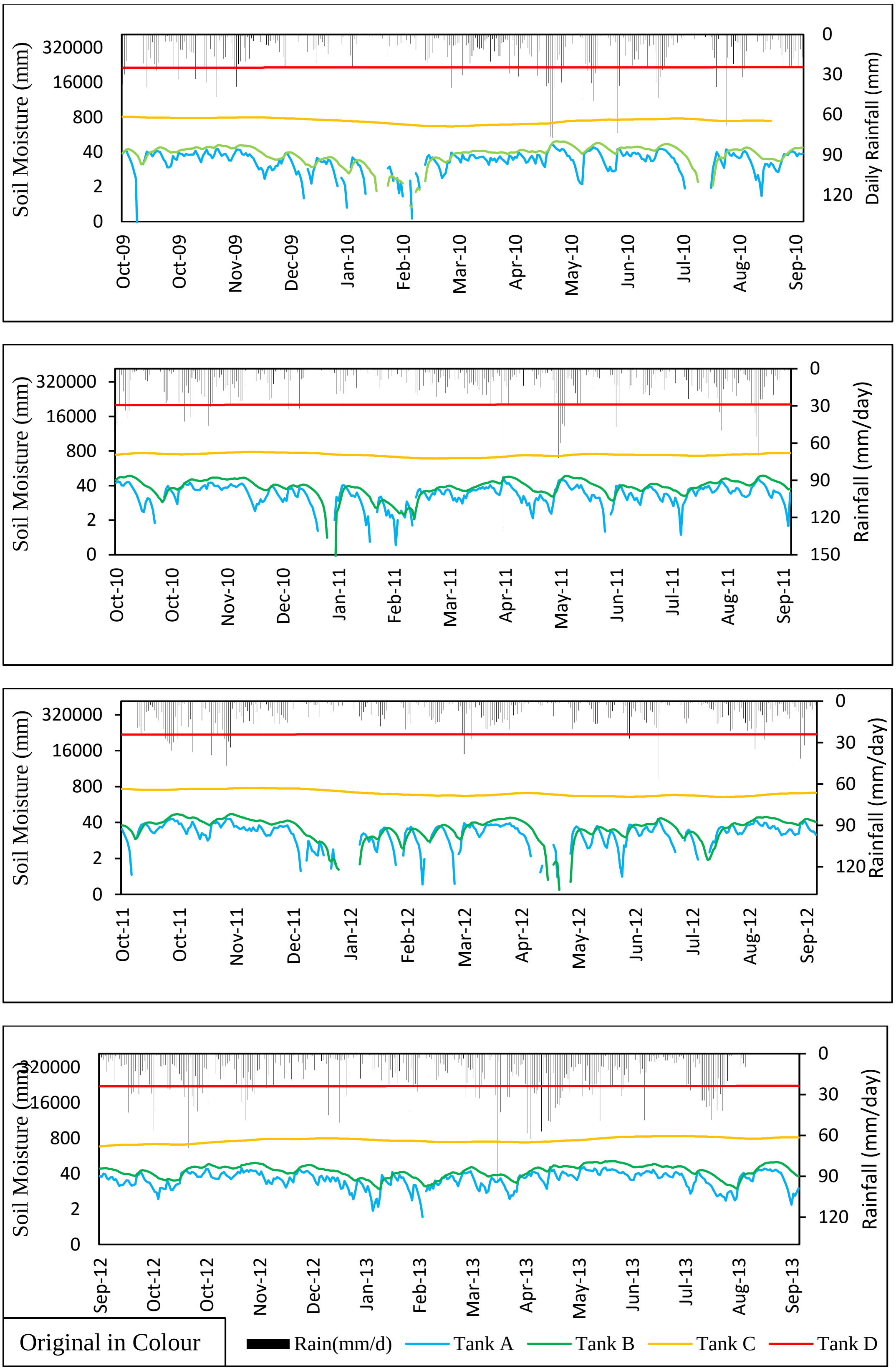



Figure D-2 Soil moisture behaviour of Tank model in calibration period- Ratnapura

