SUITABILITY OF A SELECTED HYDROLOGICAL MODEL AND OBJECTIVE FUNCTION FOR RURAL WATERSHED MANAGEMENT IN SRI LANKA

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Sri Lanka

May 2018

DECLARATION

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ABSTRACT

In a period where water resources are becoming scarce due to increased population and human activities, it is very important to have appropriate models and objective functions for water resources management especially in rural contexts. Therefore, the selection of appropriate model and objective function and to ascertain their suitability on a rural watershed is necessary. Preliminary screening of hydrological models was carried out based on the application availabilities and modelling purpose. Five models namely HEC-HMS, SWAT, TOPMODEL, MIKE SHE and SWMM were shortlisted. The shortlisted models were reviewed under several criteria such temporal scale, spatial scale, hydrological processes, documentation, resources requirement, user interface and model acquisition cost. Similarly, objective functions recommended on 'Guide for hydro-meteorological practices' by WMO namely NSE, RMSE, RAEM and MRAE were reviewed. Review of the objective functions was based on criteria such as mathematical implications, flow regimes and modelling purpose. The review of hydrological models and objective function suggested the Storm Water Management Model (SWMM) and Mean Ratio of Absolute Error (MRAE) as an appropriate model and objective function respectively for water resources modelling in rural watersheds. Accordingly, the SWMM was applied to the Ellagawa (1342 km^2) and Ratnapura (653 km^2) watersheds in the Kalu river basin of Sri Lanka using observed rainfall and streamflow from 2006-2014. In the present work, the SWMM model was calibrated and validated while investigating the effect of layout modifications to carry out continuous simulation of streamflow. Initially, two lumped models were developed for Ellagawa and Ratnapura watershed. Then a semi-distributed model with three sub-watersheds was developed for Ellagawa watershed. Model calibration was done for 2006-2010, and verification was carried out for the period 2011-2014. High, medium and low flow in the flow duration curve and the annual water balance were also observed during the calibration and validation. Ellagawa and Ratnapura lumped were calibrated with MRAE 0.3634 and 0.4531 respectively and validated with MRAE 0.5865 and 0.7843 respectively. Annual water balance errors of Ellagawa and Ratnapura lumped model were 38% and 31% respectively during calibration and 10.25% and 11% respectively during validation. Ellagawa and Ratnapura lumped models calibrated intermediate flow with MRAE 0.40 and 0.37 respectively. Manning's roughness coefficient for pervious layer, depression storage for pervious layer, saturated hydraulic conductivity and initial defect, lateral discharge coefficient and deep percolation coefficient were the main parameters to be calibrated. Manning's roughness coefficient of pervious layer (n-pervious) was optimized in the range (0.02-0.028), depression storage of pervious layer (d-store pervious) was optimized in the range of (1.2mm-2.5mm). Similarly, saturated hydraulic conductivity (K_{sat}) was optimized in the range of (0.3mm/hr.-0.67mm/hr.). Furthermore, the initial moisture deficit (Θ) was optimized in the range of (0.2-0.5). Ellagawa semi-distributed model showed some improvement in overall and intermediate flow compared to Ellagawa lumped model. MRAE for overall hydrograph was reduced by 19% and MRAE for intermediate flow was reduced by 24%. However, Ellagawa semi-distributed model showed a poor estimation of annual, seasonal and monthly streamflow compared to Ellagawa lumped model. Hence, the semi-distributed model with single gauging cannot be considered as a better and meaningful modelling option in SWMM with certainty. This study recommends more application of SWMM for continuous modelling of streamflow in monsoon regions and more research on automatic optimization, objective function and groundwater.

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1. INTRODUCTION

1.1. General

River systems around the world are being greatly impacted by various anthropogenic and natural causes like urbanization, deforestation, and landuse change. As such, hydrological models are developed to predict river system behaviour and understand the underlying hydrological process (Devia, Ganasri, & Dwarakish, 2015). Hydrological models are now considered as an important and necessary tool for water resources management.

A model is a simplified representation of the real world. The best model is the one which gives result close to reality with the use of least parameter and model complexity (Devia, Ganasri, & Dwarakish, 2015). Some of the hydrological models are designed to be used for urban catchments while some may be well suited for large rural basins. Similarly, there are models which simulate only design storms and events while some are more competent for continuous long term simulations. There are many popular mathematical models that have user-friendly interfaces, use elaborated modelling tools, physics-based with several process sub-models and produce detailed outputs. Most of such models focus on relatively small watersheds; have constraints on functionality; have limitations with respect to parameter optimization and demands large data requirements.

No model can be identified as ideal for all range of hydrological conditions and watershed characteristics. Marshall, Nott & Sharma (2005) stated that hydrological models selection is not supposed to be solely reliant on its predictive performance. The modeller's preference and familiarity in using particular models, the aim of the modelling task, the time available to develop and apply the model and the level of accuracy required should also be taken into account. There have been several studies for the selection of the appropriate model for a particular purpose in a specific geographical zone. Unduche et al. (2018) carried out an evaluation of the hydrological model for operational flood forecasting in Prairie watershed, Canada. Similarly, Onyutha (2016) studied the influence of hydrological model selection on moderate and extreme flow simulation in the Blue Nile basin. Surfleet (2012) compared hydrological modelling approaches for climate change assessment. However, there have been no studies carried out to identify an appropriate model in predominantly rural watersheds for sustainable water resources management. Hence, the selection of a fitting up-to-date model using an evaluation of the functionality, modeller requirements and modelling experiences are needed for sustainable water resources management in rural watersheds. Rural watersheds are generally large, has less impervious surface and heterogeneous in nature. Spatial variability of landuse, vegetation and topography within the watershed significantly affect the hydrological processes. As such, a lumped model (which assumes whole watershed a unit) may not be adequate to represent spatial variability of a rural watershed. On the other hand, distributed models (which disaggregates watershed in a number of finer resolution sub-unit) require streamflow time-series data recorded at each of the sub-divisions. Therefore, a distributed model with sub-watersheds gauged at a single outlet is common in practice (Examples: Carpenter & Georgakakos, 2006; Kanchanamala, Herath, & Nandalal, 2016). Similarly, selection of appropriate objective function is equally crucial for hydrological modelling processes. Hydrological models serve various purposes such as estimation of design storms, flood forecasting, drought forecasting etc. Diskin & Simon (1977) stated that the choice of the objective functions to be used for any given model is a subjective decision which influences the values of the model parameters and the performance of the model. Hence, an objective function should be appropriately selected depending upon the objective of the study. In a period where water resources are becoming scarce due to increased population and human activities, it is very important to have appropriate models and objective functions for water resources management, especially in rural contexts. Hence, the selection of an appropriate model and objective function and ascertain their suitability on a rural watershed by a case study is necessary.

1.2. Study Area

The Kalu River originates from the central hills of Sri Lanka, flows through Ratnapura and Horana and empties into the Indian ocean at Kalutara with a total length of about 129 km and watershed area of 2,690 km^2. The river basin lies entirely within the wet zone of the country and average annual rainfall in the basin is 4,040 mm with ranging from 6,000 mm in mountainous areas and 2,000 mm in the lower plain. Ellagawa watershed (1342 km^2) and Ratnapura watershed (650 km^2) are upstream watersheds of Kalu Ganga which covers 48 % and 24 % area of the Kalu river basin. Ellagawa watershed is a predominantly rural watershed. It consists of only 12 km^2 of total built up area which is only 0.1 % of total watershed area. Figure 1-1 shows the study area (Ellagawa and Ratnapura watershed) of the research.

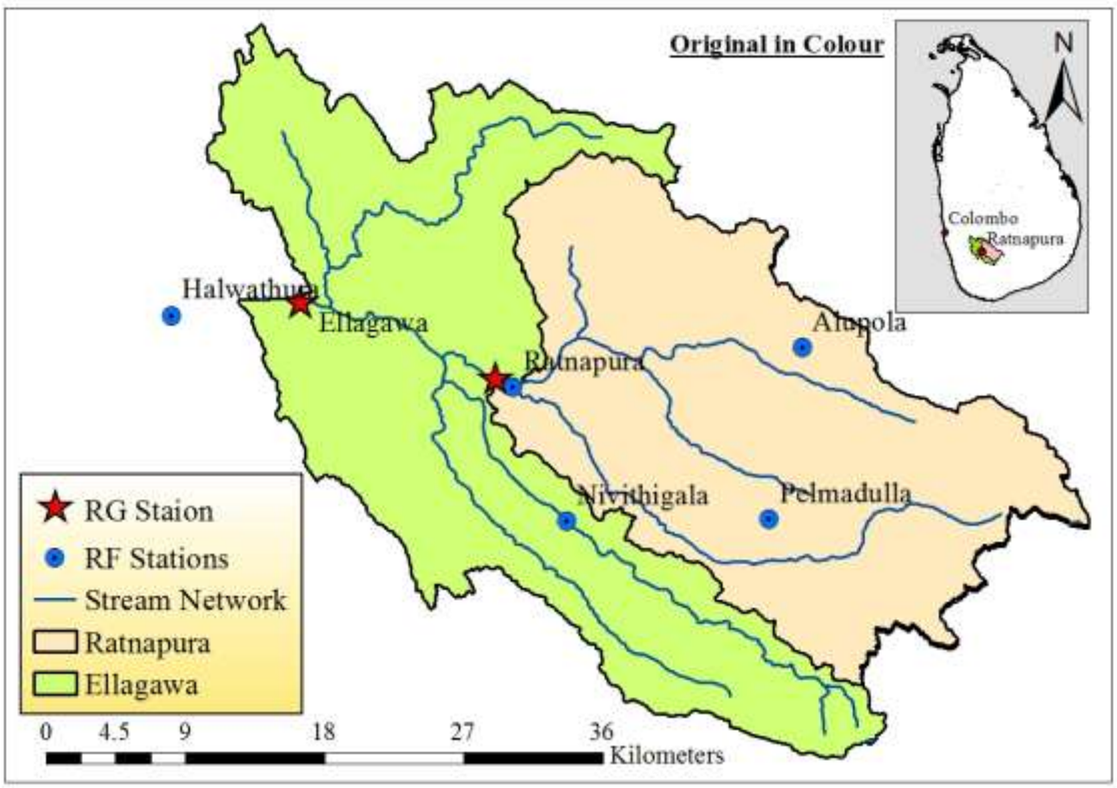

Figure 1-1 Study Area

1.3. Objective of the Study

1.3.1. Overall Objective:

The overall objective of this study is to evaluate of state of art on hydrological model and objective function for rural watersheds, identify the merits and demerits of selected model and objective function and ascertain the suitability of selected model and objective function (SWMM and MRAE) in Kalu river basin of Sri Lanka for sustainable water resources management.

1.3.2. Specific Objectives

1. State of art review and criteria evaluation for the selection of hydrological model and objective function for sustainable water resources management on rural watershed.
2. Develop lumped models (Ratnapura and Ellagawa) and Ellagawa semi-distributed model on Kalu river basin of Sri Lanka using selected model (SWMM).
3. Calibrate and validate the lumped model (Ratnapura and Ellagawa) and Ellagawa semi-distributed model on Kalu river basin of Sri Lanka using selected objective function (MRAE).
4. Compare the performance and parameters of different scale of model developed on Kalu river basin.
5. Recommend the meaningful modeling option (lumped or semi-distributed) for sustainable water resources management in predominantly rural watershed.

2. LITRATURE REVIEW

2.1. Hydrological Modelling Practice

According to Moradkhani & Sorooshian (2009), a model is a simplified representation of the real world. The best model is the one which gives results close to reality with the use of least parameter and model complexity (Devia, Ganasri, & Dwarakish, 2015b). Hydrological models have been classified into many types. According to Clarke (1973) mathematical models on hydrology are classified into stochastic-empirical, stochastic-conceptual, deterministic-empirical, deterministic-conceptual. Chow et al. (1988) classified hydrological models into two simple categories physical and abstract. Hydrological models can be classified into lumped, semi-distributed and distributed under spatial representation category. Empirical (black box), conceptual (grey box) and physical (white box) under the category of theory and assumptions, event-based and continuous under time scale category (Jajarmizad et al., 2012; Moradkhani & Sorooshian, 2009).

There are a large number of hydrological models available for a variety of applications. The most rational way for an initial selection of model would be to assume that a model would be popular only if it can be used easily, produces satisfactory results, hydrological systems are rationalized, data demands are reasonable, resource requirements are affordable etc. Therefore in this work, the initial model selection was carried out by considering whether the model would (1) serve the purpose (2) popularity (3) availability of user manuals (4) details of technical processes (5) preferred use over a long period (6) potential of distributed application (7) data requirements (8) model acquisition costs (9) human resources for application of the model

2.2. Preliminary Screening of Hydrological model

Every hydrological modeling study involves the selection of a hydrological model. This step is crucial, because the outcomes of the study depend on the selection of the model (Addor & Melsen, 2019). Therefore, the selection of this model should ideally be based on its adequacy for the research question (such as the landscape of the region, the temporal and spatial scales, and the purpose of the study, flood modeling or water resources management). Unduche et al. (2018) evaluated four hydrological models namely: WATFLOOD, HBV, HEC-HMS and HSPF model for flood forecasting. Devia et al. (2015b) reviewed SWAT, MIKE SHE, VIC and TOP model. Acharya (2018) analyzed performance of SWAT and SWMM for assessment of hydrological models in mixed landuse watershed. Similarly, Cunderlink (2003) did a detail comparison of 18 different types of models for the assessment of water resource risk and vulnerability in changing climatic conditions. Lumped: IHACRES, SRM, WATBAL; Semi-distributed models: HBV, HEC-HMS, HFAM, HSPF, PRMS, SSARR, SWAT, SWMM, TOPMODEL; Distributed model: CSCD, CEQUAU, GAWSER, HYDROTEL, MIKE SHE, WATFLOOD. A preliminary screening conducted by using application availability and modeling purpose of hydrological models is listed below in Table 2-1.

Table 2-1 Literature Survey for Preliminary Screening of Hydrological Models

Model	Area of modelling	Application availability
WATBAL	Climate change impact assessment on river basin (Yates, 1996)	Limited application Keig & Mcalpine (1969) used WATBAL for the estimation and analysis of soil moisture regimes from simple climatic data.
HBV	Flood forecasting (Grillakis et al., 2010)	Several applications can be found. Kobold & Brilly (2006) used HBV model for flash flood forecasting in Slovenia. Şorman et al. (2009) used HBV model Modelling and forecasting snowmelt runoff process in eastern Turkey.
VIC Variable Infiltration Capacity	Large scale basin modeling (Xia et al., 2018)	Several applications can be found. Lohmann et al. (1998) used VIC for regional scale hydrological modelling. Guo et al. (2009) used VIC model predict climate change impact in the Hanjiang basin.
HEC HMS	Simulate the complete hydrologic	Halwatura & Najim (2013) applied HEC-HMS model for runoff simulation in a tropical

(Hydrological modelling system)	processes of watershed (Feldman, 2010)	catchment. Oleyiblo & Li. (2010) applied HEC-HMS for flood forecasting Mesai and Wanan catchments.
HSPF (Hydrologic Simulation Program-Fortran)	Simulate all water quantity and quality processes that occur in a watershed (Z. Li, et al., 2012)	Limited application Mishra, Kar & Singh (2007) used HSPF model for the determination of runoff and sediment yield from a small watershed in sub-humid subtropics.
SWAT (Soil and Water Analysis Tool)	Predict the impact of land management practices on water (Neitsch et al., 2002)	Several applications can be found. Grey, et al. (2014) applied SWAT as tool in small tropical island for integrated watershed and coastal zone management. LéVesque, et al. (2008) for streamflow simulation two small watersheds under snowmelt and rainfall.
SWMM (Stormwater management model)	Analysis of quantity and quality problems associated with urban runoff (Rossman & Huber, 2016)	Several applications can be found. Tsihrintzis & Hamid (1998) used SWMM for runoff quality prediction of small catchments Moynihan & Vasconcelos (2014) used SWMM for modeling of a Rural Watershed in the Lower Coastal Plains of the United States.
TOPMODEL (Topography Model)	Analysis of hydrology on the basis of basin topography (Beven, 1997)	Several applications can be found. Gao et al. (2015) used TOPMODEL for modelling impacts of land-cover change on river flow in upland peatland catchments.
MIKE SHE	Simulation of discharge in river systems (Sandu & Virsta, 2015)	Several applications can be found. Thompson et al. (2004) used MIKE SHE for modelling system to lowland wet grassland in southeast England. Sandu & Virsta (2015) used MIKE SHE to Simulate Hydrology in Argesel River Catchment.

Modelling purpose of HEC-HMS, SWAT, SWMM, TOPMODEL, and MIKE SHE meets objective of the study and their applications can be easily found on the literature. Hence, they are selected for detailed further study, review and comparison.

2.3. Review of Hydrological Model

The shortlisted five models HEC-HMS, SWAT, SWMM, TOPMODEL and MIKE SHE were reviewed in detail. The application potential and range, modelling processes and scales of the models are described in the detail in this section.

2.3.1. Hydrological Modelling System (HEC-HMS)

HEC-HMS is a hydrological model developed by the US Army Corps of Engineers in 1998. HEC-HMS is primarily an event based model (Feldman, 2010), now it is widely used for continuous simulation of rainfall and runoff. It has ability to simulate of runoff both in short and long-term events (Gebre, 2015). It is applicable for simulating not only runoff from rural watersheds but can estimate discharge of urban watersheds as well. (Examples: Suriya & Mudgal, 2012; Gholami & Mohseni Saravi, 2010; Goff & Gentry, 2006). Feldman (2010) stated that most of the processes in HEC-HMS are empirical. HEC-HMS uses mainly kinematic wave method and Muskingum's wave method for flow routing. For the hydraulic modelling part, HEC has an additional model namely HEC-RAS where outputs of HEC-HMS serves as input data for river analysis. There have been several studies by integrating HEC-HMS and HEC-RAS for investigating the hydrological and hydraulics problems of river basin. Butt, Umar, & Qamar (2013) used HEC RAS model coupled with HEC HMS for flood risk estimation in northern Pakistan, Similarly, Thakur et al. (2017) carried out a study coupling HEC-HMS and HEC-RAS to prepare flood plain inundation map on copper slough watershed in Champaign, Illinois. HEC-HMS takes both point and gridded rainfall and streamflow data. Regarding, the physical data HEC-HMS has reasonable data requirements. Physical data required for HEC-HMS are Digital Elevation model (DEM) or contours for slope, maximum height, basin width, soil map for infiltrations parameters and Landuse map (Baumbach, Burckhard & Kant, 2015). Hydrological Engineering Centre (US army corps of engineers) provides both user manual and technical reference manual of ease-of use of the model. Halwatura & Najim (2013) stated that HEC-HMS has an advanced graphical user interface (GUI) illustrating hydrologic components with interactive features system for storing and managing data, specifically large, time variable data sets. It has inbuilt automatic optimization options for the user (Kamali, Mousavi, & Abbaspour, 2013). Hydrological Engineering Centre (HEC) has made it available freely on public domain.

2.3.2. Soil and Water Analysis Tool (SWAT)

SWAT is a river basin, or watershed, scale model developed by Dr. Jeff Arnold for USDA, Agricultural Research Service (ARS) to predict the impact of land management practices on water, sediment and agricultural chemical yields (Neitsch et al., 2002). Gassman, Sadeghi & Srinivasan (2014) stated that SWAT is a widely used model and is highly flexible in addressing a boarder range of water resource problems, as a result of the comprehensive nature of the model, strong model support, and open access status of the source code. SWAT can be used for both event based and continuous simulation of runoff quality and quantity (Borah et al, 2007). It had been always a model simulating with daily time step (Boithias et al., 2017). SWAT is a semi-distributed in nature (Neitsch et al., 2002) and had been applied for estimation runoff quality and quantity mainly in large river basin (Tuo et al., 2016). SWAT is basically a physics based model (Neitsch et al., 2002). It uses Muskingum's wave method for flow routing which is empirical in nature (LéVesque et al., 2008). It does not have additional hydraulic modelling features or models to couple/integrate. It incorporates station wise point data for rainfall and streamflow. One of the major drawback of SWAT is that it doesn't reflect the spatial distribution of precipitation over the basin (Galván et al., 2014). SWAT only uses the data of the rain gauge closest to the centroid of each sub-basin, disregarding all other stations (Masih et al., 2011). Furthermore, SWAT model is considered as moderate data demanding model comparatively. Physical data required for SWAT models are: DEM, Land use map, soil map and slope map (Tuo et al., 2016). USDA, Agricultural Research Service (ARS) periodically upgrades model features and provides documents (User manual/technical manual) for users support. It does not have its own Graphical User Interface (GUI) therefore it mainly integrates with Geographic Resources Analysis Support System (GRASS) and ArcGIS to facilitate development of model input and analysis of model output (Olivera et al., 2006). Furthermore, SWAT has inbuilt automatic parameter optimization option. There are several studies carried out on SWAT model with automatic parameter optimization (Examples: Li et al.,2010; Ozdemir & Leloglu, 2018).

2.3.3. MIKE SHE

MIKE SHE is a commercial engineering software package developed at the Danish Hydraulic Institute (DHI). MIKE SHE is a continuous model (Sandu & Virsta, 2015) and operates on hourly time steps (DHI, 2006). It is a fully distributed hydrological model and is mainly used in large river basin (Sandu & Virsta, 2015). DHI has developed separate model named MIKE-Urban for urban watersheds. MIKE is a strictly physics based hydrological model (Ma et al, 2016) where flow routing is governed by a simplified empirical stage-discharge relation method. MIKE has another model called MIKE 11 for hydraulic modelling purposes. There have been several studies carried out coupling MIKE SHE and MIKE 11 (Examples: Cleaver et al.,2016; Krishnaveni & Rajeswari,2019). MIKE needs hydro-meteorological data in a gridded format and it is considered as intensive data demanding model. Physical data required for MIKE SHE are: Topography data (DEM in 3m resolution), Detail of Landuse data (for overland flow, unsaturated and saturated zone parameters) and Vegetation data (for crop pattern and practice). There are more than 100 input parameters that need be calibrated in MIKE SHE. (Jaber et al., 2012). DHI provide supports and supporting documents for users. User’s manual and reference manual of MIKE SHE are easily available. MIKE SHE has an advance and user friendly interface (Ma et al., 2016) and it also have provision of automatic optimization option for users which reduce time and effort of modelling.