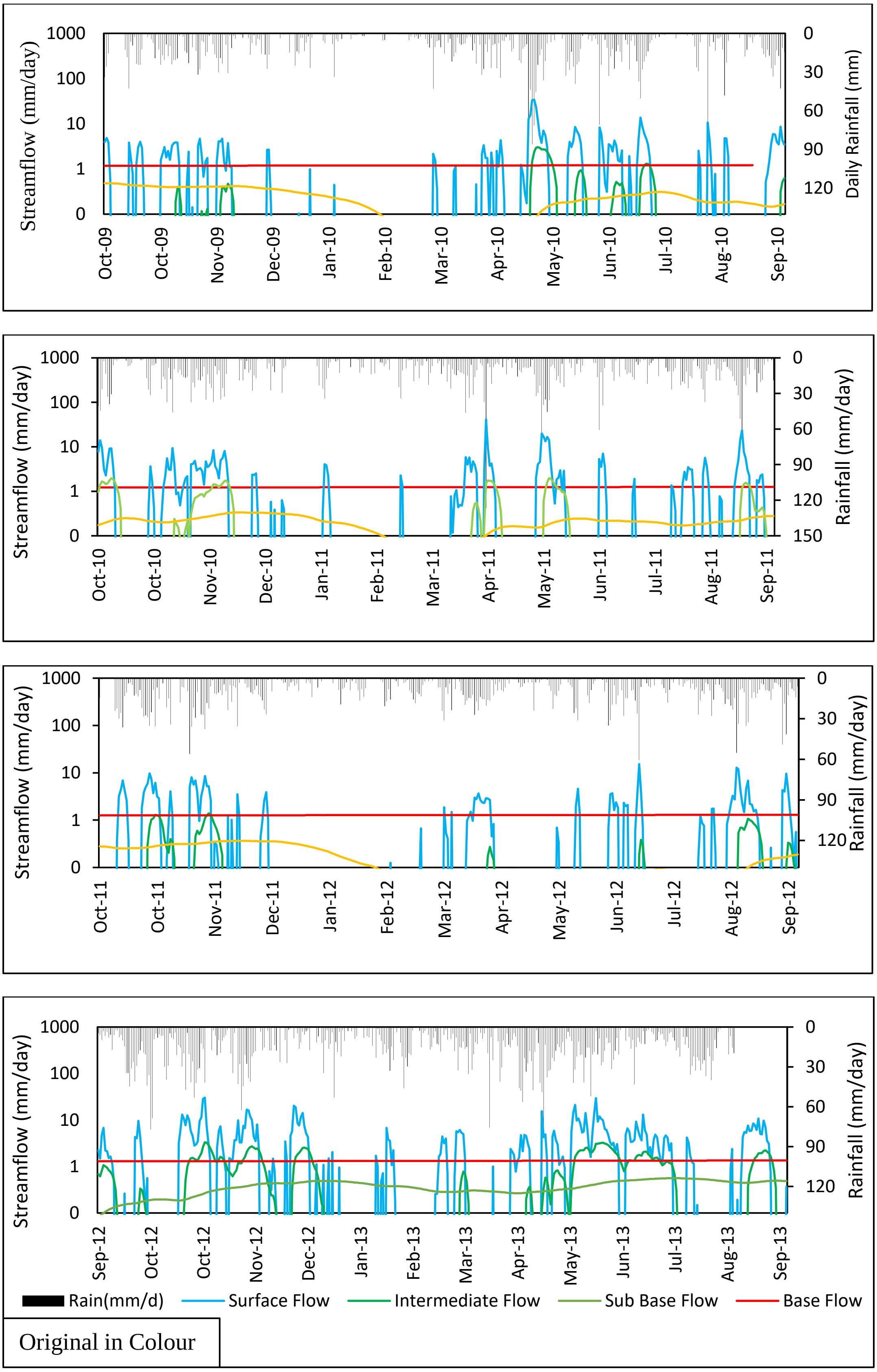



Figure D-3 Runoff components from Tank model in calibration period- Ellagawa

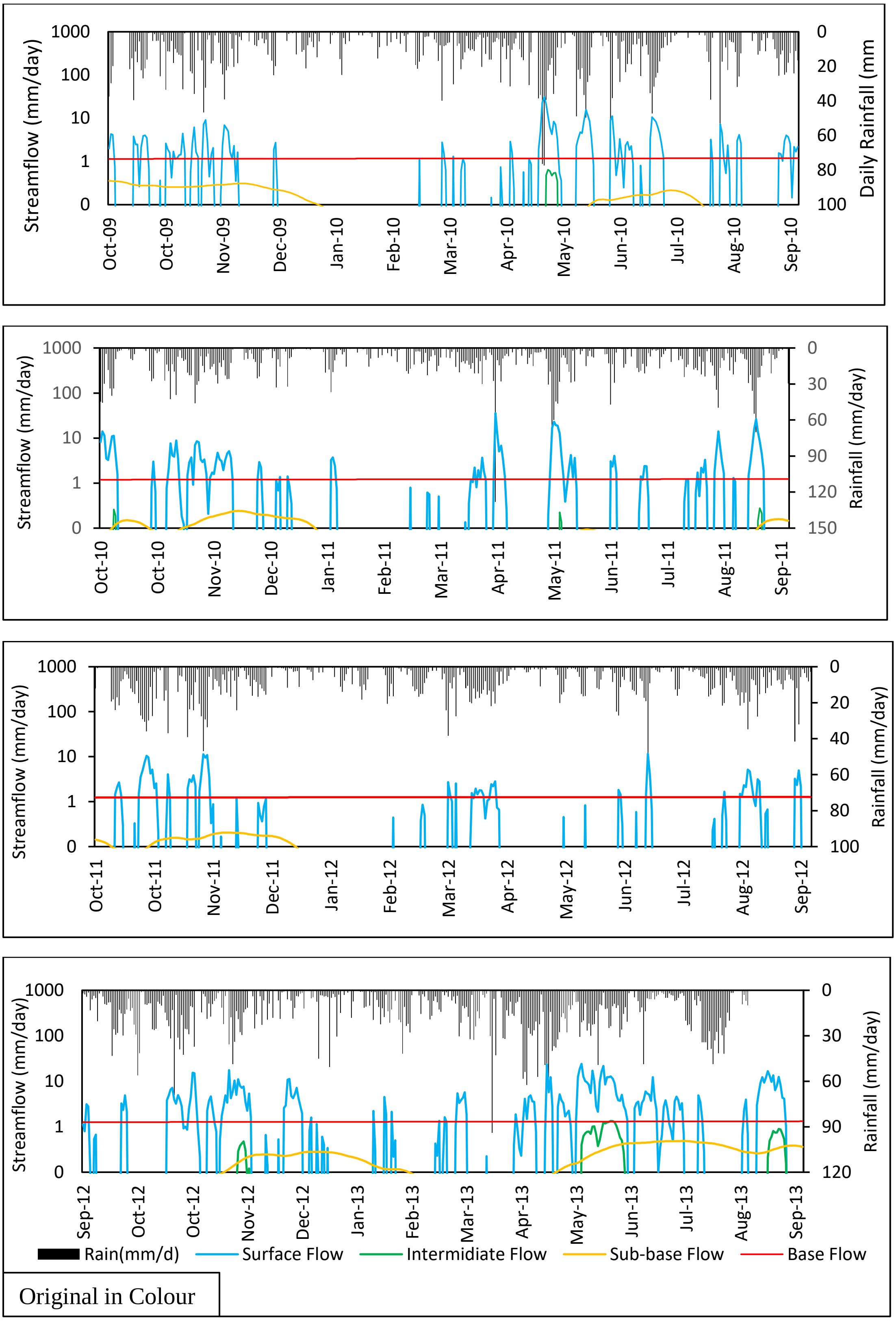



Figure D-4 Runoff components from Tank model in calibration period-Ratnapura

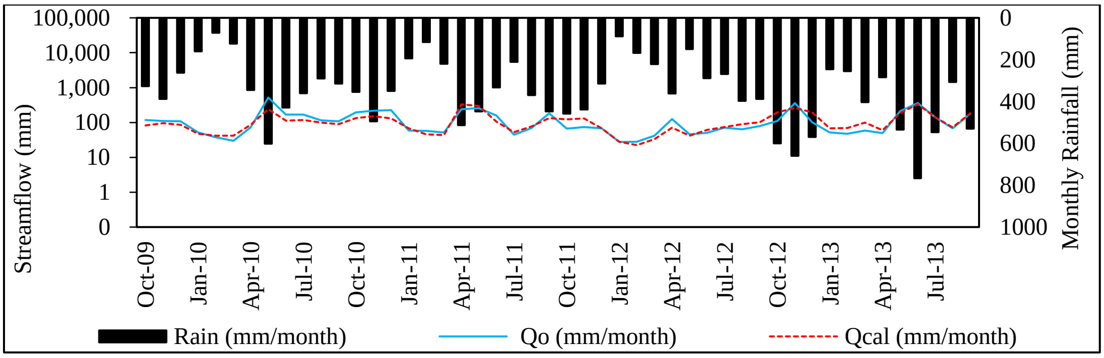



Figure D-5 Monthly hydrograph matching for calibration period of Ellagawa

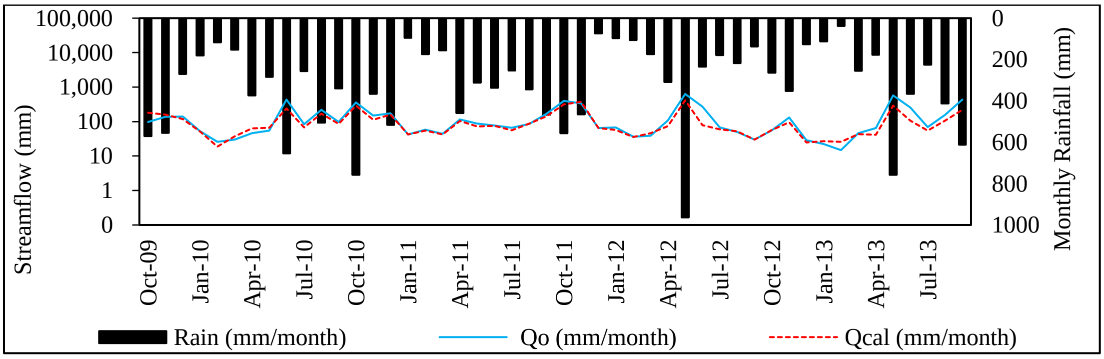



Figure D-6 Monthly hydrograph matching for verification period of Ellagawa

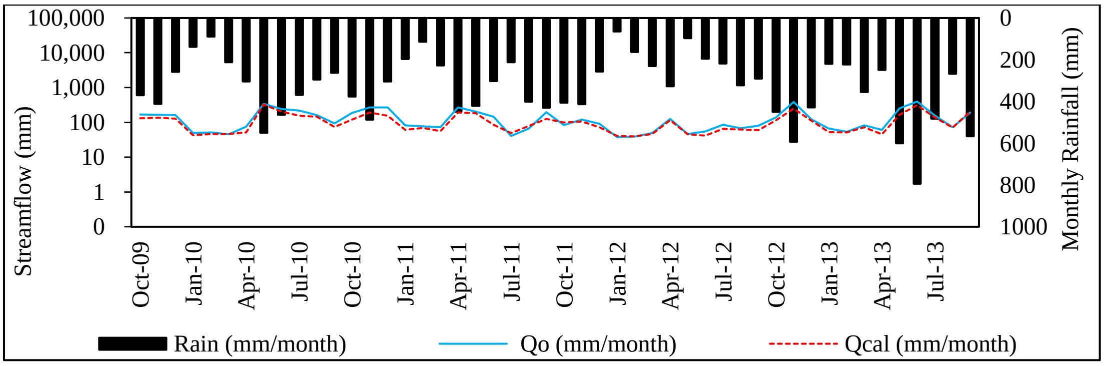



Figure D-7 Monthly hydrograph matching for calibration period of Ratnapura

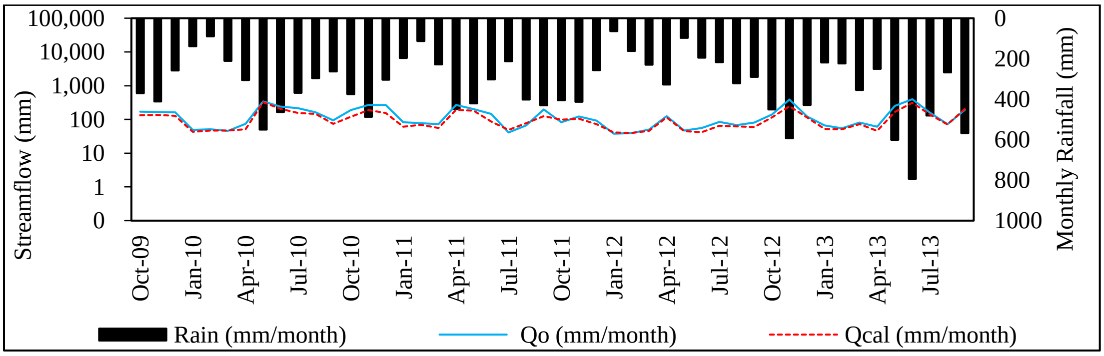
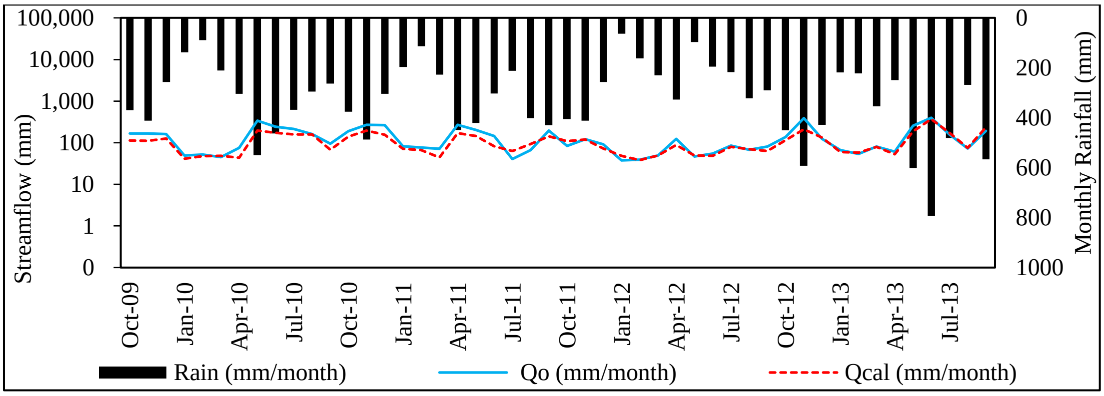



Figure D-8 Monthly hydrograph matching for verification period of Ratnapura



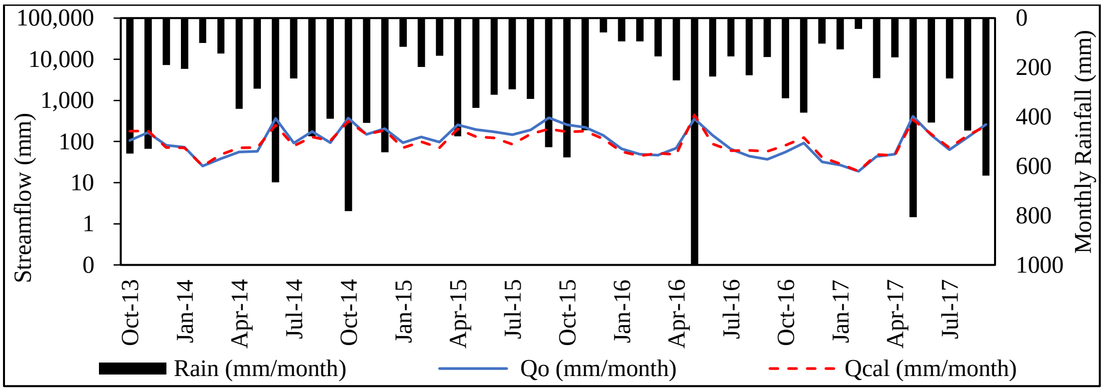
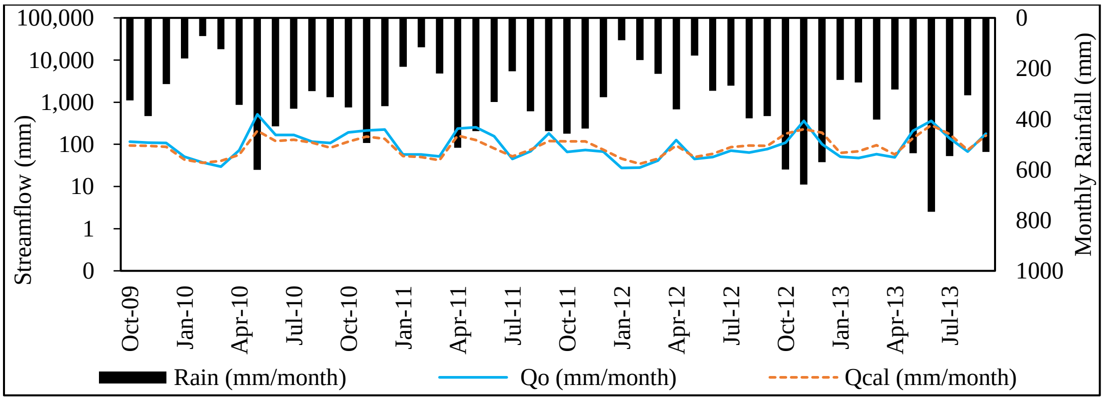