2.3.4. TOPMODEL

The development of TOPMODEL was initiated by the University of Leeds in the mid-1970s. The model was further developed by Keith Beven at the Lancaster University. Since, 1974 there have been many variants of TOPMODEL but never a “definitive" version. TOPMODEL was developed with the aim of providing a physically realistic but parametrically simpler rainfall runoff model which have the ability to predict different types of hydrological response (Beven, 1997). TOPMODEL is a continuous, semi-distributed and conceptual hydrological model (Beven, 1997). It generally operates on daily time steps but there has been few studies using TOPMODEL on hourly time step as well (Examples : Holko & Lepisto, 1997; Blazkova, Beven & Kulasova, 2002). TOPMODEL uses Muskingum's method for routing the overland flow (Takeuchi, & Ishidaira, 1999). TOPMODEL does not have additional hydraulic model to couple or integrate with. Users/Technical manual of TOPMODEL are not documented properly. TOPMODEL is freely available model. The source code of TOPMODEL is written in FOTRAN and operates in DOS. It does have in its own Graphical User Interface (GUI) (Beven, 1997).

2.3.5. Storm Water Management Model (SWMM)

SWMM is a conceptual hydrodynamics model capable of simulating events or continuous runoff quality and quantity developed by US EPA in 1977 (Rossman & Huber, 2016). It is considered to be widely used model throughout the world for planning, analysis and design related stormwater runoff, combined sewers and other drainage system. SWMM is used for both event based and continuous simulation of runoff quality and quantity (Cambez & David, 2008). It can operate in minutes/hours/daily time steps (Rossman & Huber, 2016). SWMM is known as a semi-distributed model (Rossman & Huber, 2016). Moynihan & Vasconcelos (2014) stated that the SWMM has proven as highly effective for urban and suburban watersheds modeling since its conception. Although it was primarily developed for urban watershed modeling, application of SWMM is not limited only to the urban watershed (Rossman & Huber, 2016). The flow routing method in SWMM is governed by the conservation of mass and momentum equations (Saint-Venant's equation). SWMM allows users to choice the options for flow routing namely the steady flow routing; the kinematic wave routing; or the full dynamic wave routing (Cambez & David, 2008). SWMM is freely available model on public domain. User's manual and reference manual of

SWMM are well documented and made easily available by US EPA. SWMM operates on its own GUI (Rossman & Huber,2016; Lin et al., 2010). SWMM do not have automatic optimization option hence it needs third party programs like PCSWMM for automatic calibrations of parameters (Xi Jin et al., 2011; Barco Janet et al., 2008; Tscheikner et al., 2016).

2.4. Criteria for the Selection of Model

The selection of hydrological models is a crucial and subjective process. No model can be identified as ideal for the all range of hydrological conditions and watershed characteristics. Marshall, Nott, & Sharma (2005) stated that hydrological model selection is not supposed to be solely reliant on its predictive performance. The modeler's preference and familiarity in using particular models, the aim of the modeling task, the time available to develop and apply a model and the level of accuracy required should also be taken into account. Addor & Melsen (2019) stated that outcomes of the study depend directly upon the model selected for the study. The bases of the selection of model for this study are purpose of study, nature of watershed, availability of data, adequate knowledge on model's parameters, knowledge on models processes and steps, complexity of models and cost/availability of model.

Considering the aforementioned basis of selection of hydrological model criteria for the selection was developed. The criteria for model selections for the hydrological model are (1) Temporal scale (2) Spatial Scale (3) Hydrological Processes (4) Documentation (5) Resources Requirement (6) User Interface (7) Model Acquisition. Each of the criteria is comprised with number of factors. Criteria and factors for the selection of hydrological model are described below.

2.4.1. Temporal Scale

Temporal scale is considered important criterion for the selection of model. Temporal scale of the model have significant role on objective and outputs of the modelling study.

Depending upon the objective of the modelling study, models are selected. For example: if modelling is to be carried out for estimation of design flood/storm then event based model should be selected and if modelling is to be carried out for analysis of flood, drought and water resources continuous models should be selected. Similarly, if natural process on the watershed is expected to be detailed in model then the model with shorter simulation time step should be chosen. Factors under temporal scale are temporal resolution of the model and the simulation time steps that model can perform.

2.4.1.1. Temporal Resolution

Event based modeling requires single event or discrete events and its applications is limited to the estimation of design storms (Lamb, 1999) while continuous modeling requires a series of such events in long term continuous form. Hydrological problems like water resources management and flood management are generally approached by continuous rainfall runoff (Wagener & Wheater, 2006). Therefore, hydrological model which perform both events and continuous simulations are highly preferred while model which can perform only continuous simulation are moderately preferred and model which perform only event(s) simulation are preferred low.

2.4.1.2. Simulation Time Steps

Runoff generation is highly affected by dynamics of precipitation, particularly where the infiltration-excess overland flow mechanism dominates the rainfall-runoff response (Koch & Kekhia,1987). The shorter time step modelling contains more information of dynamics of the process. However, the shorter time step modelling requires finer resolution of input data (Precipitation, streamflow, evaporation). Finer resolution of precipitation, streamflow and evaporation data are scarce in most of the part of the world. Hydrological models which can operate on shorter time step and capture the effect of sub-daily variability on output with daily data input are desirable (Kandel, Western & Grayson, 2005). Hence, models with flexible simulation time steps (minutes/hours/day) are highly preferred. Similarly, models with simulation time steps (hours/day) are moderately preferred and models only with daily simulation time steps are given low preference.

2.4.2. Spatial Scale

Spatial scale is another important criterion for the selection of the hydrological model. Spatial scale of the model is directly associated with the objective of the modelling.

Depending upon the level of the accuracy required on the modelling outputs and preparedness to deal with the complexity of the modeling procedure hydrological models is selected. If the modelling study is focused on representing spatial variability of precipitation (and other meteorological factors) and non-uniformity of watershed characteristics like topography, landuse, vegetation than suitable modeling approach would be distributed modelling. If the spatial variability of meteorological factors and watershed characteristics are not supposed to be represented on model than suitable modelling approached would be lumped. The complexity of modelling procedure increases in the order of 'lumped' to 'distributed' so as the accuracy. Therefore, modelers should decide upon the selection of appropriate model with respect to the need of accuracy in output and complexity in procedure to deal with. Similarly, hydrological models have certain range of watershed to be applied. For example: large watersheds or small watersheds, rural watersheds or urban watersheds. Depending of the study area of the modelling appropriate model should be selected. Hence, factors considered under the spatial scale criterion, are spatial representation, and nature of watershed.

2.4.2.1. Spatial Representation

Lumped models assume entire watershed as a single unit whereas, a distributed model disaggregates a watershed as a number of sub-units. A fully distributed model divides a watershed into sub-unis in fine resolution whereas a semi-distributed or a pseudo distributed model can operate in a sub-watershed scale. Khakbaz et al. (2012) stated the advantage of distributed model over lumped is not only better prediction of streamflow but also its ability to produce streamflow prediction in the interior location of the system (catchments) where flow measurement may not be available. Onyando, Schumann & Schultz (2003) stated that a fully distributed model has limited application due high cost associated with input data. Jajarmizad et al. (2012) stated that a semi-distributed model can overcome the limitations of lumped model and can predict streamflow at defined sub-units with relatively less amount of data and computation complexity than with a fully distributed model. Therefore, Semi-distributed models are highly preferred whereas fully distributed and lumped models are given moderate and low preference respectively.

2.4.2.2. Nature of the Watershed

Watershed can be classified into rural/urban or large/small. Rural watersheds are comparatively bigger than urban watersheds and characterized by spatial heterogeneities, relatively high vegetation cover and increased impervious areas. Hydrological models which can simulate both rural and urban watersheds are highly favored whereas models which can only model rural watersheds are moderately preferred and models which can only model urban watersheds are given low preference.

2.4.3. Modelling Process

Model process is one of the core criterions for the selection of the hydrological model. It is also crucial to identify the appropriate model with suitable modelling process to serve the objective of the modelling study. Depending upon the purpose of the study, level of accuracy need, data availability and need of the supporting tools models are selected. If high accuracy is needed for the modelling and higher resolution data are available then physics based model are suitable model to be selected. If the modelling demands fair accuracy in case of limited availability of data then conceptual models are suitable. In addition, hydrologic and hydraulic process integration is considered crucial for comprehensive and holistic modelling of hydrological systems. Therefore, it is important to know the possibility of hydrologic and hydraulic process integration in the model. Similarly, flow routing options available in model is another important component to be considered. Flow routing is the procedure to determine the flow hydrograph at any given point of the watershed. It accounts the flow hydrograph as the flow passes the downstream. It helps in accounting the storage and attenuation of the flow peaks. There are different types of flow routings options available in models. Hence, model with desirable flow routing option should be selected to meet the objective of the modelling. Factors considered under the modelling processes criterion, are theory and assumption, process integration, flow routing options.

2.4.3.1. Theory and Assumption

Models can be classified into empirical, conceptual and physics based under this category. Empirical models are developed without considering any underlying physical process while physical model describes natural systems by mathematical representation (Refsgaard, 1996). Number of the reviewer suggested preferring physically based models over conceptual models on their theoretical analysis but the real scenario is a bit different. Parameters of physics based model needs value from real observation data. Hughes,(1989) stated that if the value of physics based model have to be estimated or guessed due to lack of availability of filed measurements then the result are not likely to be reliable than the result obtained from simple conceptual model. Furthermore, Kunstmann et al. (2006) stated physics based model demands high input data and detailed information of spatial distribution of soils, vegetation and land surface properties which are often not available.

2.4.3.2. Options for Flow Routing

Generally, there are three kinds of flow routing methods: Kinematic wave, dynamic wave and Muskingum wave. Although, Kinematic wave is well established among the existing methods to solve unsteady, one-dimensional, gradually varied open-channel flow, inertial component on the flow is too small to be of any practical importance (Ponce,1991). The kinematic wave method is valid only if the local accelerations are negligible and a slope of surface water is assumed same as bed slope (Chaudhry, 2008). Furthermore, Hromadka & DeVries (1988) and Weinman & Laurensen (1979) indicated serious limitations on fundamental assumptions and computation error of Kinematic wave equation which affects peak flow estimates and hydrograph timing. On the other hand, Muskingum wave is simple method for flow routing which consists of spatially lumped equations based on empirical linear stage-discharge relationship (Singh & McCann, 1980). The output hydrograph from Muskingum wave flow routing is only at one point of river. Due to applied assumptions in this method wave attenuations occurs and lowers the accuracy (Askari & Shayannejad, 2016; Singh & McCann,1980b). Dynamic wave routing models include the Saint-Venant’s equations and perform well for most rivers. It has been widely applied to river flow routing (X. Zhang & Bao, 2012). Dynamic wave method uses finite element method, finite volume method, and finite difference method have been used to solve the unsteady-flow equations considering all the terms of the momentum equation: the pressure gradient, inertia, gravity, and flow resistance terms (Zhang, 2005). Hence, the dynamic wave flow routing is most appropriate, realistic as a method of flow routing in natural streams (Barati, Rahimi & Akbari, 2012). Therefore, hydrological model which has option of dynamic wave routing is given high priority similarly, a model which has option of kinematic and Muskingum wave routing wave routing is given moderate priority and low priority respectively.

2.4.3.3. Process Integration (Hydrology and Hydraulics)

In the field of water resources engineering, combined hydrologic and hydraulic modeling is a tool commonly used for engineering analysis and to evaluate the benefits of proposed improvements. Hydrology represents the quantity of water (runoff) generated from a specific area or watershed. Hydraulics deals with the physical properties of water that influence flow over the surface and along the streams. A combined hydrologic/hydraulic model allows a user to evaluate the impacts of various scenarios and the benefits that would be achieved. Combined/coupled/integrated hydrological and hydraulic modeling is being practiced for flood plain management, river/lake restoration and to understand geomorphology of the streams. Anselmo et al. (1996) integrated hydrological and hydraulic modelling approach for flood risk assessment on effects of extreme flood events on the Montalto di Castro. Similarly, Biancamaria et al. (2009) coupled hydrologic and hydraulic modelling of the Ob River in Siberia and Bravo et al, (2012) coupled Hydrologic-Hydraulic Modeling of the Upper Paraguay River Basin. Kiesel (2013) applied hydraulic-hydrological modelling for investigating water and sediment fluxes in catchment, channel and reach of low land watershed of Kielstau Basin, a northern Germany. Therefore, fully integrated hydraulic-hydrological models are highly preferred, partially integrated hydraulic–hydrological model are moderately preferred and model which cannot be integrated with hydraulic model are given low preferences.

2.4.4. Resources Requirement

Hydrological models needs data like precipitation data, streamflow data or physical data as an input resources. Finer resolution data is assumed to give better result but there are there are two constraint associated with finer resolution of data: (a) complexity on the modeling process (b) Scarcity of the data with finer resolution. Hence, depending upon the objective of the modelling study and level of accuracy needs in the output adequate demanding model should be selected. Factors considered under the resource requirement criterion, hydro-metrological data requirements and physical data requirements

2.4.4.1. Hydro-meteorological Data Requirement

The spatial scale of hydro-meteorological data can be classified into: gridded data point, station data and averaged data. Gridded precipitation data are not widely available at a daily resolution (Liebmann & Allured, 2005) and hence, most of the gridded data are in fact interpolated from point (station) data itself. For examples: Perry & Hollis (2005) generated monthly gridded precipitation data for UK using station data. Similarly, Yatagai, Xie & Alpert (2008) developed daily precipitation gridded data for Middle east using limited station data. Furthermore, importance of gridded data is more on climate research rather than hydrological research. Station data are collected from rainfall stations or river gauging stations. These type data are generally available for most of the watersheds around the world. Averaged data or aggregated data are processed precipitation or discharge data from external or secondary data sources. Hence, Models which requires station wise data are highly preferred similarly, model demanding gridded data and aggregated data are given moderate and ow preferences respectively.

2.4.4.2. Physical Data Requirement

Hydrological models need physical data such as soil properties data, landuse data, topography data, morphological data, vegetation data and ecology data. Availability of hydrological data is major issue in real life hydrological application. In such case, models which demands lesser amounts of data and produce satisfactory results are often selected. Based on data demand for model processing it can be classified into intensive data demanding model, moderate data demanding models and reasonable data demanding model. Hence, reasonable data demanding models are highly preferred and intensive data demanding models are given low preferences.

2.4.5. Documentation Support

Hydrological models are based on different theory and assumptions. Most of the models conceptualizes the process of overland flow, infiltration and subsurface flow and their inter relation in a unique and different way. Furthermore, for the model setup, pre-processing of data and post-processing output a documented guide in necessary. Therefore, hydrological model developer provides two sets of manuals namely technical manual and user manual. Factors considered under the documentation support criterion are availability of reference manuals.

2.4.5.1. Availability of Reference Manual

Generally, a model has two types of manuals and they are technical manuals and user manuals. Technical manuals describe underlying process in details whereas user manual instruct and guide user on the use of the model. Both manuals are important for the better understanding and the theory and the ease-of-. Hence, a model which has both manuals is highly preferred. Similarly the models which have very poor manual have given low preference. The models with quality of manuals falling in between are classified as moderately preferred.

2.4.6. User Interface

A user interface (UI) is a conduit between user and system interaction. It is the space where a user will interact with a system to complete tasks. Hydrological models now a day mainly computer based hence, user interface is an important part of the model to be considered. For the efficient use of the model and user ease user interface plays a vital role. Factors considered under the user interface criterion are graphical user interference (GUI) and automatic optimization.

2.4.6.1.Graphical User Interface

Graphical user interface (GUI) helps to prepare data, calibrate a model, run a simulation and helps to visualize static and dynamic graphs of outputs. GUI is a necessary component in hydrological modelling for ease and efficiency of the model usage. Some hydrological models have advanced GUI where modelers can manage data, visualize every components and process of model and display output in graphical and tabular format. GUI of some models is not advanced enough to manage data and visualize outputs. On the other hand, source code of some models is written in FOTRAN and MATLAB and they do not have their own GUI. Most of such model operates on Geographic Resources Analysis Support System (GRASS) or ArcGIS. Hence, models with advanced GUI are highly preferred. Models with their own GUI but not advance enough to manage data and visualize outputs are moderately preferred and models which do not have their own GUI are given low preference.

2.4.6.2.Automatic Optimization

The development of automated (computer-based) calibration methods has focused mainly on the selection of objective measure of the variation between the model-simulated output and the observed data and the selection of an automatic optimization algorithm is to search for the parameter values which minimize that variation (Yapo, Gupta & Sorooshian,1998). Most of hydrological models have automatic, global and multi objective optimization functions whereas some models use third party software for optimization and some models do not have automatic optimization at all. Hence, the model with inbuilt automatic optimization function is highly preferred similarly, models which use third party software for optimization is moderately preferred and models which do not have automatic optimization at all are given low preference.

2.4.7. Model Acquisition Cost

2.4.7.1 Availability of the Model

On the basis of availability, hydrological models can be classified into public domain or freely available models, exclusive models and commercial models. Public domain models are available for free of charge, source are available with easy access. Whereas, exclusive models are not easily available but do not cost for model acquisition. An exclusive model needs authorizations or permission from the developer before use. Commercial models are developed for commercial usage and need to be purchased. Hence, models available in public domain is highly preferred, exclusive models are moderately preferred and commercial model are given less preference.

2.5. Criteria Evaluation for Model Selection

Seven criteria such as temporal scale, spatial scale, modelling process, documentation, resource requirement, and user interface and model acquisition cost and their respective factors were listed. Each of the factors is ranked into three classes: high preference, moderate preference and low preference. Modelling objective, expected accuracy of output, ease of use, availability of data was considered for assigning the class to each of the components of the factors. Furthermore, score is assigned to each of the class in the scale of 1-3. Highly preferred component is given the score of 3 and component with low preference is given score 1 whereas moderately preferred component is given score 2. Rank and score for a particular criteria and their respective factor are given in a tabular form in Table 2-2. Characteristic and feature of 5 (five) shortlisted model were reviewed in the Section 2-3. Feature of each models are assorted in the order of the classified factor. Each of the model features were ranked and provided the respective score. The commutative score of each of the shortlisted the models were calculated. Finally, models were ranked based on the cumulative score obtained. SWMM had cumulative score of 37 and hence, ranked highest as a most preferred model. Based on criteria, factors, ranks and scores given in Table 2-2 criteria evaluation was carried out. SWMM had cumulative score of 37 and hence, ranked highest as a most preferred model. Similarly, TOPMODEL had cumulative score 22 and ranked lowest as least preferred among the selected. Detail of criteria evaluation is given in Table 2-3

Table 2-2 Criteria, Factors, Ranks and Scores for the Selection of the Model

Criteria	Factors	Highly Preferred[3]	Moderately Preferred [2]	Low Preferred [1]
Temporal Scale	Event/Continuous	Both	Continuous	Event only
	Times steps	(Min/hours/day)	Hours/day	Day
Spatial Scale	Spatial representation	Semi-distributed	Distributed	Lumped
	Nature of watershed	Flexible	Rural	Urban
Modelling Process	Theory	Conceptual	Physics Based	Empirical
	Flow routing	Dynamic	Kinematic	Muskingum
	Process integration (Hydraulic/hydrologic)	Integrated	Semi-Integrated	Not integrated
Documentation	Availability of Reference Manual	User manual and Technical manual	User manual or Technical	Poor
Resources Requirement	Hydromet data Requirement	Station wise data	Aggregated data	Gridded data
	Physical data Requirement	Reasonable data demand	Moderate data demand	Intensive data demand
User Interface	GUI	Advance GUI	Moderate	No GUI
	Optimization	Automatic Optimization	Third party	Manual
Model Acquisition	Availability	Public Domain	Exclusive	Commercial

Table 2-3 Criteria Evaluation for the Selection of the Model

Evaluation Criteria	Factors	Models, Ranks and Scores				
		HEC HMS	SWAT	TOP	MIKE SHE	SWMM
Temporal Scale	Event/Continuous	Both Highly Preferred [3]	Both Highly Preferred [3]	Both Highly Preferred [3]	Both Highly preferred[3]	Both Highly Preferred [3]
	Simulation time	Flexible Highly Preferred [3]	Hours/day Moderately Preferred [2]	Hours/day Moderately Preferred [2]	Flexible Highly Preferred [3]	Flexible Highly Preferred [3]
Spatial Scale	Spatial representation	Semi-distributed Highly Preferred [3]	Semi distributed Highly Preferred [3]	Semi distributed Highly Preferred [3]	Distributed Moderately Preferred[2]	Semi distributed Highly Preferred [3]
	Nature of watershed	Rural/Urban HP [3]	Rural/Urban HP [3]	Rural/urban HP [3]	Rural MP [2]	Urban/Rural HP [3]
Process	Theory	Empirical LP [1]	Physics based MP 2]	Conceptual HP [2]	Physics based MP [2]	Conceptual HP [3]
	Flow Routing	Kinematic MP [2]	Muskingum LP [1]	Muskingum LP [1]	Stage discharge LP [1]	Dynamic HP [3]
	Process integration	Semi integrated MP [2]	Not Integrated LP [1]	Not Integrated LP [1]	Semi Integrated MP [2]	Fully Integrated HP [3]
Documentation	Reference Manual	User/Technical HP [3]	User/Technical HP [3]	None LP [1]	User/Technical HP [3]	User/Technical HP [3]

Evaluation Criteria	Factors	HEC HMS	SWAT	TOPMODEL	MIKE SHE	SWMM
Resource requirement	Hydro met data	Station wise data Highly Preferred [3]	Station wise data Highly Preferred [3]	Aggregated data Low Preferred [1]	Gridded data Moderately Preferred [2]	Station wise data Highly Preferred [3]
	Physical data	Reasonable data demand Highly Preferred [3]	Intensive data demand Low Preferred [1]	Moderate data demand Moderately Preferred [2]	Intensive data demand Low Preferred [1]	Reasonable data demand Highly Preferred [3]
User Interface	GUI	Advance GUI Highly Preferred [3]	Moderate GUI Moderately Preferred [2]	No GUI Low Preferred [1]	Advance GUI Highly Preferred [3]	Moderate GUI Moderately Preferred [2]
	Optimization	Inbuilt automatic optimization Highly Preferred [3]	Inbuilt automatic optimization Highly Preferred [3]	Manual optimization Low Preferred [1]	Inbuilt automatic optimization Highly Preferred [3]	Third party optimization Moderately Preferred [2]
Acquisition	Availability	Public domain Highly Preferred [3]	Public Domain Highly Preferred [3]	Public domain Highly Preferred [3]	Commercial Low Preferred [1]	Public domain Highly Preferred [3]
Cumulative SCORE		**35**	**28**	**22**	**26**	**37**

2.6. Storm Water Management Model (SWMM)

The criteria evaluation in section 2-5 showed that SWMM is highly preferred among the popular hydrological model. SWMM is a dynamic hydrology-hydraulic model which has been continually maintained and updated and is perhaps the best known and most widely used among the available urban runoff quantity/quality models (Huber & Roesner, 2012). Moynihan & Vasconcelos (2014) stated that the SWMM has proven to be highly effective for urban and suburban watersheds modeling since its conception. Although it was primarily developed for urban watershed modeling, its applications are not limited to it (Rossman & Huber, 2016). Although it is heavily preferred model for the simulation of urban and semi urban watersheds, its performance in rural/non-urban watersheds has been less assessed. Hence, it is important to ascertain the applicability of SWMM in rural watershed.

2.6.1. General Description

SWMM was first developed in 1971 and has undergone several major upgrades since then. It continuous to be widely used throughout the world for planning, analysis and design related stormwater runoff, combined sewers and other drainage system. (Rossman & Huber, 2016)

SWMM conceptualizes this system as a series of water and material flows between several major environmental compartments. These compartments include:

- The Atmosphere compartment, which generates precipitation and deposits pollutants onto the Land Surface compartment.
- The Land Surface compartment receives precipitation from the Atmosphere compartment in the form of rain. It sends outflow in the forms of (1) evaporation back to the Atmosphere compartment, (2) infiltration into the Sub-Surface compartment and (3) surface runoff on to the Conveyance compartment.
- The Sub-Surface compartment receives infiltration from the Land Surface compartment and transfers a portion of this inflow to the Conveyance compartment as groundwater interflow.

- The Conveyance compartment contains a network of elements (channels, pipes, pumps, and regulators) and storage/treatment units that convey water to outfalls or to treatment facilities. Inflows to this compartment can come from surface runoff, groundwater interflow or from user-defined time series.

The schematic of SWMM for generating total hydrograph is given in the figure 2-1.

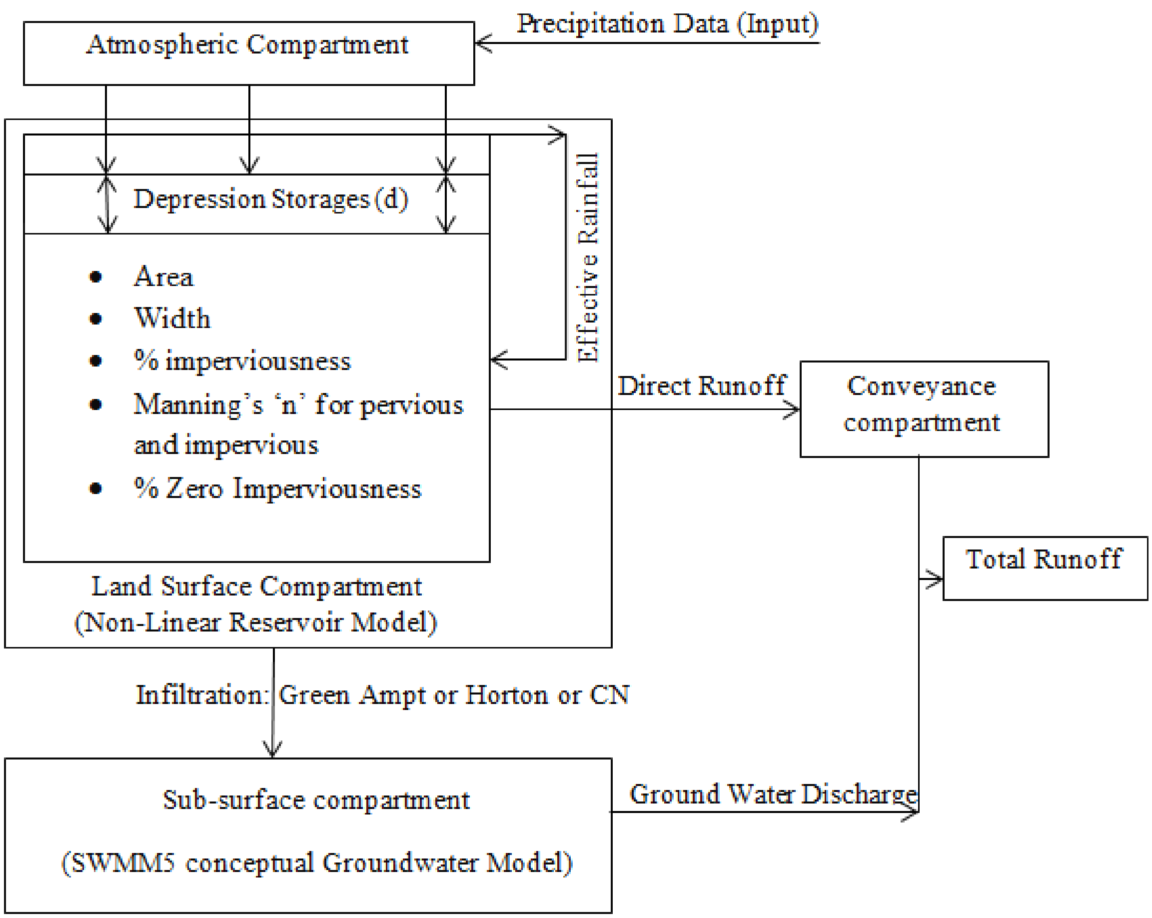

Figure 2-1 SWMM Schematic (Rossman & Huber, 2016).

2.7. Review on SWMM Parameters

In the SWMM model geometric characteristics of a basin is described by three parameters: area, slope and sub-basin width. The remaining parameters such as percentage of impervious areas, Manning's roughness coefficient, depression storage and the infiltration parameters are calibration parameters (Beling et al, 2011).

2.7.1. Depression Storages

Depression (retention) storage in SWMM is a volume is filled prior to the occurrence of runoff on both pervious and impervious areas. It represents a loss or "initial abstraction" caused by such phenomena as surface ponding, surface wetting, interception and evaporation. The depth of retention for a homogenous surface depends on its type, roughness and slope. In the case of runoff from an impervious surface of catchment, the depression storage often represents all hydrological losses including wetting losses and evaporation (Skotnicki & Sowiński, 2015). Pervious depression storage values are expected in the range of 0.1-0.3 inches and impervious depression storage is very less in comparison with pervious, it ranges from 0.03-0.04 inches. Optimum value for depression storage found by Warwick & Tadepalli (1991) are; 0.2 inches for pervious and 0.039 inches for imperious. Furthermore, Tsihrintzis & Hamid (1998a) had identified that impervious depression storage to be more sensitive to calibration than pervious depression storage. Default value for depression storage is recommended by several model manuals are within the range 0.6-2.5 mm. However actual value of depression storage for the watershed should be evaluated experimentally. In a study of influence of depression storage on runoff, Skotnicki & Sowiński (2015) concluded that influence of spatial distribution of depression storage in the watershed is insignificant.

2.7.2. Manning's Roughness Coefficients

In SWMM Manning's roughness coefficients represent the resistance to flood flows in channels and flood plains. Mwendera & Feyen (1992) stated that Manning's roughness coefficients are based on topographic parameters which may be considered hydrologically stable. Most important factors that affect the selection of channel 'n' values are the type and size of the materials that compose the bed and banks of a channel and the shape of a channel (Arcement & Scheider,1989). Similarly, Ramesh et al. (2000) stated that estimation of roughness coefficient depends upon several factors and they are surface roughness characteristics, vegetation cover and channel irregularities. However, Value of Manning's roughness coefficient for the same surface roughness may vary with flow depth (Mwendera & Feyen,1992). Rosa, Clausen & Dietz (2015) calibrated and validated SWMM model for LID and found that roughness coefficient one of the sensitive parameters. Akdogan & Guven (2016) while assessing sensitivity of SWMM to variation in hydrologic and hydraulic parameters also found manning's roughness coefficient as a highly sensitive parameter with an inverse correlation with model output. McCuen (2016) and Rossman & Huber (2016a) are general reference for the initial estimate of Manning's roughness coefficient in general. Manning's roughness values for different surfaces are commonly used for stormwater modelling are listed out SWMM's user manual (Beling et al., 2011).

2.7.3. Infiltration Parameters

SWMM allows the user to choose three of the most widely used infiltration methods. They are: Horton's method, the Green-Ampt method, and the Curve Number method. Green-Ampt method is a physically based model, Horton equation is semi-empirical and CN method is empirical model. In a study of comparison of model (S. K. Mishra, Tyagi, & Singh, 2003), found that the physical based model performs better than the others. Among the available model SCS-CN method cannot be used for continuous modelling purposes due to its inability to take account the moisture available in soil. Literature Summary on comparison of infiltration model is provided in the Table 2-4 and Table 2-5

Table 2-4 Literature summary of CN method

Models	Literature	References
Curve Number Method	CN method does not take account long term losses thus has been restricted to modelling storm losses.	(Kannan et al., 2008)
	CN method computes the direct runoff by considering only available rainfall on current day without taking account of the moisture available.	(Geetha et al., 2008)
	CN method was originally developed for lumped model and still being used for lumped model for storm event.	(Soulis & Valiantzas, 2012)
	Curve number method was not designed for use in non-event modelling, it was designed for single storm event and day-to-day analysis	(K. W. King, J. G. Arnold, & R. L. Bingner, 1999)

Table 2-5 Comparison of Horton's and Green Ampt Method

	Literature	References
Horton's and Green Ampt Model	There is advantage Green-Ampt over Horton's of using physically based parameter that can be determined a priori. Horton needs empirical data and requires special studies.	(Tsihrintzis & Hamid, 1998)
	Green-Ampt model were derived from physical principles governing equation while Horton's model is empirical in nature.	(Nishat, Guo & Baetz, 2007)
	The Green-Ampt and Philp formulas fit better than Horton formula in terms of infiltration rate curves. The Horton's parameter, exponential decay rate is very difficult for user to find, calculate or assume.	(Hsu, Ni & Hung, 2002)

Green-Ampt method for modelling of infiltration assumes that a sharp wetting front exists in the soil column, separating unsaturated soil from saturated soil below. Input parameters required are, initial moisture deficit of the soil (mm/mm), soil hydraulic conductivity K(mm/h), and suction head at the wetting front (S_u)mm. (Gironás, Roesner, Rossman & Davis, 2010). Rawls (1976) had classified the soil type 11 groups and listed the typical values of hydraulic conductivity(in/hour), suction head(in), porosity (fraction), Field capacity (Fraction), Wilting point (Fraction). SWMM user manual V. 5.1 provides recommendation for the selection of values.

2.8 Sensitivity Analysis

Sensitivity of model components and parameters is potentially useful in the formulation, calibration and verification of a hydrologic model. However, in the past, the use of sensitivity has been limited to the determination of an optimal set of model parameters (McCuen, 1973). Sensitivity analyses are conducted for various reasons. It helps to know which parameters require additional research for strengthening the knowledge base, thereby reducing output uncertainty, similarly which parameters are insignificant and can be eliminated from the final model and which inputs contribute most to output variability (Hamby, 1994). Lenhart et al. (2002), on their study had compared two different approaches for sensitivity analysis for hydrological model. In both approaches, one parameter was varied at a time while holding the others fixed, but the way of defining the range of variation was different. Similar, results were obtained suggesting that parameter sensitivity may be determined without the results being influenced by the chosen method. They had found soil physical properties and hydraulic conductivity as most sensitive parameter.

There are several approaches to perform model sensitivity analysis. According to Hamby,(1994), the most simplest analysis is the one-at-a-time method where sensitivity measures are determined by varying each parameter while all other are held constant. Zaghloul (1983) found that the most sensitive parameter in the runoff block of SWMM is the percentage imperviousness. Increase in percentage imperviousness tends to linearly increase the runoff peak and volume. Similarly, second important parameter was found as the width of overland flow for individual sub-catchments. In a study, Barco, Wong, & Stenstrom (2008) evaluating the impact of SWMM parameters on large urban catchments indicated that model output are most sensitive to imperviousness and impervious depression storage.

2.9. Model Calibration and Validation

Calibration is the process of adjusting parameters of the model to obtain optimal agreement between model output and observed data. On the other hand model validation involves running a model using input parameters measured or determined during calibration (Moriasi et al., 2007). The process of model calibration is normally done either manually or by using computer-based automatic procedures. In manual calibration, a trial-and error parameter adjustment is made. In this case, the goodness-of-fit of the calibrated model is basically based on a visual judgement by comparing the simulated and the observed hydrographs (Madsen, 2000).

General methodologies related to model calibration and validation has been subject to considerable discussion and dispute during the past decade. Refsgaard (1997) stated that much attention has been given to specific procedures for parameter assessment, calibration and validation of lumped models. But the very limited attention has given to the more complicated tasks in connection with distributed models, where problems related to validation of internal variables and multiple scales also have to be considered.

In a study of real time flood study carried out by Garrote & Bras (1995), trial and error process was followed during calibration.

2.10. Objective Function

Hydrologic simulation models are calibrated by comparing observed data with data generated by the models. The objective function is normally defined as a function of the difference between computed and observed data during the calibration period. Diskin & Simon (1977) stated that the choice of an objective function for any given model is a subjective decision which influences the values of the model parameters and the performance of the model. There is a definite link between the mathematical formulation of an objective function and the type of engineering application for which the model is used. Better results are obtained if the objective function is selected according to the engineering application (Diskin & Simon,1977). There are several objective function with different application in hydrological modelling among them objective functions listed on Guide for hydro-meteorological practices by World Meteorological Organization (WMO, 1975). They are Nash-Sutcliffe, Mean Absolute Error (MAE), Root Mean Square Error (RMSE), Mean Ratio of Absolute Error (MRAE), and Ratio of Absolute Error to mean (RAEM). Khandu (2017) reviewed six objective function stated Nash-Sutcliff efficiency is favorable for high flows and moderately favorable for intermediate flow, low flow and overall hydrograph. Similarly, RMSE is moderately favorable for high flows and overall hydrograph and not favorable for intermediate flows and low flows. Similarly, RAEM is not favorable for high flows and overall hydrograph but moderately favorable for intermediate flows and low flows. Similarly, MRAE is favorable for all flow regimes and overall hydrograph. Application of Nash-Sutcliff Efficiency is generally for flood forecasting and flood estimation modelling. Achleitner et al. (2012) used NSE for analyzing the operational performance of the hydrological models in an alpine flood forecasting system. Badrzadeh, Sarukkalige & Jayawardena (2015) applied NSE for hourly runoff forecasting for flood risk management. Similarly, for the prediction of peak flows in real time on a transboundary river watershed NSE was used as objective function (Shahid et al., 2016). On the other hand, MRAE had been the mostly used objective function for water resources modelling in Sri Lankan catchment. Wijeskerera & Musiake (1990), Wijesekera & Rajapakse, (2013), Thapa & Wijeskera (2017) and Jayadeera (2017) used MRAE for water resources modelling in Sri Lankan catchments. Although, RAEM is mentioned on WMO, 1975 there had been no literature cited on it. Jayadevan (2017) used it as a secondary objection for water resources modelling on Kalu river basin.

2.10.1. Nash-Sutcliffe Efficiency (NSE)

The Nash-Sutcliffe Efficiency is a normalized statistic that determines the relative magnitude of the residual variance compared to the measured data variance (Nash & Sutcliffe, 1970).

$$NSE = 1 - [\frac{\sum_{i=1}^{n}(Qobs - Qcal)^2}{\sum_{i=1}^{n}(Qobs - Qmean)^2}]$$

Where, Qobs: Observed Discharge; Qcal: Simulated Discharge; Qmin: mean discharge

Krause, Boyle, & Bäse (2005) stated that the largest drawback of the Nash-Sutcliffe efficiency is the differences between the observed and simulated values are calculated as squared values. As a result, larger values in a time series would be overestimated whereas lower values would get neglected. While quantifying the runoff, NSE leads to an underestimation during low flow conditions. Moriasi et al. (2007) stated that Nash-Sutcliffe efficiency (NSE) as the best objective function to reflect the peak flow matching on a hydrograph. Nash-Sutcliffe efficiency is the widely used objective function for flood modelling. (Example: Komi et al,2017; Skhakhfa & Ouerdachi, 2016; Monte et al, 2016; Chen et al, 2017) but it is not preferred objective function on modelling for water resources management purposes.

2.10.2. Root Mean Square Error (RMSE)

Root-mean-square error (RMSE) is a frequently used measure of the differences between values predicted by a model and the values actually observed. Root mean square error is the standard deviation of residual or prediction error (i.e. observed–Simulated)

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(Qobs, i - Qcal, i)^2}{n}}$$

Where, Qobs: Observed Discharge; Qcal: Simulated Discharge; n: is the number of observations used for comparison.

RMSE has been used widely for low flow modelling. For Examples: Nicolle et al., (2014) used RMSE as objective function for benchmarking hydrological models for low-flow simulation and forecasting on French catchments. Similarly, Demirel et al. (2009) used RMSE as objective function for appropriate low flow forecast for the Meuse River.

Li, (2017) stated that RMSE is commonly used measures for assessing the predictive accuracy however it is unit/scale dependent and moreover the accuracy can bot be ascertained.

2.10.3. Ratio of Absolute Error to Mean (RAEM)

Among the several objective function recommended by World Meteorological Organization (WMO,1975) Ratio of Absolute Error to Mean (RAEM) is as given below:

$$\text{RAEM} = \frac{1}{\text{n}}\frac{\sum|\text{Qobs} - \text{Qcal}|}{(\text{Qobs})\text{mean}}$$

Where, Qobs: Observed Discharge, Qcal: Simulated Discharge, $(\text{Qobs})_{\text{mean}}$: Mean of observed discharges.

Jayadeera (2017) in a study of developing mathematical model in Kalu river basin had used RAEM as secondary objective function. Jayadeera (2017) stated that RAEM indicates the ratio between observed and calculated discharge with respect to the mean of observed discharges. It depends on the characteristics of the observed flow series. When there are big and small peaks, the error values may not enable easy comparison and mean of observed flow does not reflect the real mean value of the flow series. Therefore, RAEM is not preferred objective function for water resources assessments.

2.6.4. Mean Ratio of Absolute Error (MRAE)

Mean Ratio of Absolute Error (MRAE) is the difference between calculated and observed flow with respect to that particular observation and it is defined as,

$$\text{MRAE} = \frac{1}{n}\sum\frac{|\text{Qobs}-\text{Qcal}|}{\text{Qobs}}$$

Where, Qobs is the observed streamflow

Qcal is the calculated streamflow &

n is the number of observations used for comparison.

Best fit between observed and calculated values would have a zero value of MRAE.

Wijesekera & Musiake (1990) had used MRAE as the objective function for the streamflow modelling of Mahaweli Ganga of Sri Lanka. Later number of successful uses (especially in the tropical watershed of Sri Lanka) of MRAE has been reported. (Examples: Wijesekera & Rajapakse, 2013; Wanniarachchi, 2013; Thapa &

Wijesekera, 2017). Since, this objective function compares the errors with respect to each observed flow, it gives better representation when contrasting data are present in the observed data set. It provides the information about the predicting capability as well as the distribution of the prediction errors of the model (Jayadeera, 2017).

Table 2-6 Merits and Demerits of the Selected Objective Function

Objective function	Merits	Demerits	Application
NSE	Sensitive to flow magnitude; highly used flood modelling (Moriasi et al., 2007)	Larger values in a time series would be overestimated whereas lower values would get neglected	Flood modelling (Komi et al., 2017), (Monte et al., 2016), (Chen et al., 2017)
RMSE	Measures uncertainty in prediction (Kavuncuoglu et al., 2018)	Cannot tell how accurate the models are (Li, 2017) It emphasizes greater errors than the small ones	Drought modelling (Demirel et al., 2009) (Nicolle et al., 2014)
RAEM	Gives error relative to the mean of observed data	When there are big and small peaks, the error values may not enable for easy comparison and mean of observed flow does not reflect the real mean value of the flow series.	Application of RAEM is negligible in literature
MRAE	Gives better representation when contrasting data are present in the observed data set. .	It cannot be used if there is zero in observed values because there would be a division by zero (Hwang, Ham, & Kim, 2012).	Water resources modelling (Wijesekera & Musiake, 1990) (Wijesekera & Rajapakse, 2013)

2.11. Criteria for the Selection of Objective Function

Objective functions were compared under three criteria: Mathematical implication, flow regime and modeling purposes.