Figure D-9 Monthly hydrograph matching for parameter transfer to Ratnapura



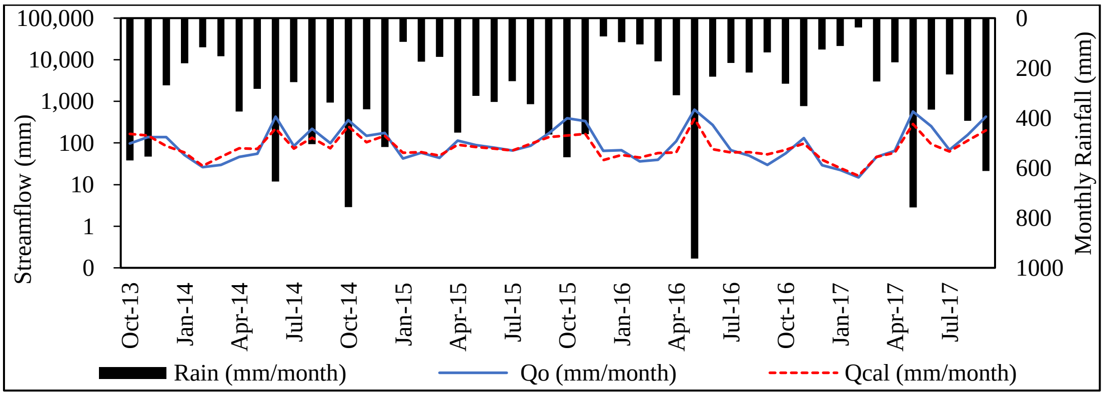




Figure D-10 Monthly hydrograph matching for parameter transfer to Ellagawa

Table D-1 Monthly output of the model for the calibration period of Ellagawa

| Date Month-Year | Rain (mm/d) | Evaporation (mm) | Observed Streamflow (mm) | Simulated Streamflow (mm) |
|---|---|---|---|---|
| Oct-09 | 325.87 | 67.85 | 116.86 | 82.85 |
| Nov-09 | 388.04 | 31.59 | 109.84 | 94.43 |
| Dec-09 | 262.00 | 31.01 | 107.50 | 86.45 |
| Jan-10 | 159.70 | 68.10 | 51.33 | 46.99 |
| Feb-10 | 71.69 | 70.76 | 37.41 | 41.37 |
| Mar-10 | 123.85 | 78.97 | 29.63 | 41.70 |
| Apr-10 | 344.40 | 71.80 | 72.24 | 85.38 |
| May-10 | 600.64 | 55.29 | 516.38 | 239.20 |
| Jun-10 | 428.87 | 52.77 | 166.80 | 111.85 |
| Jul-10 | 359.28 | 65.20 | 168.18 | 117.23 |
| Aug-10 | 289.24 | 64.14 | 116.22 | 98.96 |
| Sep-10 | 313.79 | 49.14 | 107.79 | 89.51 |
| Oct-10 | 353.34 | 54.08 | 194.13 | 133.47 |
| Nov-10 | 494.65 | 40.13 | 214.82 | 149.92 |
| Dec-10 | 349.07 | 38.89 | 224.66 | 131.90 |
| Jan-11 | 193.55 | 48.83 | 57.94 | 67.48 |
| Feb-11 | 115.63 | 56.01 | 57.22 | 45.56 |
| Mar-11 | 219.43 | 66.63 | 51.80 | 43.87 |
| Apr-11 | 513.11 | 66.02 | 238.34 | 330.09 |
| May-11 | 447.23 | 66.53 | 255.94 | 295.80 |
| Jun-11 | 332.90 | 66.65 | 156.31 | 105.17 |
| Jul-11 | 210.46 | 54.38 | 44.91 | 52.17 |
| Aug-11 | 368.72 | 59.48 | 68.77 | 76.87 |
| Sep-11 | 446.93 | 63.81 | 182.04 | 132.10 |
| Oct-11 | 457.45 | 62.90 | 66.61 | 121.82 |
| Nov-11 | 437.48 | 50.59 | 73.79 | 131.90 |
| Dec-11 | 313.49 | 54.14 | 67.66 | 68.43 |
| Jan-12 | 88.60 | 77.85 | 27.62 | 28.09 |
| Feb-12 | 166.76 | 60.39 | 27.94 | 22.35 |
| Mar-12 | 221.32 | 85.28 | 41.37 | 33.10 |
| Apr-12 | 361.47 | 61.54 | 125.42 | 71.41 |
| May-12 | 148.83 | 71.93 | 45.38 | 42.19 |
| Jun-12 | 288.56 | 57.90 | 50.01 | 61.00 |
| Jul-12 | 268.38 | 65.78 | 70.78 | 73.11 |
| Aug-12 | 397.08 | 58.99 | 64.16 | 89.02 |
| Sep-12 | 388.14 | 51.60 | 77.97 | 102.04 |
| Oct-12 | 599.58 | 58.24 | 109.84 | 194.70 |

Table D – 1 (Continued)

| Date Month-Year | Rain (mm/d) | Evaporation (mm) | Observed Streamflow (mm) | Simulated Streamflow (mm) |
|---|---|---|---|---|
| Nov-12 | 659.35 | 56.61 | 360.80 | 262.87 |
| Dec-12 | 569.76 | 47.04 | 101.41 | 196.51 |
| Jan-13 | 244.90 | 57.50 | 51.37 | 67.97 |
| Feb-13 | 254.73 | 63.95 | 47.31 | 69.17 |
| Mar-13 | 402.19 | 67.36 | 58.57 | 99.01 |
| Apr-13 | 283.57 | 73.82 | 49.41 | 59.44 |
| May-13 | 534.50 | 43.58 | 210.25 | 187.20 |
| Jun-13 | 766.08 | 41.11 | 360.49 | 331.36 |
| Jul-13 | 546.21 | 48.57 | 141.63 | 143.22 |
| Aug-13 | 305.86 | 61.58 | 67.88 | 72.64 |
| Sep-13 | 529.42 | 55.57 | 179.19 | 182.03 |

Table D-2 Monthly output of the model for the verification period of Ellagawa

| Date Month-Year | Rain (mm/d) | Evaporation (mm) | Observed Streamflow (mm) | Simulated Streamflow (mm) |
|---|---|---|---|---|
| Oct-13 | 569.57 | 70.84 | 96.55 | 179.14 |
| Nov-13 | 554.32 | 75.72 | 138.24 | 158.51 |
| Dec-13 | 269.70 | 69.81 | 139.26 | 118.10 |
| Jan-14 | 180.58 | 85.55 | 51.83 | 50.94 |
| Feb-14 | 116.72 | 98.22 | 26.08 | 18.78 |
| Mar-14 | 152.18 | 107.35 | 29.91 | 37.49 |
| Apr-14 | 374.11 | 69.17 | 46.53 | 63.23 |
| May-14 | 283.68 | 64.77 | 54.85 | 66.89 |
| Jun-14 | 653.76 | 74.54 | 431.20 | 238.13 |
| Jul-14 | 256.20 | 81.86 | 83.98 | 68.16 |
| Aug-14 | 504.31 | 58.27 | 218.09 | 169.22 |
| Sep-14 | 338.69 | 66.56 | 98.24 | 85.18 |
| Oct-14 | 757.44 | 53.57 | 355.03 | 290.26 |
| Nov-14 | 365.01 | 52.73 | 148.88 | 111.97 |
| Dec-14 | 516.22 | 55.63 | 173.16 | 160.36 |
| Jan-15 | 94.47 | 90.54 | 42.39 | 42.35 |
| Feb-15 | 174.09 | 82.96 | 58.27 | 54.70 |
| Mar-15 | 155.19 | 96.47 | 43.72 | 42.43 |
| Apr-15 | 458.30 | 93.53 | 114.36 | 103.38 |
| May-15 | 311.06 | 75.33 | 88.41 | 72.21 |