2.11.1. Mathematical Implication

2.11.1.1. Error and Variance

Objective functions are classified as Scale dependent measures (SDM), Measures based on relative errors (MBR) and Relative measures (RM) (Hwang, Ham & Kim, 2012). Scale-dependent measures (SDM) can provide a good measure of model performance, but significant variations in the assessment of different data sets will occur, since the evaluation measure is dependent on the scale of the data set being analyzed. Measures based on relative errors (MBR) are scale-independent, and are therefore frequently used to compare forecast performance across different data sets and less sensitive to the larger errors that usually occur at higher magnitudes. Relative measures (RM), larger values in a time series are strongly overestimated, whereas lower values are neglected. Therefore, MBR is highly preferred highly preferred, SDM is moderate preferred and RM is given low preference**.**

2.11.2. Flow Regimes

2.11.2.1. Intermediate Flows

Hydrological flow is classified into low, intermediate and high. Risley et al. (2009) classified 5th and 10th percent exceedances as high flow, considers the 95th percent exceedance as low flows. Wijesekera (2018) states that high streamflow lead to floods while low flows are considered essential for the sustenance of riverine environment. Intermediate flows are the most important when planning infrastructure to harness water as a resource. Therefore, in case of water resource assessments objective functions favorable for intermediate flows are highly preferred. Similarly, objective function low flows are moderately preferred and objective function only for high flows are less preferred.

2.11.3. Modelling Purpose

2.11.3.1. Water Resources Modelling

Objective functions which are favorable for flood modelling, drought modelling and water resources are listed out. Objective functions which are favorable for water resources modelling are highly preferred. Objective functions favorable for drought modelling and moderately favorable for water resources modelling are moderately preferred. Objective function only favorable for flood modelling is objective function is low preferred.

2.12. Criteria Evaluation for the Selection Objective Function

Criteria for the selection of the objective functions were determined. Three criteria namely mathematical implication, Flow regime and modelling purpose and their respective factors were listed. Each of the components of the factors is ranked into three classes: high preference, moderate preference and low preference. Characteristic and feature of four shortlisted objective functions were reviewed in the Section 2-10. Each of the factors of objective functions was ranked in the scale of 1-3. Finally, cumulative score of the objective functions were calculated. It found that MRAE is most suitable objective function for water resources modelling.

Table 2-7 Criteria, Factors, Ranks and Scores for the Selection of Objective Function

Criteria	Factors	Rank and Score		
		Highly preferred [3]	Moderately Preferred [3]	Low preferred[3]
Mathematical Implication	Error and variance	Relative error	Standard Error	Normalized Variance
Flow Regime	HML flow	Good for intermediate flows	Good for low flows and moderately good for intermediate flows	Good for high flows (only)
	Overall hydrograph	Favorable for overall hydrograph	Moderate for overall hydrograph	Not favorable for overall hydrograph
Modelling Purpose	Water resources modelling	Water resources modelling	Water resources an drought modelling	Flood modelling

Table 2-8 Criteria Evaluation for the Selection of Objective Function

Criteria	Factors	NSE	RMSE	RAEM	MRAE
Mathematical Implication	Error and variance	RM	SDM	MBR	MBR
		Low [1]	Medium [2]	High [3]	High [3]
Flow Regime	HML flows	High flows	Low flows	Intermediate flows	Intermediate flows
		Low [1]	Medium [2]	High [3]	High [3]
	Overall hydrograph	Moderate	Not favorable	Moderate	Favorable
		Medium [2]	Low [1]	Medium [2]	High [3]
Modelling Purpose	Water resources modelling	Flood modelling	Drought modelling	No application	Water resources modelling
		Low [1]	Medium [2]	N/A	High [3]
Score		**5**	**7**	**8**	**12**

Table 2-7 shows criteria, factors, ranks and scores for the selection of objective function. Based on the determined rank and scores for each criterion, a criteria evaluation was performed. Criteria evaluation for the selection of the objective function is given in Table 2-8. MRAE which is good for intermediate flows match and had been mostly used for water resources modelling in rural watershed of Sri Lanka was found highly preferred objective function.

3. METHODOLOGY

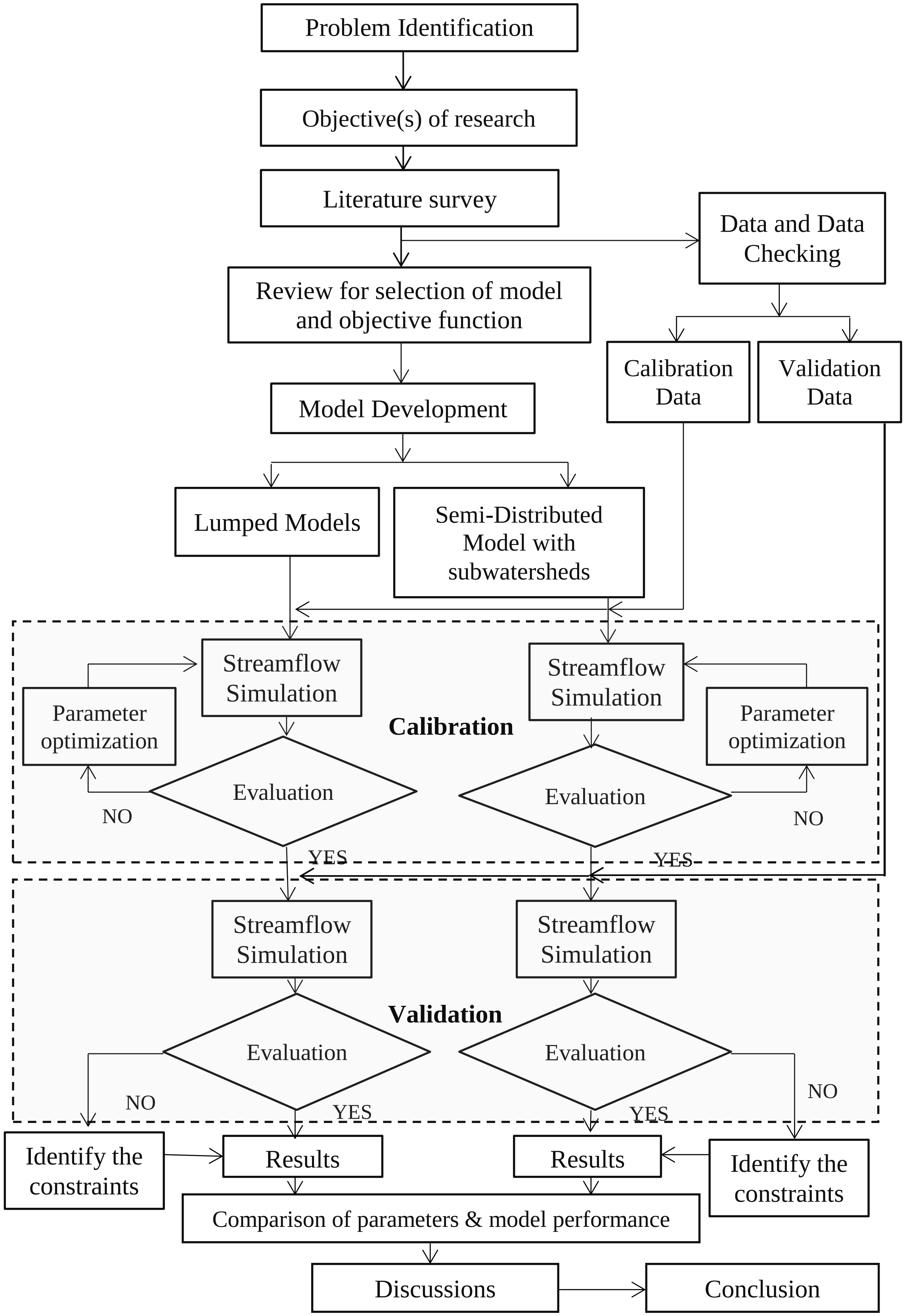

Figure 3-1 Methodology flowchart

This study started with identification of problem on hydrological modelling for water resources management in rural watersheds. After identifying the problem, objectives of the research were listed and literature review was carried out to select a model and objective function. Then, model development process was started. Two lumped models (Ratnapura and Ellagawa) and a semi-distributed model (Ellagawa) were developed. On the other side, streamflow and rainfall data from 2006-2014 was collected. Four year data from October 2006 to September 2007 were used for model calibration and the balance four year data from October 2010 to September 2014 were used for model validation. After inputting calibration data on developed models, simulation runs was started. Models performance was evaluated objectively with Mean Ration of Absolute Error (MRAE) for overall hydrograph. Similarly, MRAE for High, Medium low flow, Annual water balance error were check for the observation. Parameters are optimized until the performance of model becomes satisfactory. Once the models are calibrated, validations of the models were carried out. Validation data set (October 2010 to September 2014) was feed on to the model. Parameters are not supposed to alter at the time of validation. Hence, if the model performance comes satisfactory then model is said to be successfully validated else, the constraint on data and model were identified and preceded further. Finally, the calibration and validation results of both lumped models and distributed models were compared. The improvements on model performance after shifting the scale of the watershed on model were noted. Physical and calibration parameters of the model were compared and parameter ranges are recommended. The merits and demerits of selected model, objective function and scale of watersheds were discussed and recommendations were made for modelers and planners for water resources management in rural watersheds.

4. DATA AND DATA CHECKING

4.1. Study Area

The Kalu River originates in the central hills of Sri Lanka flows through Ratnapura and Horana and empties into the Indian Ocean at Kalutara with a total length of about 129 km and watershed area of 2,690 km^2. The river basin lies entirely within the wet zone of the country and average annual rainfall in the basin is 4,040 mm with ranging from 6,000 mm in mountainous areas and 2,000 mm in the low plain.

Ellagawa Watershed with spatial extent of 1342 km^2 is a sub-basin (upstream watershed of Kalu Ganga) which covers 48% area of the Kalu river basin.

Four (4) rainfall stations namely Ratnapura, Alupola, Pelmadula and Nivithigala are located within the study area whereas a station Halwathura is situated outside the boundary of the catchment. The river flowing within the watershed is gauged with two river gauging station namely Ratnapura and Ellagawa.

The geographical location of the rainfall stations and river gauging station are given in Table 4-1 and Table 4-2.

Table 4-1 Coordinates of Rainfall Stations

Rainfall Station	Location	
	Longitude (DMS)	Latitude (DMS)
Halwathura	80^0 21 36’’ E	6^0 48’ 0’’ N
Ratnapura	80^0 24’ 0’’ E	6^0 5’ 30’’ N
Alupola	80^0 34’ 48’’ E	6^0 43’ 12’’ N
Pelmadula	80^0 31’ 48’’ E	6^0 37’ 12’’ N
Nivithigala	80^0 15’ 36’’ E	6^0 21’ 36’’ N

Table 4-2 Coordinates of Streamflow gauging Stations

River Gauging Station	Location	
	Longitude (DMS)	Latitude (DMS)
Ratnapura	80^0 27’ 10’’E	6^0 37’ 20’’ N
Ellagawa	80^0 13’ 0’’ E	6^0 43’ 53’’ N

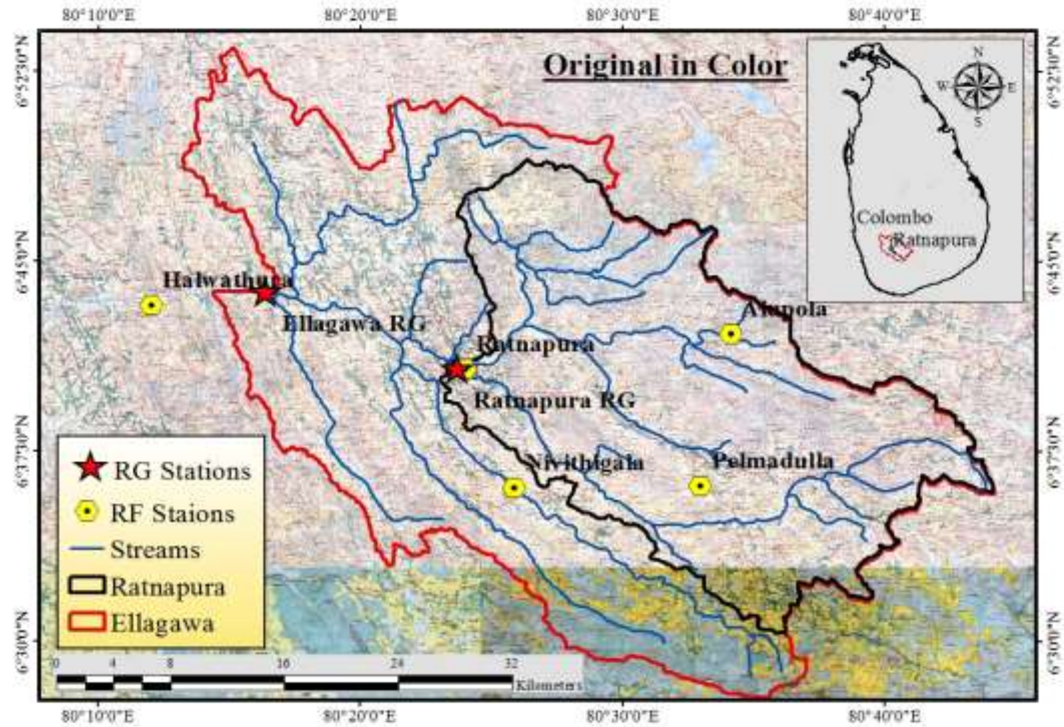

Figure 4-1 Study Area in Topographical Map

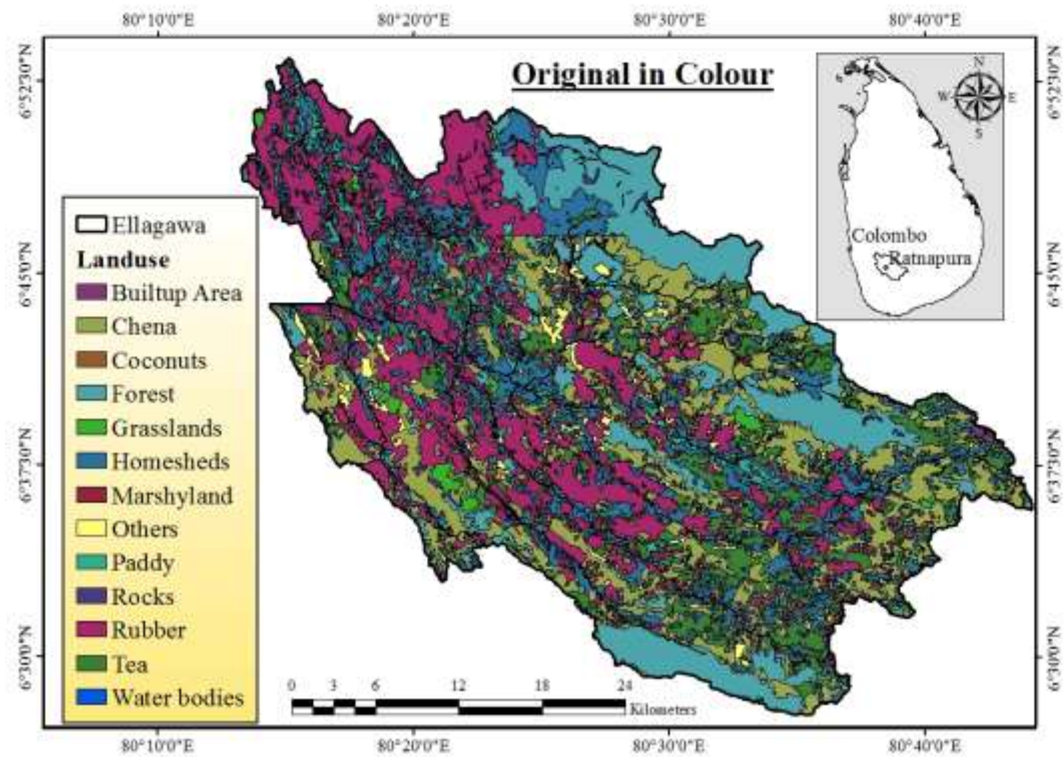

Figure 4-2 Landuse Map of Ellagawa Watershed

Table 4-3 Landuse Coverage on Ellagawa Watershed

S.N	Landuse	Area (km^2)	Percentage (%)	Landuse Cluster	Cluster Areas (km^2)	Cluster Percentage (%)
1	Rocks	250.23	1.86	Non-permeable areas	263.22	1.96
2	Buildup area	12.99	0.10			
3	Homestead	2398.71	17.87	Semi-permeable areas	2398.71	17.87
4	Chena	2861.40	21.32	Cultivation areas	5010.96	37.33
5	Paddy	925.89	6.90			
6	Tea	1223.66	9.12			
7	Grassland	15.18	0.11	Grasslands	15.18	0.11
8	Forest	2124.10	15.83	Woods	5290.87	39.42
9	Coconuts	32.59	0.24			
10	Rubber	3134.17	23.35			
11	Water Bodies	178.56	1.33	Water Bodies	180.79	1.35
12	Marshy Land	2.22	0.02			
13	Others	262.70	1.96	Others	262.70	1.96

Figure 4-1 shows the study area in topographical and Figure 4-2 shows the landuse coverage of the Ellagawa watershed. Landuse pattern gives a tentative idea and rough estimate of the runoff over the watershed. In general practice it is believed that more the buildup areas or non-permeable surface then lesser are the infiltration and higher becomes the surface runoff. The non-permeable and semi-permeable area altogether covers around 20% of Ellagawa watershed. On the other hand, the watershed extent has a high percentage of cultivation and forest area coverage 37% and 39% respectively. Therefore, Ellagawa watershed can be considered as a general case of rural/non-urban watershed.

4.2. Data Collection Summary

Continuous rainfall-runoff modelling needs long term time series of precipitation and discharge. Eight (8) years daily data time series (October 2006-September 14) of rainfall and streamflow was collected. The sources of these data are Department of Meteorology and Department of Irrigation. In addition topographic map of 1:50000 spatial resolution, contours of 1:10000 spatial resolutions and landuse map of 1:50000 resolutions were collected from Department of survey. The collected data types, spatial and temporal resolutions and sources are presented in Table 4-4 below.

Table 4-4 Data Summary

Data Type	Temporal Resolution	Data Period	Data Source
Rainfall	Daily	October 2006 to September 2014	Department of Meteorology/ Department of Irrigation
Streamflow	Daily		Department of Irrigation,
Evaporation	Month		Department of Irrigation
Topographic	1:50000		Department of Survey
Contours	1:10000		Department of Survey
Land Use	1:50000		Department of Survey

4.3. Data Screening

Initial step on any hydrological analysis is to check the consistency and homogeneity of the collected data. By consistency it means whether the record at a station maintains the same relationship over time to the other stations in the basin. Station consistency is checked by using a double mass analysis. In this technique the data for each station is plotted against the average of the data for a group of other stations. Station homogeneity is checked by using single mass analysis. In this technique year wise cumulative data series of all stations are plotted in a graph and compared.

The mass curve analysis for all the available stations showed data were consistent and homogeneous. Single mass curve of all the stations is given in Appendix A in Figure A-1 and Double mass curve of all the stations are given in Appendix A from Figure A-2 to Figure A-6.

4.4. Annual Water Balance

Table 4-5 Variation of Annual Rainfall and Streamflow on Ellagawa Watershed

Year	Annual Streamflow (mm)	Annual Rainfall(mm)	Annual Losses (mm)	Annual Runoff Coefficients
2006/2007	1425.6	2745.6	1320	0.51
2007/2008	2130.2	2824.0	694	**0.75**
2008/2009	1434.6	2872.9	1438	0.49
2009/2010	1658.1	3352.9	1694	0.49
2010/2011	1810.1	3203.4	1393	0.56
2011/2012	764	2682.8	1918	**0.28**
2012/2013	1801	4048.4	2247	0.44
2013/2014	1383	3422.9	2039	0.40

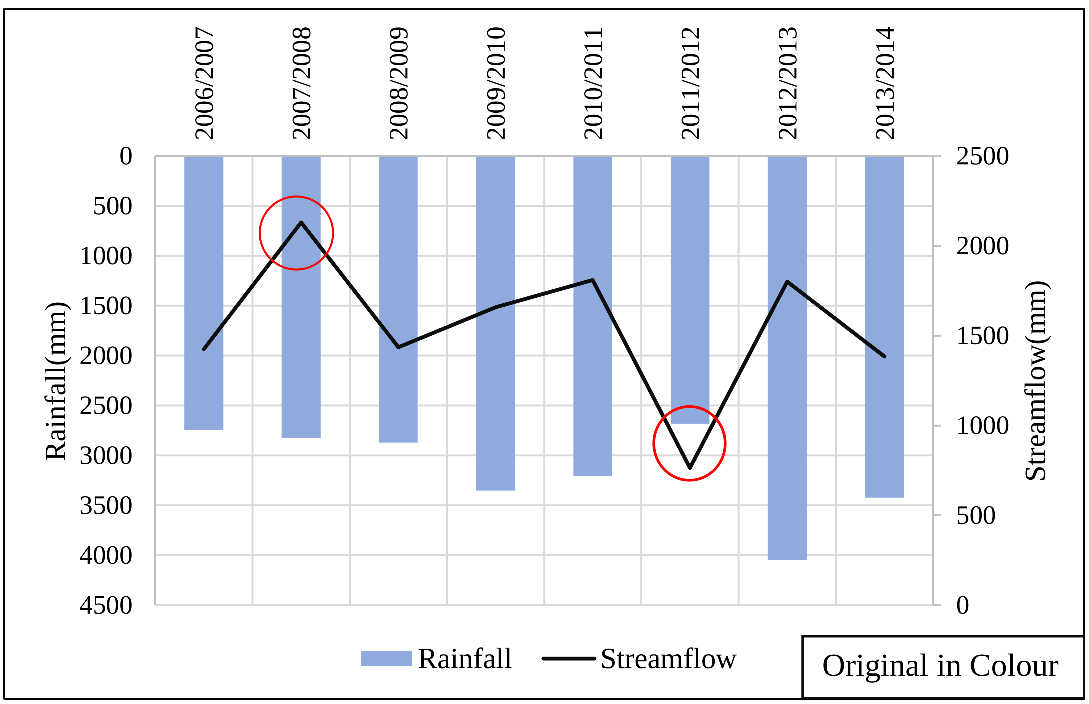

Figure 4-3 Annual Rainfall vs Observed Annual Streamflow on Ellagawa Watershed

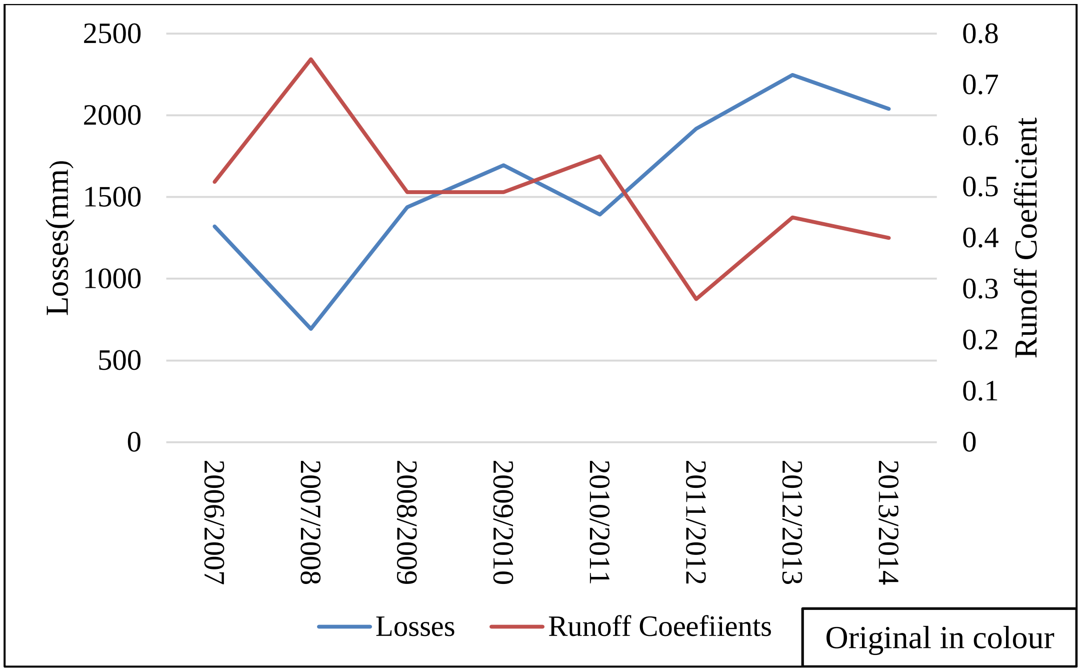

Figure 4-4 Variation of Annual Losses and Runoff on Ellagawa Watershed

Annual water balance of Ellagawa watershed is performed inorder to check error in the data. Annual water balance gives broader picture of data error or points a year where there can be error in the data. If streamflow in the particular year does not correspond to the rainfall or if there is significantly unreasonable losses or runoff coefficient then there could be some error in the data. The identified year should be noted and further checked with seasonal water balance, monthly water balance and daily plots.

Table 4-5 and Figures 4-3 and Figure 4-4 showed that runoff coefficients are varying from 0.28 to 0.75. The lowest value of runoff coefficient is in 2011/2012 and highest is in 2007/2008. The highest losses are seen in the year 2012/2013. Considering all the rainfall, runoff coefficients and the losses value it can be concluded that streamflows trend in the year 2007/2008 is unusual compared to others. 2007/2008 year has runoff coefficient of 0.75, which is much higher runoff value for rural/non-urban watershed similarly, 2011/2012 has runoff coefficient 0.28 while 72% of rainfall are accounted on losses this again gives unusual signal and room to doubt. Hence, the year 2007/2008 and 2011/2012 are the years for further scrutiny.

Table 4-6 Variation of Annual Rainfall and Streamflow at Ratnapura Watershed

Year	Annual Streamflow(mm/year)	Annual Rainfall(mm/year)	Annual Losses (mm)	Runoff Coefficient
2006/2007	1585.28	2612.87	1027.59	0.61
2007/2008	1960.88	3019.77	1058.89	0.65
2008/2009	1434.59	2768.15	1333.56	0.52
2009/2010	1668.85	3190.98	1522.13	0.52
2010/2011	1802.96	3199.89	1396.93	0.56
2011/2012	845.31	2265.80	1420.49	**0.37**
2012/2013	1909.66	3628.78	1719.12	0.53
2013/2014	1275.25	3222.88	1947.63	**0.40**

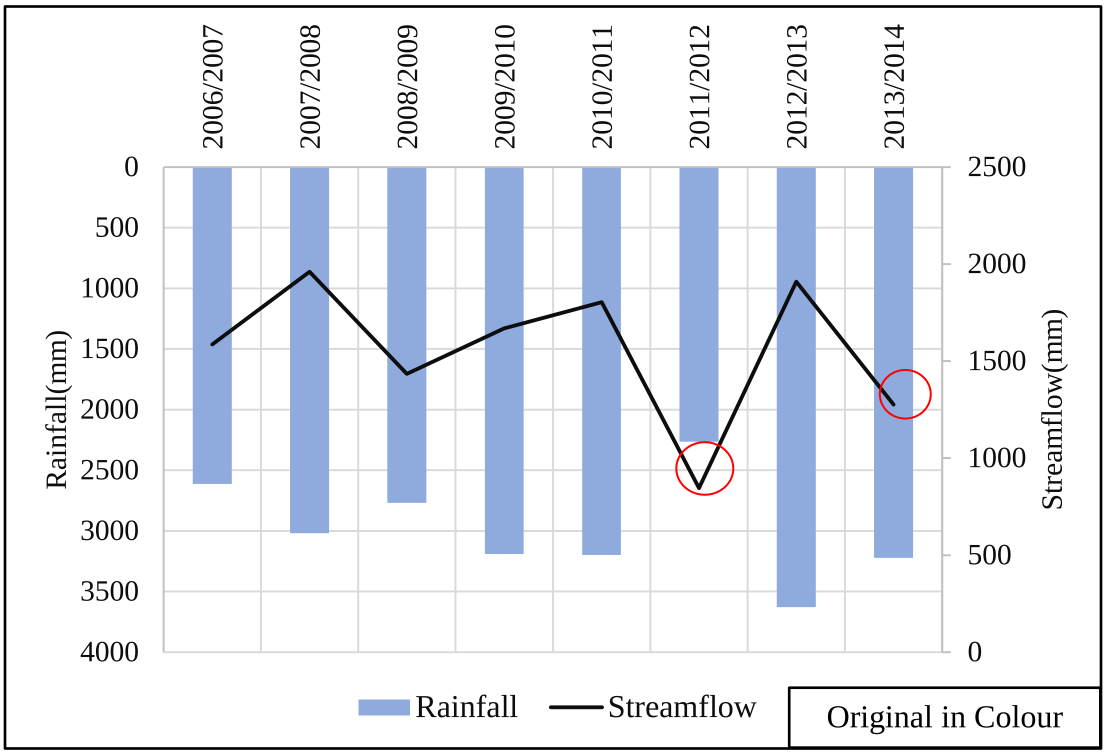

Figure 4-5 Variation of Annual Rainfall and Streamflow on Ratnapura Watershed

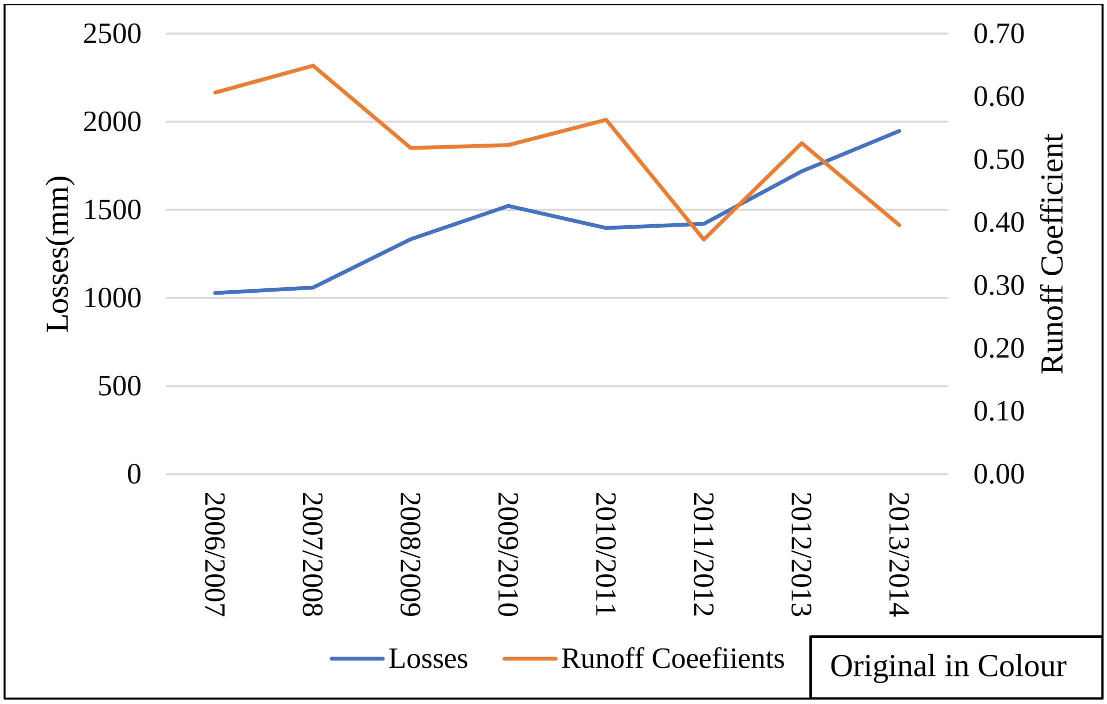

Figure 4-6 Variation of Annual Losses and Runoff at Ratnapura Watershed

Table 4-6 summarizes variation of Annual Rainfall and Streamflow at Ratnapura watershed. Figure 4-5 shows the annual variation of rainfall, streamflow and Figure 4-6 shows the losses and runoff coefficient respectively. Similarly, 2011/2012 is the driest year in Ratnapura watershed as well. Streamflow responses to rainfall are very poor resulting very less streamflow volume with a low runoff coefficient. 2012/2013 and 2013/2014 are marked by high rainfall years, but the losses in 2013/2014 is very high followed by lower value of runoff coefficient as compared to 2012/2013 . This again shows the non-responsiveness of streamflow to rainfall during these years. Therefore, years 2011/2012 and 2013/2014 are noted as the years with probable data errors.

4.5. Streamflow Response to Rainfall (Seasonal)

Table 4-7 Streamflow corresponding to Seasonal Rainfall (2006-2014)

No.	Years	Streamflow at Ellagawa (mm)		Streamflow at Ratnapura (mm)		Arithmetic Mean of Rainfall (mm)	
		Maha	Yala	Maha	Yala	Maha	Yala
1	2006-2007	744.8	680.7	780.3	804.9	1196.2	1425.3
2	2007-2008	545	1591	751.6	1209.2	920.6	1595.6
3	2008-2009	454.7	979.8	538.8	1121.4	1091.2	1781.6
4	2009-2010	468.9	1189.1	584.1	1084.7	1142	2210.8
5	2010-2011	829.5	980.5	919.5	883.3	1505	1698.3
6	2011-2012	316	447.9	405.3	439.9	1218.5	1464.2
7	2012-2013	755.6	1045.3	819.4	1090.2	2060.6	1987.8
8	2013-2014	416.3	966.6	468.2	806.9	1271	2151.8

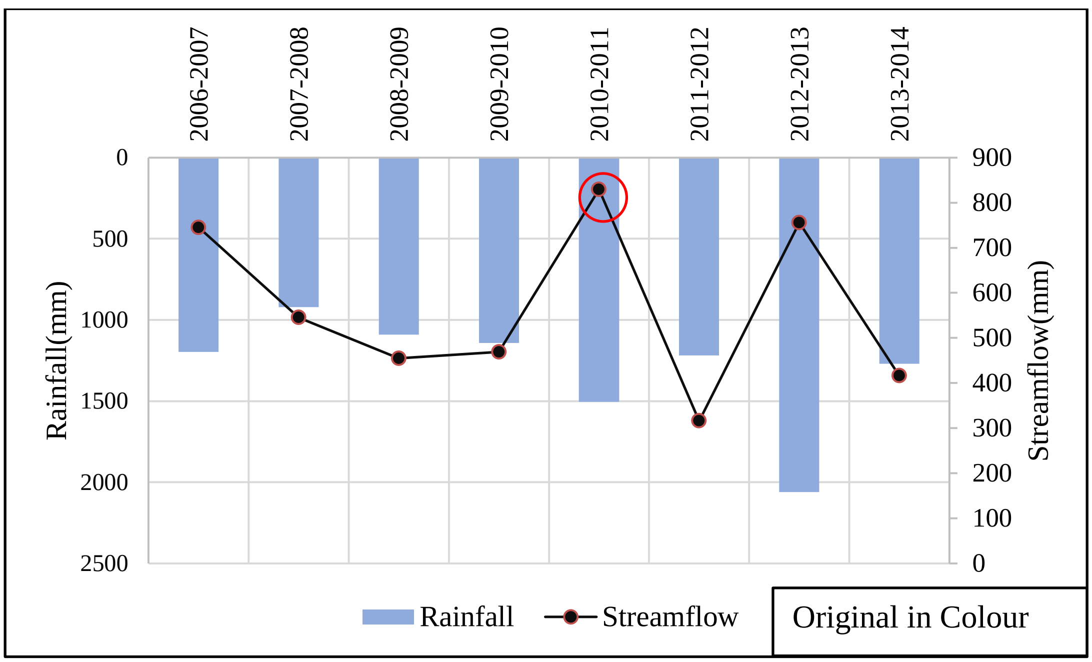

Figure 4-7 Streamflow at Ellagawa corresponding to Maha Season (2006-2014)

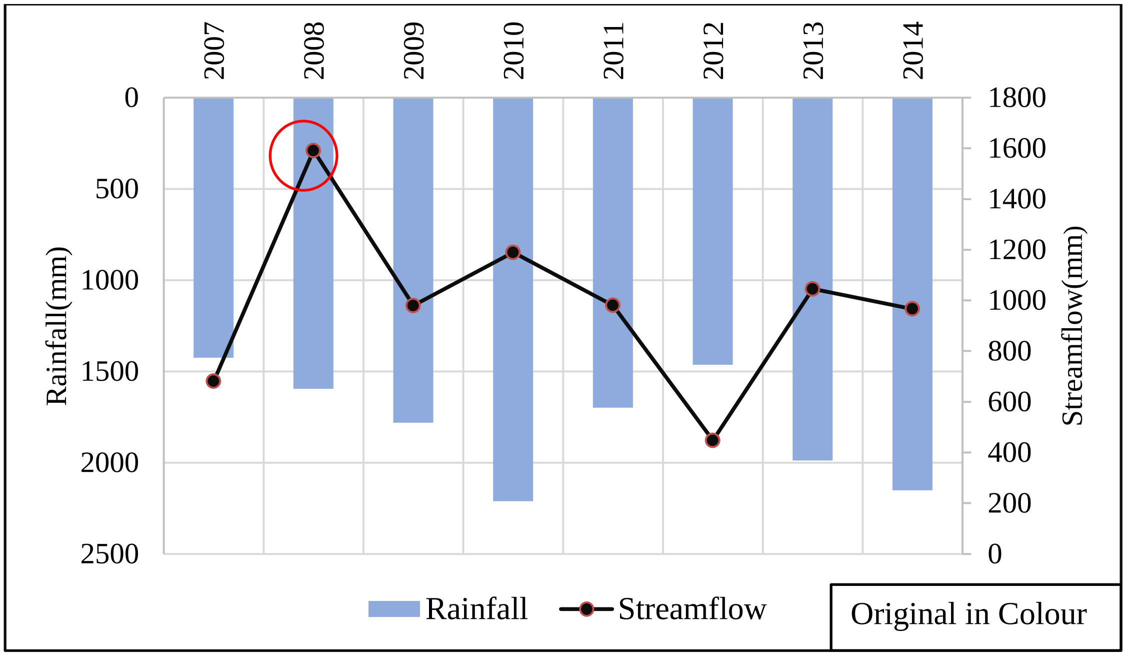

Figure 4-8 Streamflow at Ellagawa corresponding to Yala Season (2006-2014)

Table 4-7 and Figure 4-7, Figure 4-8 are the graphical representation of seasonal variation of rainfall and streamflow. Sri Lanka basically experiences two rainy seasons, the Maha (Oct.-March) season is marked by heavy rain and incidences of floods. Comparatively the Yala season (April-Sept.) is marked by prolong period of dry days and experiences water shortages. Streamflow corresponding to rainfall in both seasons are plotted in figure 6 and 7 respectively.

As per the pattern of the plot, in the year 2008 of Yala season has some usual trend. The rise of streamflow is sharp as compared to rainfall. Similarly, when Maha season of 2010-2011, and 2012-2013 are compared then it can be noted that rainfall and streamflow patterns is not corresponding to each other. Maha of 2012-2013 has high rainfall than Maha of 2010-2011 but in response streamflow pattern is reverse. Therefore, April 2008-Sept of 2008 and Oct 2010-March 2011 similarly Oct 2012-March 2013 are noted as data error periods.

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4.6. Streamflow Response to Rainfall (Monthly)

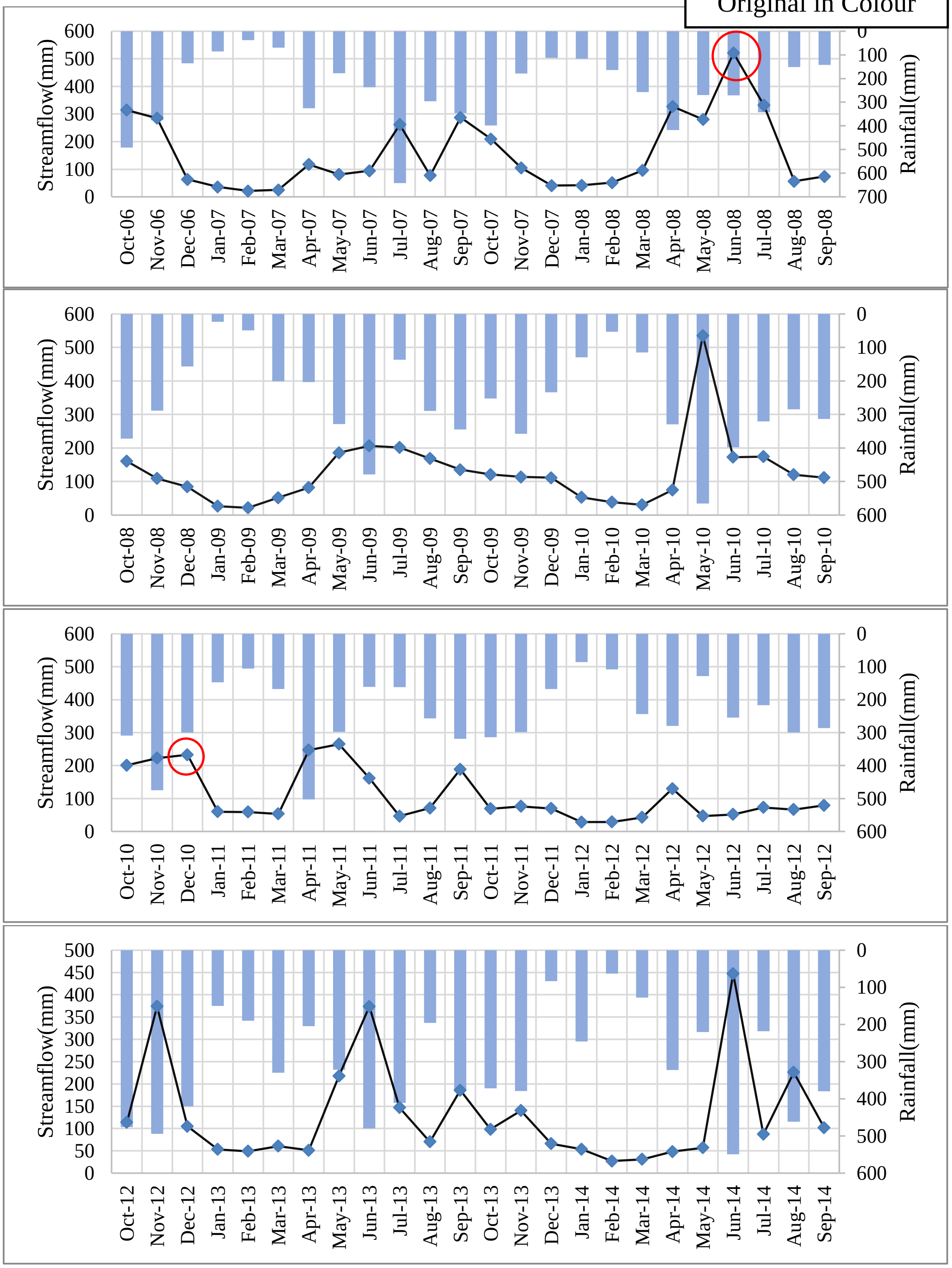

Figure 4-9 Ellagawa Monthly Rainfall in Response to Streamflow (2006-20014)

Figure 4-9 is the monthly streamflow in response to monthly rainfall for Ellagawa watershed. As per identified years, 2008 Maha and 2010-2012 Yala of seasonal plot of rainfall and streamflow, the monthly graphs were drawn. When the identified seasons of the year were further scrutinized on a monthly basis, June of 2008 and Dec of 2010 were identified to be with some unusual pattern. 2007/2008 and 2011/2012 were the years for scrutinisation as annual rainfall and annual streamflow fails to correspond to each other. Daily graphs of streamflow and rainfall shows there some irresponsiveness of streamflow in date 07-Jan, 21-Jan, 26-May, and 28-April of 2008 for Ratnapura, Alupola and Nivithigala stations. Detail check revealed that the streamflow peaks without rainfall pulses may due to contribution of upstream. The Ellagawa watershed is responsive to Ratnapura catchment. The detail daily streamflow and rainfall variation are shown in Figure B1, Figure B2, Figure B3 and Figure B4 of Appendix B.