Table D – 2 (Continued)

| Date Month-Year | Rain (mm/d) | Evaporation (mm) | Observed Streamflow (mm) | Simulated Streamflow (mm) |
|---|---|---|---|---|
| Jun-15 | 336.11 | 73.87 | 77.28 | 76.13 |
| Jul-15 | 252.43 | 76.88 | 65.95 | 56.15 |
| Aug-15 | 344.22 | 95.39 | 86.30 | 87.68 |
| Sep-15 | 466.77 | 60.18 | 170.22 | 143.11 |
| Oct-15 | 556.84 | 65.41 | 395.90 | 315.43 |
| Nov-15 | 465.24 | 66.49 | 336.18 | 372.99 |
| Dec-15 | 73.21 | 51.04 | 64.95 | 64.84 |
| Jan-16 | 96.12 | 66.62 | 67.41 | 57.52 |
| Feb-16 | 105.25 | 69.83 | 36.05 | 35.61 |
| Mar-16 | 173.45 | 94.75 | 39.18 | 45.77 |
| Apr-16 | 309.02 | 80.52 | 109.07 | 74.19 |
| May-16 | 962.99 | 57.29 | 632.62 | 414.05 |
| Jun-16 | 234.98 | 72.75 | 270.20 | 77.91 |
| Jul-16 | 179.21 | 84.43 | 67.20 | 59.18 |
| Aug-16 | 217.70 | 79.45 | 49.77 | 51.85 |
| Sep-16 | 137.17 | 75.09 | 29.77 | 29.73 |
| Oct-16 | 262.90 | 74.41 | 56.26 | 56.52 |
| Nov-16 | 352.24 | 58.69 | 131.94 | 94.52 |
| Dec-16 | 125.97 | 72.93 | 28.97 | 24.90 |
| Jan-17 | 111.76 | 81.38 | 22.29 | 26.75 |
| Feb-17 | 37.44 | 85.63 | 14.86 | 25.91 |
| Mar-17 | 253.71 | 88.04 | 46.38 | 42.81 |
| Apr-17 | 177.23 | 92.00 | 64.87 | 41.10 |
| May-17 | 757.65 | 72.17 | 568.15 | 289.59 |
| Jun-17 | 365.74 | 67.51 | 252.64 | 105.21 |
| Jul-17 | 225.19 | 73.67 | 68.66 | 54.47 |
| Aug-17 | 411.47 | 67.70 | 155.49 | 106.59 |
| Sep-17 | 611.77 | 65.03 | 431.50 | 218.57 |

Table D-3  Monthly output of the model for the calibration period of Ratnapura

| Date Month-Year | Rain (mm/d) | Evaporation (mm) | Observed Streamflow (mm) | Simulated Streamflow (mm) |
|---|---|---|---|---|
| Oct-09 | 369.86 | 67.85 | 168.13 | 131.88 |
| Nov-09 | 411.36 | 31.59 | 166.67 | 135.12 |
| Dec-09 | 257.40 | 31.99 | 162.16 | 128.41 |

Table D – 3 (Continued)

| Date Month-Year | Rain (mm/d) | Evaporation (mm) | Observed Streamflow (mm) | Simulated Streamflow (mm) |
|---|---|---|---|---|
| Jan-10 | 137.75 | 67.32 | 48.85 | 42.77 |
| Feb-10 | 89.03 | 69.92 | 51.49 | 46.55 |
| Mar-10 | 211.30 | 78.10 | 45.28 | 46.36 |
| Apr-10 | 304.78 | 69.65 | 74.77 | 51.11 |
| May-10 | 550.05 | 54.81 | 337.77 | 323.80 |
| Jun-10 | 463.32 | 52.70 | 242.45 | 206.14 |
| Jul-10 | 367.95 | 64.79 | 215.35 | 154.98 |
| Aug-10 | 295.58 | 62.61 | 162.04 | 144.29 |
| Sep-10 | 263.37 | 49.19 | 93.95 | 73.56 |
| Oct-10 | 375.71 | 53.91 | 188.63 | 119.16 |
| Nov-10 | 486.73 | 40.83 | 270.39 | 189.83 |
| Dec-10 | 304.38 | 39.76 | 266.17 | 154.36 |
| Jan-11 | 196.43 | 48.83 | 82.79 | 61.03 |
| Feb-11 | 113.01 | 56.01 | 76.99 | 69.52 |
| Mar-11 | 227.49 | 66.17 | 71.94 | 56.04 |
| Apr-11 | 448.73 | 64.42 | 270.80 | 192.68 |
| May-11 | 421.34 | 65.15 | 201.99 | 181.94 |
| Jun-11 | 302.64 | 66.65 | 144.10 | 86.35 |
| Jul-11 | 211.94 | 54.32 | 40.77 | 48.85 |
| Aug-11 | 401.05 | 59.48 | 66.24 | 78.11 |
| Sep-11 | 429.61 | 63.38 | 195.28 | 124.55 |
| Oct-11 | 405.28 | 62.90 | 83.23 | 98.42 |
| Nov-11 | 412.32 | 50.59 | 121.26 | 105.93 |
| Dec-11 | 257.13 | 54.14 | 91.40 | 72.36 |
| Jan-12 | 64.16 | 77.85 | 37.65 | 40.76 |
| Feb-12 | 162.42 | 60.39 | 38.89 | 39.63 |
| Mar-12 | 229.93 | 85.28 | 49.41 | 46.10 |
| Apr-12 | 327.49 | 60.45 | 124.54 | 114.68 |
| May-12 | 97.25 | 71.93 | 46.39 | 44.80 |
| Jun-12 | 195.31 | 57.90 | 55.19 | 41.75 |
| Jul-12 | 217.43 | 65.78 | 84.95 | 65.24 |
| Aug-12 | 321.91 | 58.56 | 67.26 | 61.84 |
| Sep-12 | 289.59 | 51.57 | 80.78 | 59.76 |
| Oct-12 | 450.59 | 57.86 | 138.15 | 114.29 |
| Nov-12 | 592.20 | 56.42 | 388.71 | 245.46 |
| Dec-12 | 428.61 | 47.55 | 123.19 | 113.44 |
| Jan-13 | 219.00 | 57.50 | 67.00 | 52.53 |
| Feb-13 | 222.72 | 63.35 | 54.06 | 51.27 |

Table D – 3 (Continued)

| Date Month-Year | Rain (mm/d) | Evaporation (mm) | Observed Streamflow (mm) | Simulated Streamflow (mm) |
|---|---|---|---|---|
| Mar-13 | 354.11 | 67.36 | 81.49 | 71.87 |
| Apr-13 | 249.55 | 73.82 | 60.62 | 45.42 |
| May-13 | 600.79 | 44.15 | 253.47 | 165.31 |
| Jun-13 | 793.73 | 41.42 | 396.91 | 312.34 |
| Jul-13 | 481.50 | 48.57 | 157.53 | 140.71 |
| Aug-13 | 267.89 | 61.58 | 72.51 | 70.22 |
| Sep-13 | 567.17 | 55.07 | 193.41 | 205.22 |