Below in Figure 4-10 and Figure 4-11 the thiessen polygon of Ellagawa and Ratnapura watershed is shown and Table 4-8 and Table 4-9 shows the theissen weightage of rainfall stations of Ellagawa and Ratnapura watersheds.

4.7.Thiessen Average Rainfall

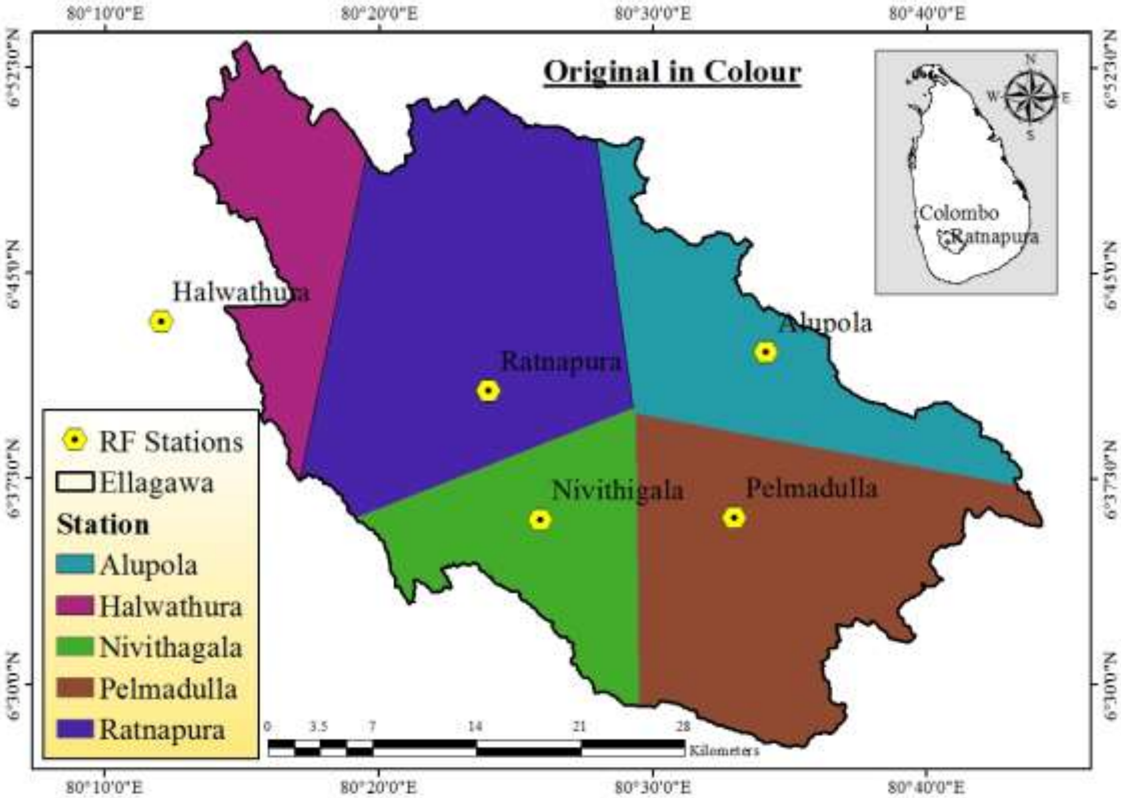

Figure 4-10 Thiessen Polygons on Ellagawa Watershed

Table 4-8 Thiessen Weight for Rainfall Station for Ellagawa watershed

S. N	Station	Thiessen Area (km^2)	Thiessen Weight
1	Halwathura	159	0.12
2	Nivithigala	183	0.14
3	Alupola	220	0.16
4	Pelmadula	347	0.26
5	Ratnapura	435	0.32

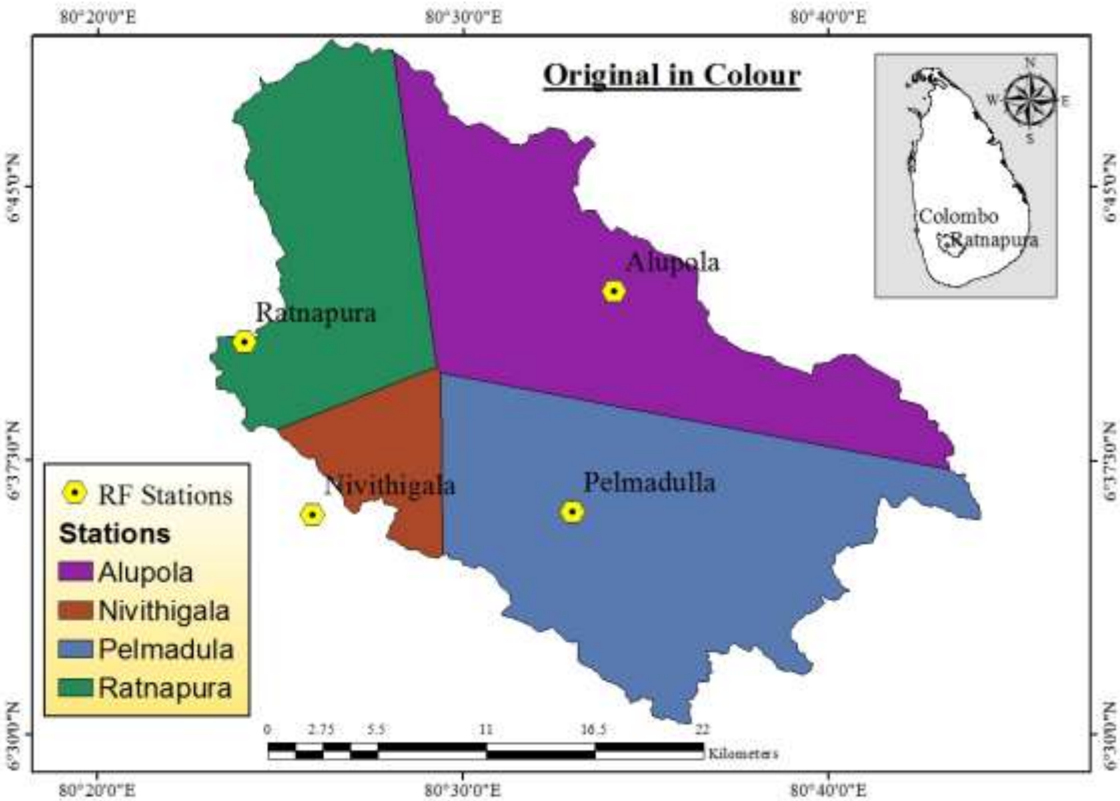

Figure 4-11 Thiessen Polygon on Ratnapura Watershed

Table 4-9.Theissen Weight of Rainfall for Ratnapura Stations

S.N.	Station	Thiessen Area (km^2)	Thiessen Weight
1	Nivithigala	44	0.07
2	Ratnapura	143	0.22
3	Alupola	211	0.32
4	Pelmadula	255	0.39

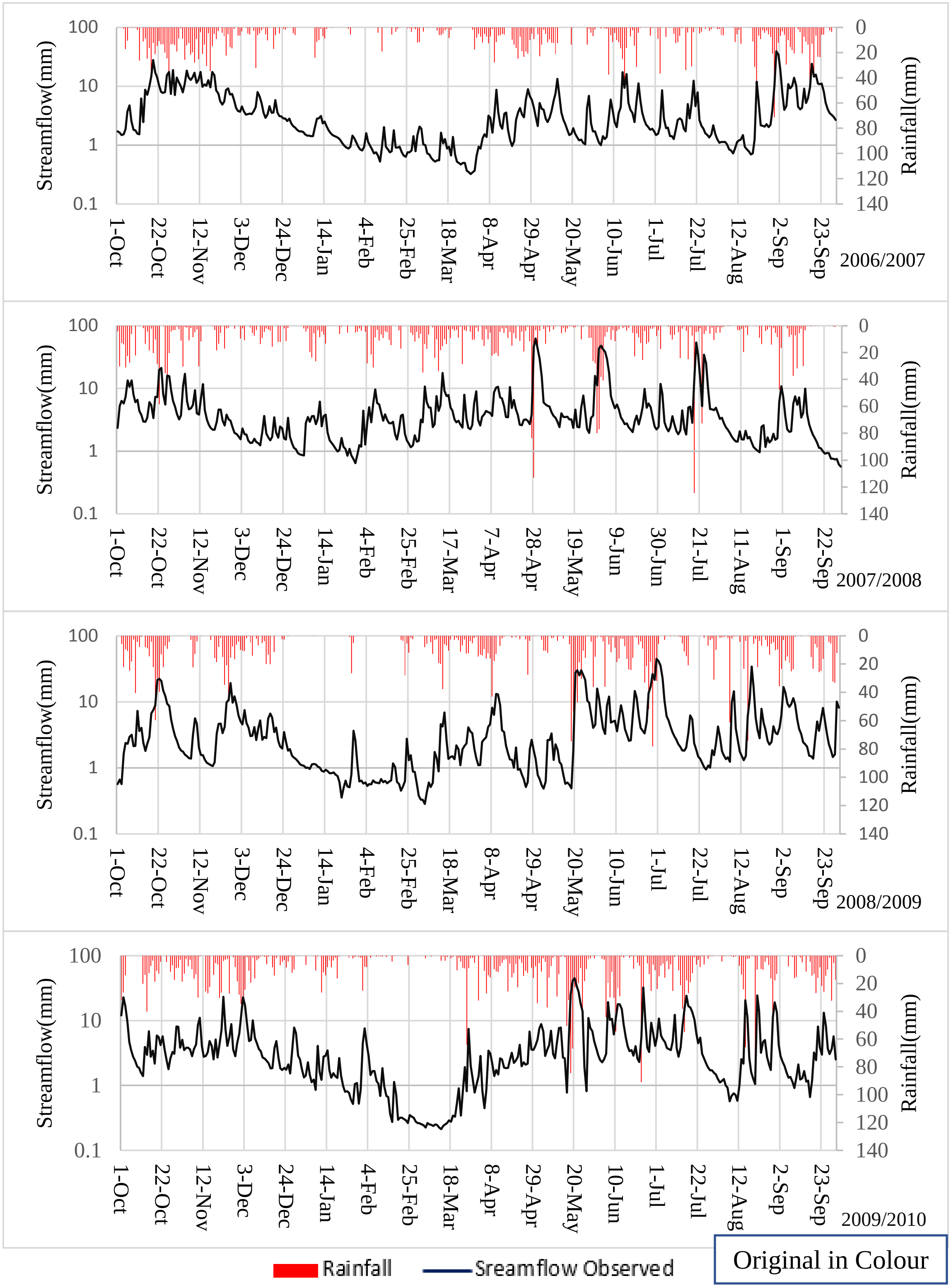

Figure 4-12 Observed Streamflow with Thiessen Rainfall at Ratnapura (Calibration period)

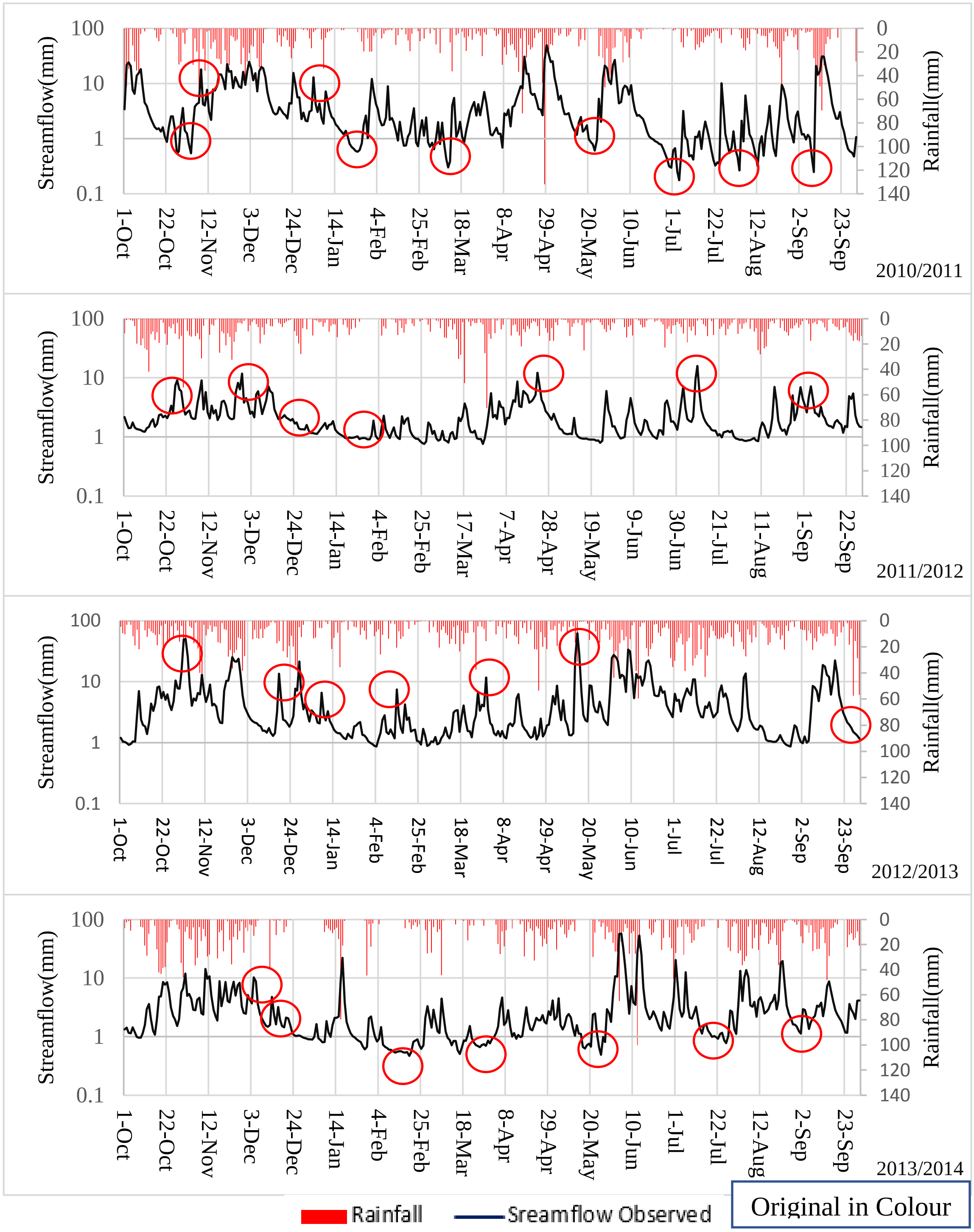

Figure 4-13 Observed Streamflow with Thiessen Rainfall at Ratnapura (Validation period)

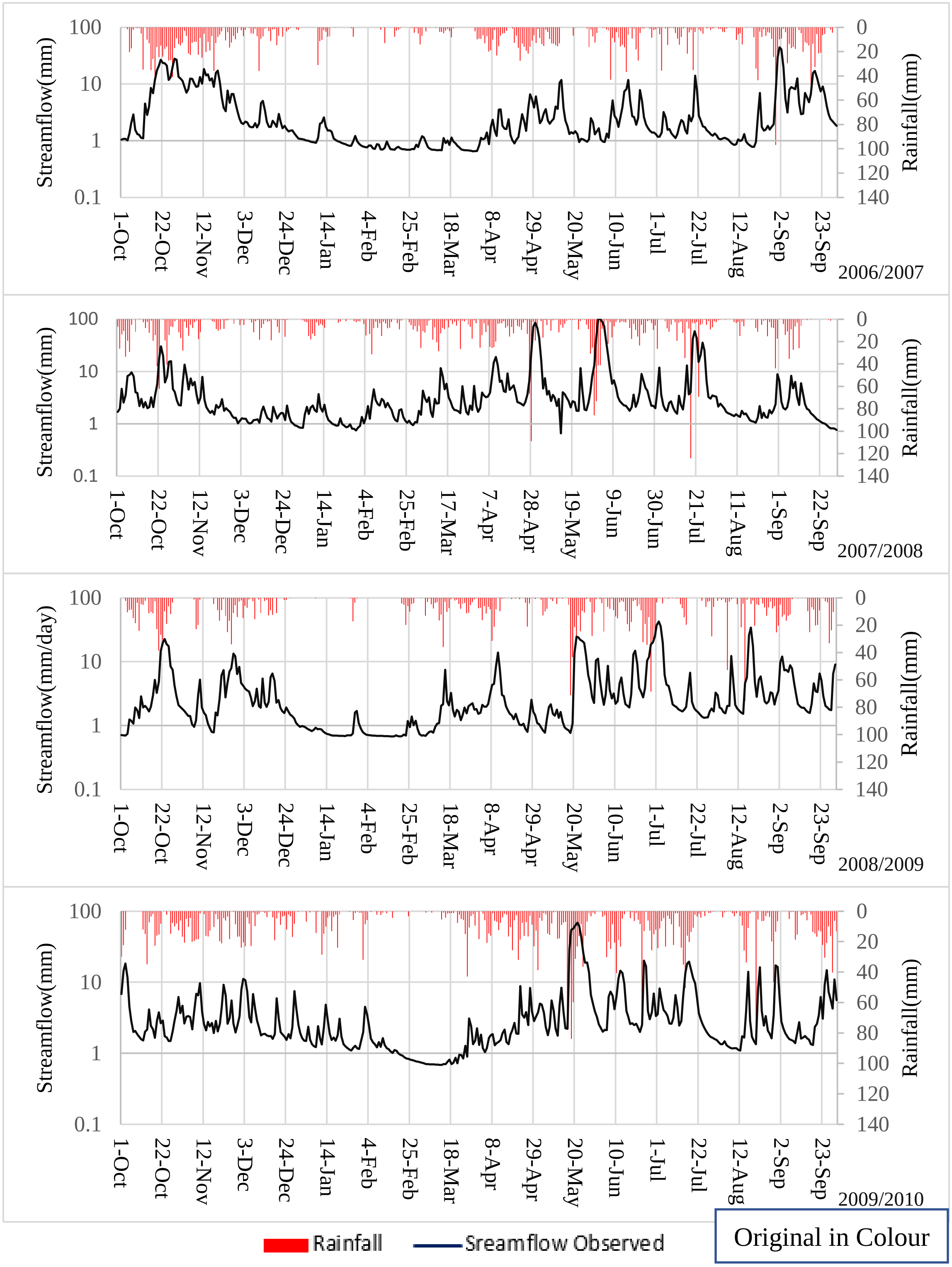

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Figure 4-14 Observed Streamflow with Thiessen Rainfall at Ellagawa (Calibration period)

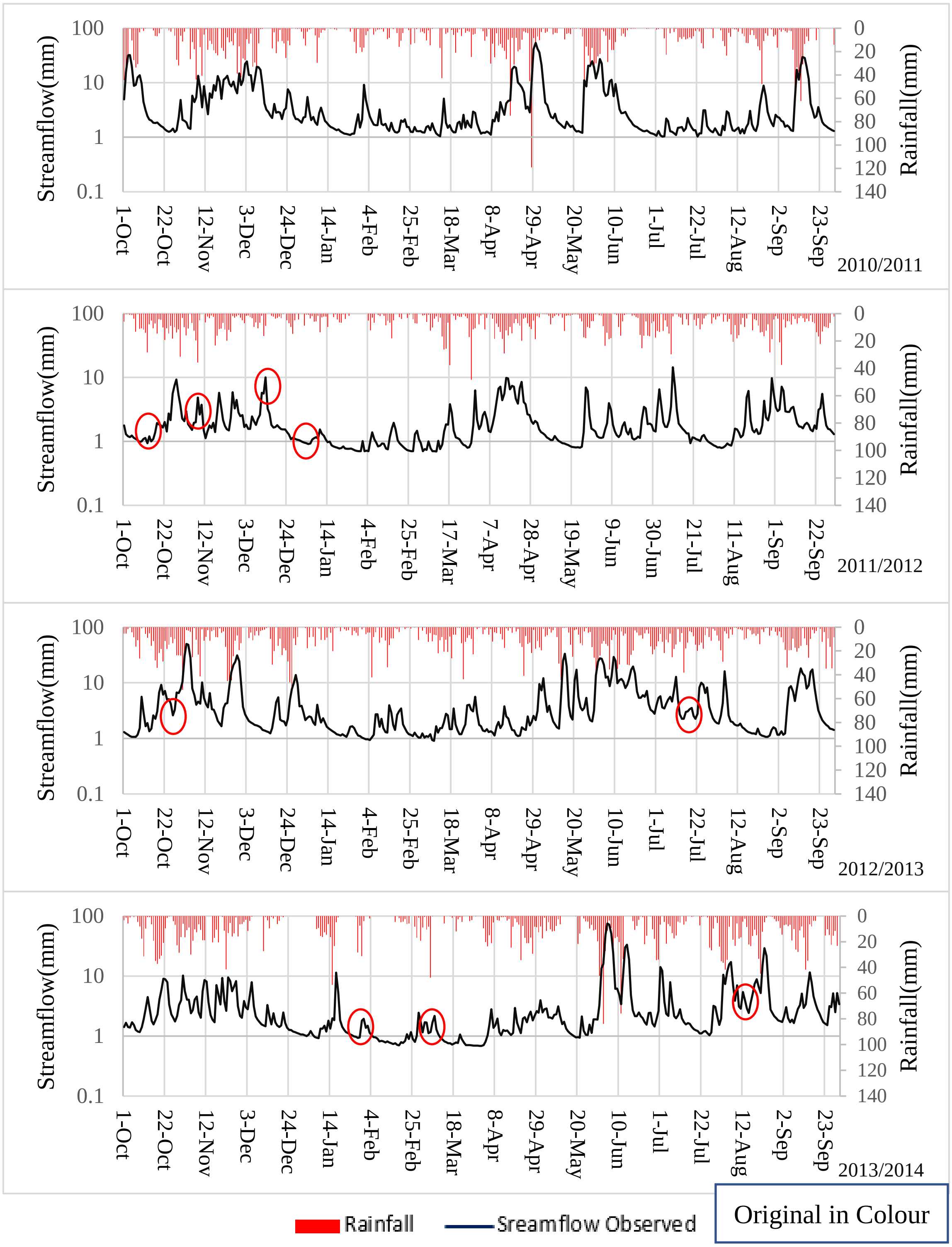

Figure 4-15 Observed Streamflow with Thiessen Rainfall at Ellagawa (Validation period)

Ratnapura streamflow and Ellagawa streamflow response to thiessen averaged rainfall for calibration and validation data periods are given the Figure 4-12, Figure 4-13, Figure 4-14 and Figure 4-15 respectively. Ratnapura calibration and validation streamflow data are noted to have more irresponsiveness to the rainfall than Ellagawa streamflow. Ratnapura validation data has several peaks without any rainfall signals, sharp recession within storm event and many more irresponsiveness to the rainfall signal can be seen. Ratnapura validation data point has many data issues which may lead to during model validations. Similarly, Ratnapura calibration data also has some irresponsiveness to streamflow and unusual lags. Furthermore, Ellagawa validation period show some data issues during 2011/2012 and 2012/2013. 2011/2012 and 2012/2013 years are noted to have major data discrepancy than other years. Ratnapura streamflow response to rainfall is weak and comprises several discrepancies than that of Ellagawa. Ellagawa calibration data set from 2006/2007 to 2009/2010 is the minimum number of noted error. The overestimated peaks, unusual recession within storm event and irresponsiveness to rainfall data are marked in the circle in Figure 4-12, Figure 4-13, Figure 4-14 and Figure 4-15.