Table D-4  Monthly output of the model for the verification period of Ratnapura

| Date Month-Year | Rain (mm/d) | Evaporation (mm) | Observed Streamflow (mm) | Simulated Streamflow (mm) |
|---|---|---|---|---|
| Oct-13 | 330.26 | 70.84 | 119.66 | 82.49 |
| Nov-13 | 389.80 | 75.72 | 112.47 | 115.94 |
| Dec-13 | 261.17 | 69.81 | 110.07 | 83.38 |
| Jan-14 | 158.52 | 76.67 | 52.56 | 41.18 |
| Feb-14 | 71.65 | 84.47 | 38.31 | 31.47 |
| Mar-14 | 125.16 | 89.81 | 30.34 | 35.15 |
| Apr-14 | 342.05 | 98.43 | 73.97 | 62.16 |
| May-14 | 595.49 | 58.86 | 528.76 | 267.49 |
| Jun-14 | 430.98 | 55.23 | 170.80 | 129.01 |
| Jul-14 | 359.36 | 64.76 | 172.21 | 137.87 |
| Aug-14 | 292.44 | 82.10 | 119.01 | 75.94 |
| Sep-14 | 308.42 | 73.43 | 110.37 | 93.51 |
| Oct-14 | 355.04 | 70.84 | 198.78 | 146.68 |
| Nov-14 | 493.96 | 75.72 | 219.97 | 159.58 |
| Dec-14 | 347.52 | 69.81 | 230.05 | 136.99 |
| Jan-15 | 195.26 | 90.54 | 59.33 | 49.30 |
| Feb-15 | 117.14 | 82.96 | 58.60 | 39.95 |
| Mar-15 | 220.57 | 96.47 | 53.04 | 40.73 |
| Apr-15 | 510.05 | 93.53 | 244.05 | 155.23 |
| May-15 | 405.24 | 75.33 | 262.08 | 131.51 |
| Jun-15 | 243.68 | 73.87 | 160.06 | 78.68 |
| Jul-15 | 174.46 | 76.65 | 45.98 | 47.31 |
| Aug-15 | 267.28 | 95.39 | 70.41 | 54.28 |
| Sep-15 | 382.79 | 60.18 | 186.41 | 105.34 |

Table D – 4 (Continued)

| Date Month-Year | Rain (mm/d) | Evaporation (mm) | Observed Streamflow (mm) | Simulated Streamflow (mm) |
|---|---|---|---|---|
| Oct-15 | 323.74 | 65.69 | 68.21 | 72.67 |
| Nov-15 | 288.01 | 66.52 | 75.56 | 75.17 |
| Dec-15 | 218.96 | 51.04 | 69.28 | 49.49 |
| Jan-16 | 85.96 | 66.62 | 28.29 | 34.87 |
| Feb-16 | 91.98 | 69.83 | 28.61 | 30.53 |
| Mar-16 | 193.21 | 93.94 | 42.37 | 35.70 |
| Apr-16 | 292.95 | 80.52 | 128.42 | 63.76 |
| May-16 | 141.09 | 58.09 | 46.47 | 34.49 |
| Jun-16 | 208.55 | 72.75 | 51.20 | 40.84 |
| Jul-16 | 220.70 | 83.96 | 72.48 | 55.94 |
| Aug-16 | 314.54 | 79.45 | 65.70 | 62.85 |
| Sep-16 | 338.67 | 75.09 | 79.84 | 89.98 |
| Oct-16 | 500.62 | 74.41 | 112.47 | 162.28 |
| Nov-16 | 613.56 | 58.69 | 369.45 | 264.58 |
| Dec-16 | 342.50 | 72.93 | 103.84 | 119.12 |
| Jan-17 | 176.83 | 81.38 | 52.60 | 47.98 |
| Feb-17 | 209.41 | 85.63 | 48.44 | 50.52 |
| Mar-17 | 336.51 | 87.45 | 59.97 | 79.67 |
| Apr-17 | 265.56 | 92.00 | 50.59 | 50.20 |
| May-17 | 446.28 | 70.95 | 215.29 | 128.49 |
| Jun-17 | 700.18 | 70.23 | 369.13 | 338.76 |
| Jul-17 | 533.05 | 67.77 | 145.03 | 241.50 |
| Aug-17 | 288.09 | 67.29 | 69.51 | 69.57 |
| Sep-17 | 450.74 | 53.52 | 183.48 | 161.93 |

Table D-5 Monthly model output for parameter transfer to Ratnapura watershed

| Date Month-Year | Rain (mm/d) | Evaporation (mm) | Observed Streamflow (mm) | Simulated Streamflow (mm) |
|---|---|---|---|---|
| Oct-09 | 369.86 | 67.85 | 168.13 | 112.28 |
| Nov-09 | 411.36 | 31.59 | 166.67 | 111.03 |
| Dec-09 | 257.40 | 31.99 | 162.16 | 124.83 |
| Jan-10 | 137.75 | 67.32 | 48.85 | 41.52 |
| Feb-10 | 89.03 | 69.92 | 51.49 | 47.22 |
| Mar-10 | 211.30 | 78.10 | 45.28 | 48.64 |
| Apr-10 | 304.78 | 69.65 | 74.77 | 43.29 |

Table D – 5 (Continued)

| Date Month-Year | Rain (mm/d) | Evaporation (mm) | Observed Streamflow (mm) | Simulated Streamflow (mm) |
|---|---|---|---|---|
| May-10 | 550.05 | 54.81 | 337.77 | 195.43 |
| Jun-10 | 463.32 | 52.70 | 242.45 | 173.24 |
| Jul-10 | 367.95 | 64.79 | 215.35 | 158.82 |
| Aug-10 | 295.58 | 62.61 | 162.04 | 159.51 |
| Sep-10 | 263.37 | 49.19 | 93.95 | 67.43 |
| Oct-10 | 375.71 | 53.91 | 188.63 | 139.55 |
| Nov-10 | 486.73 | 40.83 | 270.39 | 197.17 |
| Dec-10 | 304.38 | 39.76 | 266.17 | 155.55 |
| Jan-11 | 196.43 | 48.83 | 82.79 | 71.95 |
| Feb-11 | 113.01 | 56.01 | 76.99 | 66.77 |
| Mar-11 | 227.49 | 66.17 | 71.94 | 44.51 |
| Apr-11 | 448.73 | 64.42 | 270.80 | 170.64 |
| May-11 | 421.34 | 65.15 | 201.99 | 145.15 |
| Jun-11 | 302.64 | 66.65 | 144.10 | 82.50 |
| Jul-11 | 211.94 | 54.32 | 40.77 | 62.98 |
| Aug-11 | 401.05 | 59.48 | 66.24 | 92.69 |
| Sep-11 | 429.61 | 63.38 | 195.28 | 142.20 |
| Oct-11 | 405.28 | 62.90 | 83.23 | 108.36 |
| Nov-11 | 412.32 | 50.59 | 121.26 | 119.84 |
| Dec-11 | 257.13 | 54.14 | 91.40 | 72.48 |
| Jan-12 | 64.16 | 77.85 | 37.65 | 48.34 |
| Feb-12 | 162.42 | 60.39 | 38.89 | 38.17 |
| Mar-12 | 229.93 | 85.28 | 49.41 | 49.13 |
| Apr-12 | 327.49 | 60.45 | 124.54 | 88.64 |
| May-12 | 97.25 | 71.93 | 46.39 | 49.12 |
| Jun-12 | 195.31 | 57.90 | 55.19 | 48.24 |
| Jul-12 | 217.43 | 65.78 | 84.95 | 79.73 |
| Aug-12 | 321.91 | 58.56 | 67.26 | 70.11 |
| Sep-12 | 289.59 | 51.57 | 80.78 | 63.46 |
| Oct-12 | 450.59 | 57.86 | 138.15 | 114.30 |
| Nov-12 | 592.20 | 56.42 | 388.71 | 209.63 |
| Dec-12 | 428.61 | 47.55 | 123.19 | 133.40 |
| Jan-13 | 219.00 | 57.50 | 67.00 | 59.39 |
| Feb-13 | 222.72 | 63.35 | 54.06 | 57.54 |
| Mar-13 | 354.11 | 67.36 | 81.49 | 79.58 |
| Apr-13 | 249.55 | 73.82 | 60.62 | 52.44 |
| May-13 | 600.79 | 44.15 | 253.47 | 186.94 |