5. ANALYSIS

5.1. Selection of Watersheds

Two watersheds of Kalu river basin namely Ellagawa and Ratnapura were selected for model development. There have been several studies on streamflow modelling in Kalu river basin (Examples: Kanchanamala, Herath & Nandalal, 2016; Jayadeera, 2017). Streamflow modelling of Kalu River basin with SWMM expected to be milestone study for water resources management modelling practices. In addition, rainfall and streamflow data required for watershed model development were available.

5.2. Model Compartments

5.2.1. Surface Runoff

SWMM uses a non-linear reservoir model to estimate surface runoff produced by precipitation excess over a subcatchment. Since, SWMM is a semi-distributed model, it allows a study area to be sub- divided into any number of sub-watershed area to best capture the effects of spatial variability in topography, drainage pathway, land cover and soil characteristics on runoff generation. SWMM conceptualizes a sub-watershed as a rectangular surface that has uniform slope and width and drains into single outlet. The default non-linear reservoir model in SWMM has mostly physical parameters and can be estimated with certain accuracy. Physical parameters are Area (A), Width (W), % Slope and percentage imperviousness. Similarly, Manning's roughness coefficient and depression storages are the parameters to be estimated from reference manual and literature and further calibrated.

5.2.2. Surface Runoff Parameter Estimation

The physical parameters of the model: Area, Width, Slope and % Imperviousness were estimated with ArcGIS. The width of a sub-watershed cannot be accurately estimated. SWMM conceptualizes the geometry of the sub-watershed as a rectangle. Hence, the width of a sub-watershed is area of a watershed divided by length of its longest channel. Slope can be estimated from contour data and DEM. For the lumped model slope was estimated by highest elevation minus elevation at outlet divided by length of longest stream. % Imperviousness was estimated by using details from the landuse map from Survey department. Table 5-1 shows the parameter estimation for the runoff compartment and Table 5-2 shows the estimated parameter for Ratnapura and Ellagawa watersheds

Table 5-1 Parameter Estimation of the Surface Runoff Compartment

S.N.	Parameter	Estimation tool	Calculation Method
1	Area	ArcGIS	A (Hectares)
2	Width	ArcGIS	A/L (meters)
3	Slope	ArcGIS	$(E_1 - E_0)/L$
4	% Impervious	ArcGIS	(A-Ap)/A*100%
5	N-Impervious	Yen (2001)/Reference Manual	Calibration
6	N-Pervious	Yen (2001)/Reference Manual	Calibration
7	D-Storage pervious	Literature/Reference Manual	Calibration

Notations: A: Area of the watershed; L: Length of the longest channel; E1: Highest Elevation of the stream; E_0: Lowest Elevation of the stream; A_P: Area of the pervious layer

Table 5-2 Initial Estimation of the Parameter

S.N.	Parameter	Unit	Initial Estimation	
			Ratnapura Watershed	Ellagawa Watershed
1	Area	Hectares	65300	134200
2	Width	Meters	15000	26000
3	Slope	Meter/Meter	0.0163	0.01
4	% Impervious	%	10	8
5	N-Impervious	seconds/meter$^{1/3}$	0.011-0.015	0.011-0.015
6	N-Pervious	seconds/meter$^{1/3}$	0.017-0.025	0.025-0.035
7	D-Storage Impervious	mm	0.8-1.4	0.8-1.4
8	D-store pervious	mm	1-3.5	1-3.5

5.2.3. Infiltration

Losses due to infiltration is governed by Richard's Equation which requires the relationship between soil permeability and pore water tension as a function of soil moisture to be known (Rossman & Huber, 2016b). There is no universal agreement as to which model is best to model losses due infiltration, SWMM provides option to modelers to choose from five most widely used infiltration method: Horton's, modified Horton's, Green-Ampt and Modified Green-Ampt and the curve number method. For this study, a rational selection was done based on available literature and data availability. Modified Green-Ampt was found to be best possible option to be selected. Initial estimation of Green-Ampt parameters is given in Table 5-3.

Table 5-3 Initial Estimation of Green-Ampt Infiltration Model Parameter

S.N	Parameters	Unit	Initial Estimation	Source
1	Suction Head (ψ_s)	mm	273.5	Rawls et al., 1983
2	Conductivity (Ks)	(mm/hr)	1.016	Rawls et al., 1983
3	Maximum moisture deficit (θ_{dmax})	Difference of soil porosity- initial moisture content (Dimensionless)	0.32	Clapp and Hornberger (1973)

5.2.4. Groundwater

SWMM was originally developed for combined sewer overflows therefore the fate of infiltrated water was insignificant. However, it has been it has been continuously upgraded and updated. SWMM now can be applied for highly urbanized to completely rural area. SWMM model has its own conceptual model inbuilt to take account of infiltrated water into aquifer and recharge to stream. The aquifer in the groundwater model stores water from infiltration and parameters: porosity, wilting point, field capacity, conductivity, conductivity slope, tension slope, upper evaporation fraction, lower evaporation depth, lower ground water loss rate are to defined. SWMM analyses groundwater flow for each sub-watershed independently. It represents subsurface region beneath the subcatchment. The aquifer in the sub-watershed is comprised with two zones namely upper unsaturated zone and lower saturated zone. The infiltrated water from surface reaches up to upper unsaturated zone from which some amount of loss occurs and remaining water enters to the saturated lower zone. The recharge phenomena from lower saturated zone to stream occur in further two steps: groundwater discharge and deep percolation. The groundwater lateral discharge is immediate recharge process whereas the deep percolation store water and supply to the stream in later run. SWMM allows user to select the groundwater discharge equation either from standard ground water flow equation or user defined equation. Due to the complexity in the parameter estimations and number of parameters to be handled, the user defined equation was selected for this study. The user defined custom groundwater equation was selected from the user manual. The equation follows two stage linear reservoir models. Ground elevation (Hgw), Surface Elevation (Invert elevation of node), Groundwater discharge coefficient, Deep percolation coefficient are the parameters governing the equation.

5.3. Parameter Sensitivity and Optimization

SWMM model has a large set of parameters; among those all the parameters cannot be optimized. Parameters were classified into two groups: Physical parameters and Calibration parameters. Parameters like area, slope, and % impervious were physical parameters whose value can be determined physically. Similarly, Calibration parameters are parameters whose values cannot be calculated or estimated with accuracy and needs calibration. Furthermore, calibration parameters are also classified into two groups: Sensitive and insensitive parameters. Sensitive parameters are those parameters whose value change in small degree can change the efficiency of model. The initial estimation was carried out with help of ArcGIS, SWMM reference manual, literature and parameter sensitivity was observed. The sensitive parameters were recognized and optimized with reference to objective function. Initial Estimation of parameters was done for Ellagawa lumped model and the parameter were varied from the range -50% to +50% with the step of 10% and simultaneously the objective function was noted. A line graph was plotted against the parameter range and the objective function to identify the sensitive parameters. N-pervious in surface runoff compartment, saturated hydraulic conductivity in infiltration compartment and groundwater discharge coefficient in groundwater compartment were found most sensitive parameter to the objective function. The table and plot of the sensitivity analysis is given in the Appendix C in Figure C-1 and Figure C-2.

5.4. Development of Watershed Model

Daily streamflow data were available for Ellagawa and Ratnapura gauging stations. Ellagawa Lumped and Ratnapura Lumped model were developed and a basin model was developed for entire Ellagawa watershed considering subwatersheds.

5.5. Delineation of Subwatersheds

Sub-watershed delineation was done using Arc Hydro tool in Arc GIS software and the input data were from 30 m Digital Elevation Model (DEM) and gauging station point data.

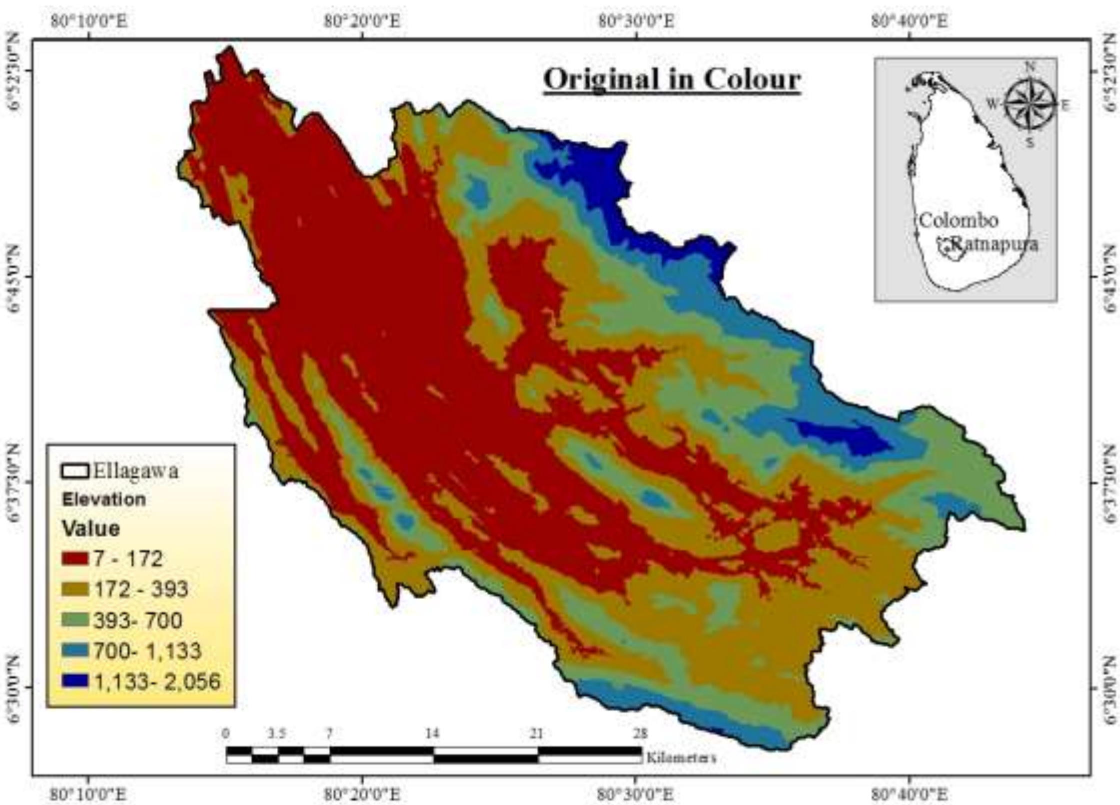

Figure 5-1 DEM of the Study Area

Arc Hydro is a set of data models and tools that operates within ArcGIS to support geospatial and temporal data analyses. Initial step was to recondition and fill the DEM and then reconditioned DEM was used identify the watersheds. Watershed for each and every stream on the stream network was delineated. Model with semi-distributed parameters approach is considered in this study. Finally, the area was divided into three major catchments as Ratnapura, Upper Ellagawa: Northern streams area, Lower Ellagawa: Southern streams area. The DEM of the study area is given in Figure 5-1 and delineated major subwatersheds on Ellagawa are given in Figure 5-2.

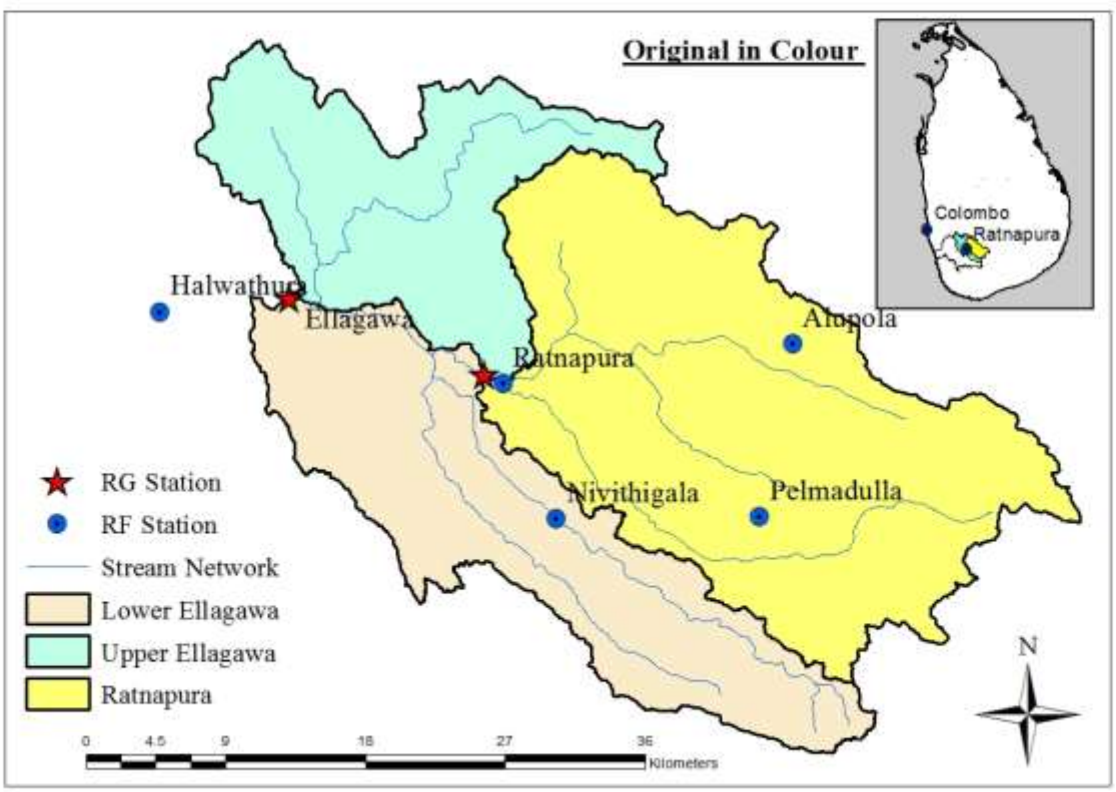

Figure 5-2 Delineated Subwatersheds of Ellagawa watershed

5.6. Development of Precipitation Model

Thiessen average method was used for the precipitation model. Thiessen Polygon was created using ArcGIS. Thiessen Polygon for Ellagawa and Ratnapura is given in Figure 4-10 and Figure 4-11 in the data checking section. Table 5-4 shows the thiessen weightage of rainfall stations for Ellagawa semi-distributed model.

Table 5-4 Thiessen Weights of Subwatersheds

Subcatchment	Thiessen Weight				
	Halwathura	Ratnapura	Alupola	Pelmadula	Nivithigala
Ellagawa	0.12	0.32	0.16	0.26	0.14
Ratnapura	-	0.22	0.32	0.39	0.07
Lower Ellagawa	0.10	0.29	-	0.24	0.37
Upper Ellagawa	0.38	0.59	0.03	-	-

5.7. Development of Lumped model

Lumped model was conceptualized with no stream network representation. All parameter was lumped into the watershed and the discharge was directly obtained at the outlet

5.8. Development of Semi-distributed Model

Ellagawa Watershed was divided into three subwatersheds: Ratnapura, Lower Ellagawa and Upper Ellagawa. SWMM model has ability to represent physical stream network into the model through nodes and conduits. Nodes are provided at the centroid of each sub-watershed and junctions at confluence points. Routing time step should be calibrated for distributed model. The additional parameters in the distributed model are nodes elevations, conduit length, conduit bottom width, and conduit geometry and conduit roughness. Invert elevation of the nodes, conduit lengths were estimated using ArcGIS.

Conduit geometry was assumed to be trapezoidal where conduit roughness was a calibration parameter.

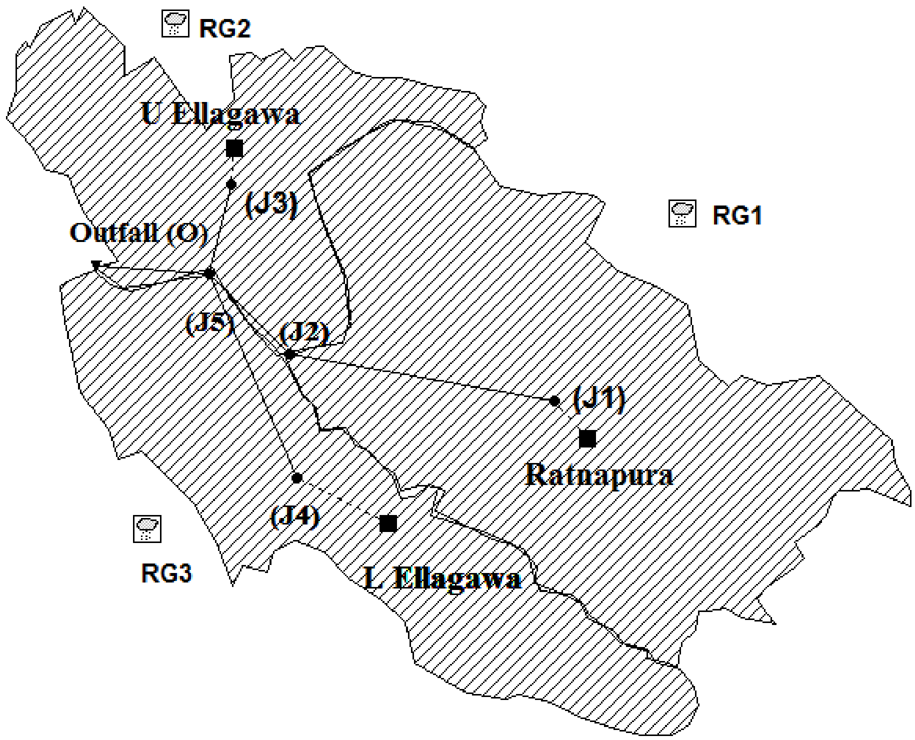

Figure 5-3 Layout of Ellagawa Model with Subwatersheds in SWMM

Figure 5-3 shows SWMM layout of Ellagawa semi-distributed with three subwatersheds. Three (3) rain gauges for precipitation model of each sub-watershed were given as input. Thiessen weighted values for precipitation model are given in Table 5-4. Five (5) junctions and five (5) conduits with an outlet were incorporated in the semi-distributed layout of Ellagawa watershed model. Junctions were placed on discharge accumulation and outlet point of each catchment. Conduits were then used to link junctions to outlets. Descriptions, parameters and their respective values of junctions and conduits are given Table 5-5 and Table 5-6 respectively.

Table 5-5 Description of Junctions and Outlets of Ellagawa Semi-Distributed Model

S.N	Nodes	Description	Invert Elevation (m)
1	J1	Flow accumulation junction within the Ratnapura catchment	75
2	J2	Flow outlet junction of Ratnapura catchment	60
3	J3	Flow accumulation junction within the upper Ellagawa catchment	90
4	J4	Flow accumulation junction within the lower Ellagawa catchment	95
5	J5	Flow outlet junction of the lower and upper Ellagawa catchment	52
6	01	Outlet of the overall catchment	38

With the junctions and conduits, it is possible to model the flow accumulation and discharge at the outlet. These junctions described in Table 5-5 are interconnected by a series of conduits. The description of conduits, its connection nodes, and other physical parameters are given in table 5-6.