Table D – 5 (Continued)

| Date Month-Year | Rain (mm/d) | Evaporation (mm) | Observed Streamflow (mm) | Simulated Streamflow (mm) |
|---|---|---|---|---|
| Jun-13 | 793.73 | 41.42 | 396.91 | 370.54 |
| Jul-13 | 481.50 | 48.57 | 157.53 | 172.60 |
| Aug-13 | 267.89 | 61.58 | 72.51 | 75.46 |
| Sep-13 | 567.17 | 55.07 | 193.41 | 232.88 |
| Oct-13 | 548.95 | 70.84 | 105.27 | 178.38 |
| Nov-13 | 529.34 | 75.72 | 164.86 | 181.17 |
| Dec-13 | 189.91 | 69.81 | 81.32 | 71.32 |
| Jan-14 | 205.99 | 76.67 | 72.40 | 70.24 |
| Feb-14 | 100.73 | 84.47 | 25.21 | 25.41 |
| Mar-14 | 143.52 | 89.81 | 38.12 | 48.07 |
| Apr-14 | 366.89 | 98.43 | 55.94 | 70.00 |
| May-14 | 285.89 | 58.86 | 57.87 | 71.98 |
| Jun-14 | 665.89 | 55.23 | 366.02 | 251.52 |
| Jul-14 | 244.82 | 64.76 | 91.47 | 78.64 |
| Aug-14 | 478.51 | 82.10 | 174.07 | 128.80 |
| Sep-14 | 408.17 | 73.43 | 94.31 | 103.43 |
| Oct-14 | 781.91 | 70.84 | 372.80 | 307.85 |
| Nov-14 | 423.85 | 75.72 | 148.99 | 147.95 |
| Dec-14 | 543.83 | 69.81 | 204.01 | 189.51 |
| Jan-15 | 116.36 | 90.54 | 93.94 | 69.93 |
| Feb-15 | 197.81 | 82.96 | 129.14 | 97.92 |
| Mar-15 | 151.95 | 96.47 | 96.91 | 70.01 |
| Apr-15 | 478.27 | 93.53 | 253.40 | 201.60 |
| May-15 | 363.75 | 75.33 | 195.90 | 131.47 |
| Jun-15 | 311.05 | 73.87 | 171.24 | 122.11 |
| Jul-15 | 287.93 | 76.65 | 146.12 | 86.09 |
| Aug-15 | 327.08 | 95.39 | 191.21 | 151.63 |
| Sep-15 | 522.93 | 60.18 | 377.15 | 203.70 |
| Oct-15 | 563.90 | 65.69 | 254.29 | 171.92 |
| Nov-15 | 454.44 | 66.52 | 222.62 | 177.36 |
| Dec-15 | 57.61 | 51.04 | 141.73 | 115.84 |
| Jan-16 | 94.05 | 66.62 | 66.38 | 56.70 |
| Feb-16 | 94.02 | 69.83 | 49.36 | 45.10 |
| Mar-16 | 154.68 | 93.94 | 46.28 | 52.02 |
| Apr-16 | 252.61 | 80.52 | 69.46 | 48.42 |
| May-16 | 997.82 | 58.09 | 355.45 | 443.17 |
| Jun-16 | 237.08 | 72.75 | 142.45 | 87.41 |

Table D – 5 (Continued)

| Date Month-Year | Rain (mm/d) | Evaporation (mm) | Observed Streamflow (mm) | Simulated Streamflow (mm) |
|---|---|---|---|---|
| Jul-16 | 155.56 | 83.96 | 65.08 | 59.63 |
| Aug-16 | 231.93 | 79.45 | 44.01 | 61.35 |
| Sep-16 | 158.29 | 75.09 | 37.09 | 58.16 |
| Oct-16 | 324.42 | 74.41 | 56.19 | 80.51 |
| Nov-16 | 382.52 | 58.69 | 92.03 | 125.55 |
| Dec-16 | 102.76 | 72.93 | 31.82 | 40.82 |
| Jan-17 | 126.14 | 81.38 | 26.70 | 28.74 |
| Feb-17 | 44.25 | 85.63 | 18.92 | 18.93 |
| Mar-17 | 242.58 | 87.45 | 43.18 | 47.90 |
| Apr-17 | 158.92 | 92.00 | 49.52 | 45.84 |
| May-17 | 807.07 | 70.95 | 410.28 | 336.90 |
| Jun-17 | 422.82 | 70.23 | 145.11 | 152.12 |
| Jul-17 | 244.64 | 67.77 | 62.62 | 70.83 |
| Aug-17 | 456.08 | 67.29 | 127.95 | 141.08 |
| Sep-17 | 637.87 | 53.52 | 259.57 | 239.21 |

Table D-6 Monthly model output for parameter transfer to Ellagawa watershed

| Date Month-Year | Rain (mm/d) | Evaporation (mm) | Observed Streamflow (mm) | Simulated Streamflow (mm) |
|---|---|---|---|---|
| Oct-09 | 325.87 | 67.85 | 116.86 | 93.29 |
| Nov-09 | 388.04 | 31.59 | 109.84 | 91.85 |
| Dec-09 | 262.00 | 31.01 | 107.50 | 88.28 |
| Jan-10 | 159.70 | 68.10 | 51.33 | 43.63 |
| Feb-10 | 71.69 | 70.76 | 37.41 | 36.32 |
| Mar-10 | 123.85 | 78.97 | 29.63 | 40.27 |
| Apr-10 | 344.40 | 71.80 | 72.24 | 56.72 |
| May-10 | 600.64 | 55.29 | 516.38 | 211.35 |
| Jun-10 | 428.87 | 52.77 | 166.80 | 121.09 |
| Jul-10 | 359.28 | 65.20 | 168.18 | 129.06 |
| Aug-10 | 289.24 | 64.14 | 116.22 | 109.28 |
| Sep-10 | 313.79 | 49.14 | 107.79 | 83.35 |
| Oct-10 | 353.34 | 54.08 | 194.13 | 116.22 |
| Nov-10 | 494.65 | 40.13 | 214.82 | 154.51 |
| Dec-10 | 349.07 | 38.89 | 224.66 | 134.69 |
| Jan-11 | 193.55 | 48.83 | 57.94 | 52.79 |

Table D – 6 (Continued)

| Date Month-Year | Rain (mm/d) | Evaporation (mm) | Observed Streamflow (mm) | Simulated Streamflow (mm) |
|---|---|---|---|---|
| Feb-11 | 115.63 | 56.01 | 57.22 | 49.90 |
| Mar-11 | 219.43 | 66.63 | 51.80 | 42.09 |
| Apr-11 | 513.11 | 66.02 | 238.34 | 160.32 |
| May-11 | 447.23 | 66.53 | 255.94 | 126.22 |
| Jun-11 | 332.90 | 66.65 | 156.31 | 80.72 |
| Jul-11 | 210.46 | 54.38 | 44.91 | 51.76 |
| Aug-11 | 368.72 | 59.48 | 68.77 | 75.54 |
| Sep-11 | 446.93 | 63.81 | 182.04 | 119.66 |
| Oct-11 | 457.45 | 62.90 | 66.61 | 117.45 |
| Nov-11 | 437.48 | 50.59 | 73.79 | 117.94 |
| Dec-11 | 313.49 | 54.14 | 67.66 | 75.40 |
| Jan-12 | 88.60 | 77.85 | 27.62 | 46.24 |
| Feb-12 | 166.76 | 60.39 | 27.94 | 34.57 |
| Mar-12 | 221.32 | 85.28 | 41.37 | 45.75 |
| Apr-12 | 361.47 | 61.54 | 125.42 | 94.79 |
| May-12 | 148.83 | 71.93 | 45.38 | 50.02 |
| Jun-12 | 288.56 | 57.90 | 50.01 | 59.97 |
| Jul-12 | 268.38 | 65.78 | 70.78 | 85.41 |
| Aug-12 | 397.08 | 58.99 | 64.16 | 93.46 |
| Sep-12 | 388.14 | 51.60 | 77.97 | 92.48 |
| Oct-12 | 599.58 | 58.24 | 109.84 | 178.67 |
| Nov-12 | 659.35 | 56.61 | 360.80 | 229.72 |
| Dec-12 | 569.76 | 47.04 | 101.41 | 188.98 |
| Jan-13 | 244.90 | 57.50 | 51.37 | 63.06 |
| Feb-13 | 254.73 | 63.95 | 47.31 | 68.96 |
| Mar-13 | 402.19 | 67.36 | 58.57 | 95.62 |
| Apr-13 | 283.57 | 73.82 | 49.41 | 57.66 |
| May-13 | 534.50 | 43.58 | 210.25 | 139.93 |
| Jun-13 | 766.08 | 41.11 | 360.49 | 285.83 |
| Jul-13 | 546.21 | 48.57 | 141.63 | 175.40 |
| Aug-13 | 305.86 | 61.58 | 67.88 | 73.04 |
| Sep-13 | 529.42 | 55.57 | 179.19 | 162.56 |
| Oct-13 | 569.57 | 70.84 | 96.55 | 165.94 |
| Nov-13 | 554.32 | 75.72 | 138.24 | 151.90 |
| Dec-13 | 269.70 | 69.81 | 139.26 | 84.79 |
| Jan-14 | 180.58 | 85.55 | 51.83 | 59.50 |
| Feb-14 | 116.72 | 98.22 | 26.08 | 27.95 |

Table D – 6 (Continued)

| Date Month-Year | Rain (mm/d) | Evaporation (mm) | Observed Streamflow (mm) | Simulated Streamflow (mm) |
|---|---|---|---|---|
| Mar-14 | 152.18 | 107.35 | 29.91 | 46.43 |
| Apr-14 | 374.11 | 69.17 | 46.53 | 74.15 |
| May-14 | 283.68 | 64.77 | 54.85 | 71.55 |
| Jun-14 | 653.76 | 74.54 | 431.20 | 221.89 |
| Jul-14 | 256.20 | 81.86 | 83.98 | 73.31 |
| Aug-14 | 504.31 | 58.27 | 218.09 | 134.19 |
| Sep-14 | 338.69 | 66.56 | 98.24 | 74.87 |
| Oct-14 | 757.44 | 53.57 | 355.03 | 252.08 |
| Nov-14 | 365.01 | 52.73 | 148.88 | 104.06 |
| Dec-14 | 516.22 | 55.63 | 173.16 | 147.81 |
| Jan-15 | 94.47 | 90.54 | 42.39 | 58.23 |
| Feb-15 | 174.09 | 82.96 | 58.27 | 60.48 |
| Mar-15 | 155.19 | 96.47 | 43.72 | 49.37 |
| Apr-15 | 458.30 | 93.53 | 114.36 | 90.98 |
| May-15 | 311.06 | 75.33 | 88.41 | 79.96 |
| Jun-15 | 336.11 | 73.87 | 77.28 | 72.74 |
| Jul-15 | 252.43 | 76.88 | 65.95 | 65.81 |
| Aug-15 | 344.22 | 95.39 | 86.30 | 96.07 |
| Sep-15 | 466.77 | 60.18 | 170.22 | 137.62 |
| Oct-15 | 556.84 | 65.41 | 395.90 | 151.90 |
| Nov-15 | 465.24 | 66.49 | 336.18 | 165.31 |
| Dec-15 | 73.21 | 51.04 | 64.95 | 38.45 |
| Jan-16 | 96.12 | 66.62 | 67.41 | 51.11 |
| Feb-16 | 105.25 | 69.83 | 36.05 | 44.98 |
| Mar-16 | 173.45 | 94.75 | 39.18 | 57.16 |
| Apr-16 | 309.02 | 80.52 | 109.07 | 59.53 |
| May-16 | 962.99 | 57.29 | 632.62 | 383.33 |
| Jun-16 | 234.98 | 72.75 | 270.20 | 70.81 |
| Jul-16 | 179.21 | 84.43 | 67.20 | 59.53 |
| Aug-16 | 217.70 | 79.45 | 49.77 | 60.25 |
| Sep-16 | 137.17 | 75.09 | 29.77 | 53.24 |
| Oct-16 | 262.90 | 74.41 | 56.26 | 68.44 |
| Nov-16 | 352.24 | 58.69 | 131.94 | 96.68 |
| Dec-16 | 125.97 | 72.93 | 28.97 | 39.35 |
| Jan-17 | 111.76 | 81.38 | 22.29 | 24.93 |
| Feb-17 | 37.44 | 85.63 | 14.86 | 16.26 |
| Mar-17 | 253.71 | 88.04 | 46.38 | 46.18 |
| Apr-17 | 177.23 | 92.00 | 64.87 | 58.56 |
| May-17 | 757.65 | 72.17 | 568.15 | 284.99 |
| Jun-17 | 365.74 | 67.51 | 252.64 | 94.40 |
| Jul-17 | 225.19 | 73.67 | 68.66 | 62.75 |
| Aug-17 | 411.47 | 67.70 | 155.49 | 114.45 |
| Sep-17 | 611.77 | 65.03 | 431.50 | 202.32 |