Table 5-6 Description of Nodes of Ellagawa Semi-Distributed Model

S.N	Conduits	Inlet node	Outlet node	Max. Depth (m)	Length (m)	Roughness
1	C1	J1	J2	6	1800	0.09
2	C2	J3	J5	3	1000	0.09
3	C3	J4	J5	4	1600	0.09
4	C4	J2	J5	6	1100	0.09
5	C5	J5	O1	5	3000	0.09

Due to lack of channel data conduits are assumed as trapezoid. Roughness manning's n value was initially estimated from literature for calibration.

5.9. Selection of Routing Method

SWMM provides three different routing methods: Steady, Kinematic Routing and Dynamic Wave Routing. Steady routing is the simplest routing method but it does not consider time lag, flow modelling. Steady routing is a routing option which just routs water from upstream to downstream without any physical representation. Kinematic wave routing solves the continuity equation and neglects local and convective acceleration and pressure of conduits. Kinematic wave is the best option to model the watershed with highly steep terrain where backwater is negligible. For Ellagawa distributed model layout dynamic wave routing which solves one dimensional Sent-Venant's equation was selected. According to Rossman & Huber (2016b) it produces theoretically accurate results. Dynamic wave routing would be appropriate in the rural watershed where there are terrain variation, tributary inflows, and backwater effects. Ellagawa watershed has mixed terrain from highly steep slopes to flat regions.

5.10. Selection of Routing Time Steps

Model computational time and model efficiency was two factors to be considered when selecting the routing time step. Time step was analyzed from 60 seconds to 3600 secs at each 60-sec interval. Considering both computational time and model efficiency, routing time step was taken as 1 hour.

5.11. Model Calibration

Model calibration was done after reviewing processes selection and development. Model efficiency depends upon its parameters. Model was calibrated by optimizing the parameters. Data from 2006/2007 to 2009/2010 were selected for calibration. Mean Ratio Absolute Error (MRAE) and Annual Water Balance (AWB) was used as statistical measures for calibration. Flow duration curve was correspondingly analyzed during calibration. MRAE for high, medium and low flow were also evaluated.. Initially Ratnapura and Ellagawa Lumped models were calibrated to compare the parameters and model efficiency. Then, Ellagawa distributed model with sub-watersheds model was calibrated.

6. RESULTS

6.1. Lumped Model Calibration

6.1.1. Ratnapura Lumped **Model** Calibration

Ratnapura lumped model was calibrated with observed streamflow at Ratnapura gauging station from 2006-2010. Table 6-1 shows the Mean Ratio of Absolute Error (MRAE), Annual water balance error and MRAE for high, medium and low flows during the calibration of Ratnapura lumped model. Mean Ratio of Absolute Error (MRAE) for overall hydrograph is 0.4531 and annual water balance error is 31%. Results shows satisfactory match in high and intermediate flow regions with MRAE 0.38 and 0.37 and comparatively poor match in low flow region.

Table 6-1 Calibration Results of Ratnapura Lumped Model

Gauging Station	MRAE	Annual water balance Error (%)	Flow Duration Curve		
			High	Intermediate	Low
			MRAE	MRAE	MRAE
Ratnapura	0.4531	31%	0.38	0.37	0.77

Table 6-2 Calibrated Parameters of Ratnapura Lumped Model

Parameters	Units	Value
Surface Runoff		
N-Pervious	$seconds/meters^{1/3}$	0.028
Depression storage Pervious	millimeters	1.2
Infiltration		
Suction head	millimeters	270
Saturated Hydraulic Conductivity	millimeters/hour	0.672
Initial Deficit	Fraction	0.46
Ground Water		
GW lateral Discharge coefficient (a)	meters/sec	0.002581
Deep Percolation coefficient (b)	meters/sec	4

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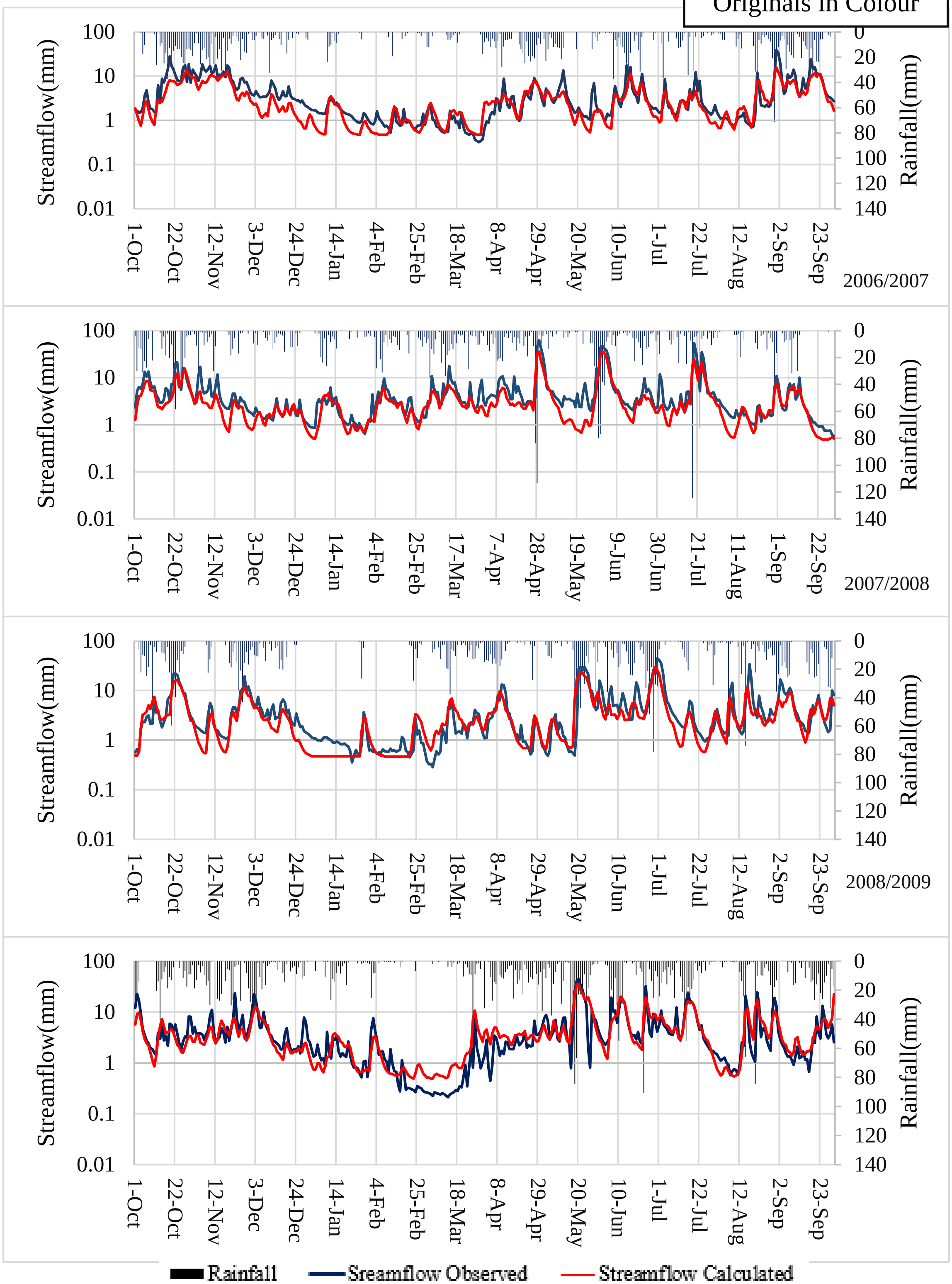

Figure 6-1 Hydrographs of Ratnapura Lumped Model (Calibration)

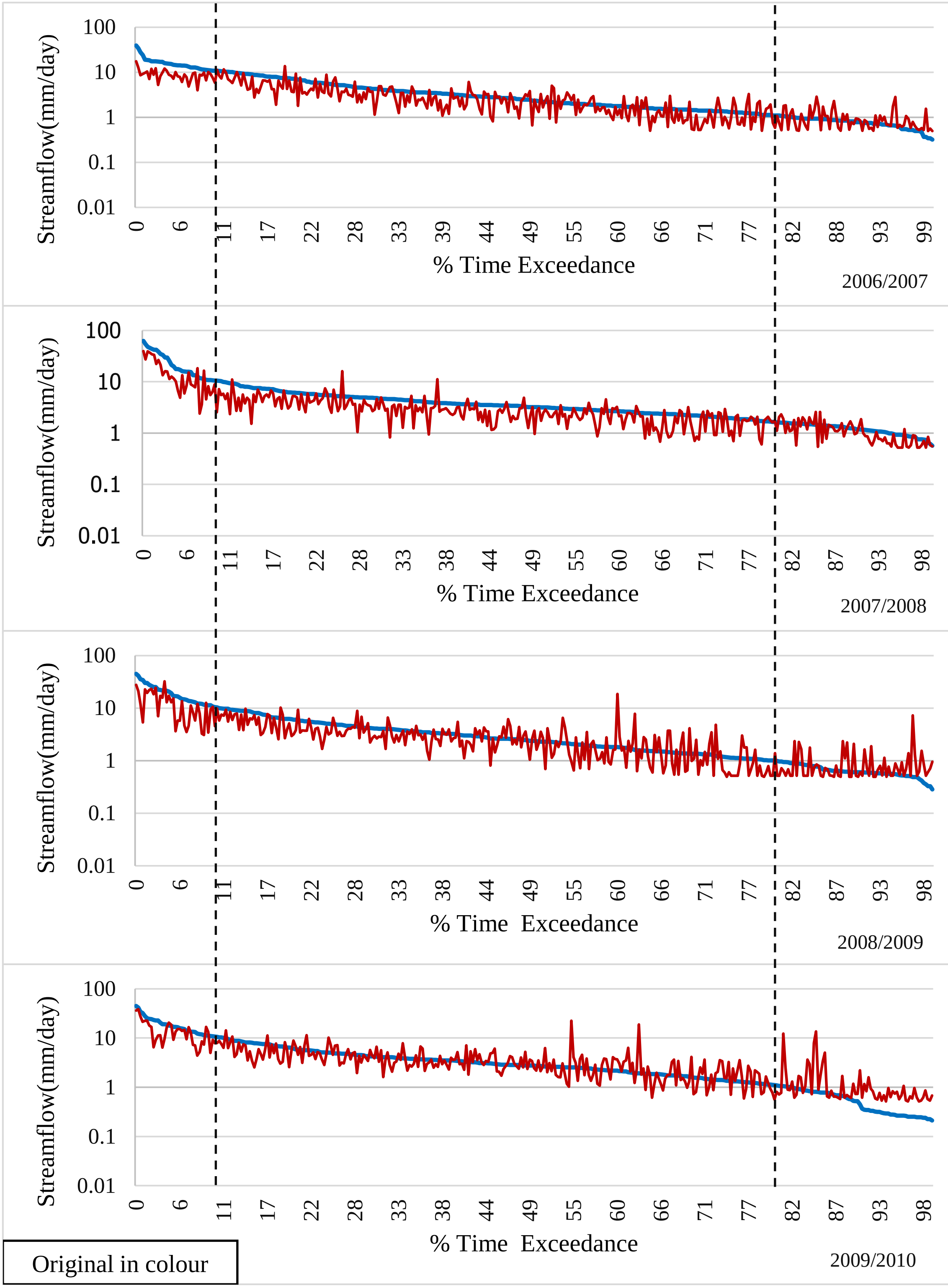

Figure 6-2 Flow Duration Curves of Ratnapura Lumped Model (Calibration)

Figure 6-1 shows the hydrographs matching of Ratnapura lumped model with observed flow during calibration. Fig 6-2 shows the Flow Duration Curves (FDC) during model calibration where the variations in observed and modelled streamflow are plotted with respect to % time exceedance. The Flow duration curves are divided into three regions: High flow (0-10 %), Intermediate Flow (10-80%) and low flows (80-100%). Overall hydrograph, high flow and intermediate flow have satisfactory match during calibration. Normal plot of the Ratnapura lumped hydrographs during calibration match are given in Appendix D in Figure D-1.

Table 6-3 Annual Water Balance of Ratnapura Lumped Model Calibration

Year (Oct-Sep)	Rainfall (mm)	Observed Streamflow (mm)	Modelled Streamflow (mm)	Observed Water Balance (mm)	Modelled Water Balance (mm)	Annual water balance error %
2006/2007	2649.5	1585.2	1141.2	1064.	1508	41
2007/2008	3070.5	1960.8	1366.4	1109.	1704	53
2008/2009	2923.6	1660.2	1288.1	1263.	1635	29
2009/2010	3465.1	1668.8	1589.0	1796.	1876	4

Table 6-4 Annual Mass Balance of Ratnapura Lumped Model Calibration

Year (Oct-Sep)	Rainfall (mm)	Observed Streamflow (mm)	Modelled Streamflow (mm)	Observed Runoff coefficient	Modelled runoff coefficient	Annual water balance error %
2006/2007	2649.5	1585.2	1141.2	0.60	0.43	28
2007/2008	3070.5	1960.8	1366.4	0.64	0.45	30
2008/2009	2923.6	1660.2	1288.1	0.48	0.44	22
2009/2010	3465.1	1668.8	1589.0	0.48	0.46	5

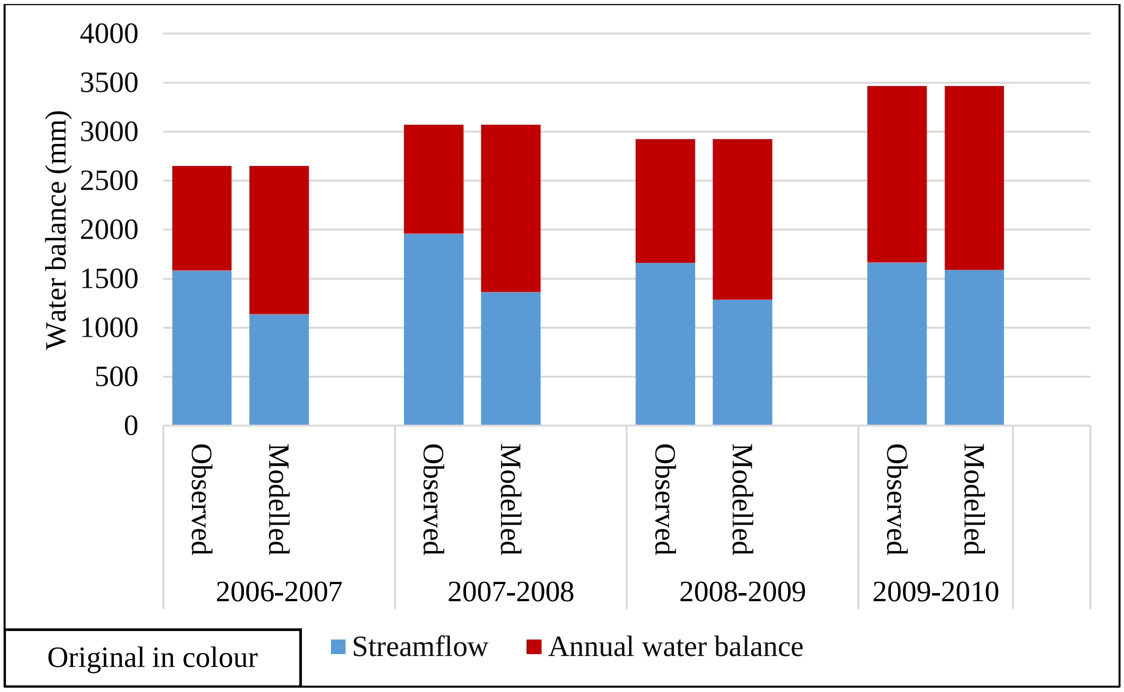

Figure 6-3 Annual Water Balance of Ratnapura Lumped Model (Calibration)

Table 6-3 and Figure 6-3 shows the annual water balance values for the calibration period 2006/2007 to 2009/2010. Water year 2006/2007 and 2007/2008 have higher annual water balance error of 41% and 53% respectively. Whereas, 2008/2009 has moderate water balance error and 2009/2010 has lowest water balance error. Furthermore, Table 6-4 shows annual mass balance and annual runoff coefficient of Ratnapura Lumped model during calibration. In the year 2006/2007 and 2007/2008 model deviates largely from observed annual streamflow. The runoff coefficient of observed streamflow was found inconsistent during calibration years i.e. 0.6-0.48. The year 2006/2007 and 2007/2008 have high observed runoff coefficient of 0.60 and 0.64 respectively which is unusual value for rural watershed. However, runoff coefficient of modelled streamflow was found consistent throughout the calibration year i.e. around 0.43-0.46. The range of the runoff coefficient of modelled streamflow is a valid range for rural watersheds.

6.1.2. Ellagawa Lumped Model Calibration

Ellagawa lumped model was calibrated with observed streamflow at Ellagawa gauging station from 2006-2010. Table 6-5 shows MRAE, Annual water balance error and MRAE for high, medium and low flows during the calibration of Ellagawa lumped model. MRAE for overall hydrograph is 0.3634 and annual water balance error is 38%. Results show good matching in all the flow regimes. The MRAE for high, intermediate and low flow are 0.2007, 0.4030 and 0.3658 respectively.

Table 6-5 Calibration Results of Ellagawa Lumped Calibration

Gauging Station	MRAE	Annual Water Balance Error (%)	Flow Duration Curve		
			High	Intermediate	Low
			MRAE	MRAE	MRAE
Ellagawa	0.3634	38%	0.3658	0.4030	0.2007

Table 6-6 Calibrated Parameter of Ellagawa Lumped Model

Parameters	Units	Value
Surface Runoff		
N-Pervious	Seconds/meters$^{1/3}$	0.02
Depression storage Pervious	Millimeters	2.5
Infiltration		
Suction head	Millimeters	270
Saturated Hydraulic Conductivity	Millimeters/hour	0.3
Initial Deficit	Fraction	0.2
Ground Water		
GW lateral Discharge coefficient (A)	Meters/sec	0.001793
Deep Percolation coefficient (B)	Meters/sec	5

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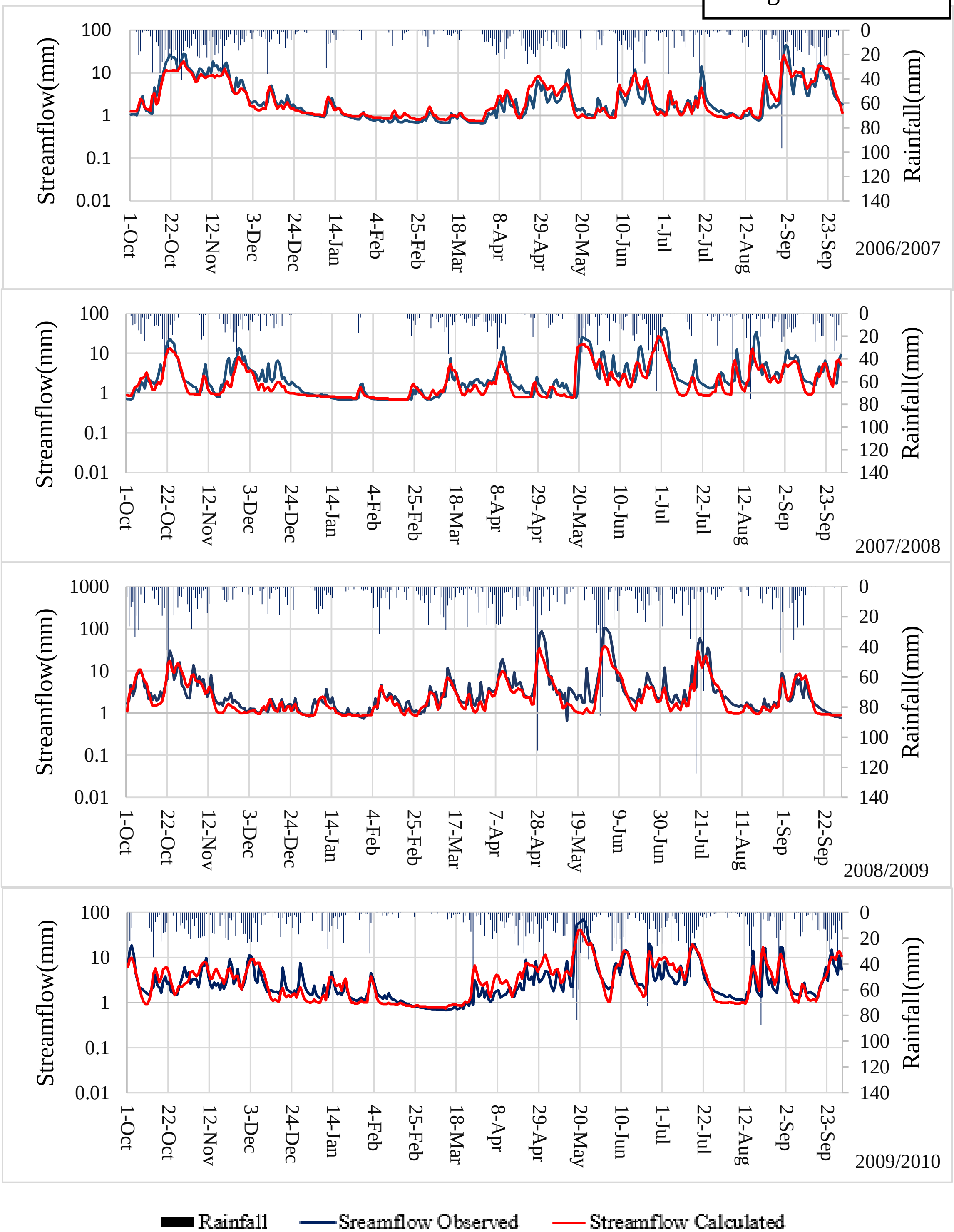

Figure 6-4 Hydrographs of Ellagawa Lumped Model (Calibration)

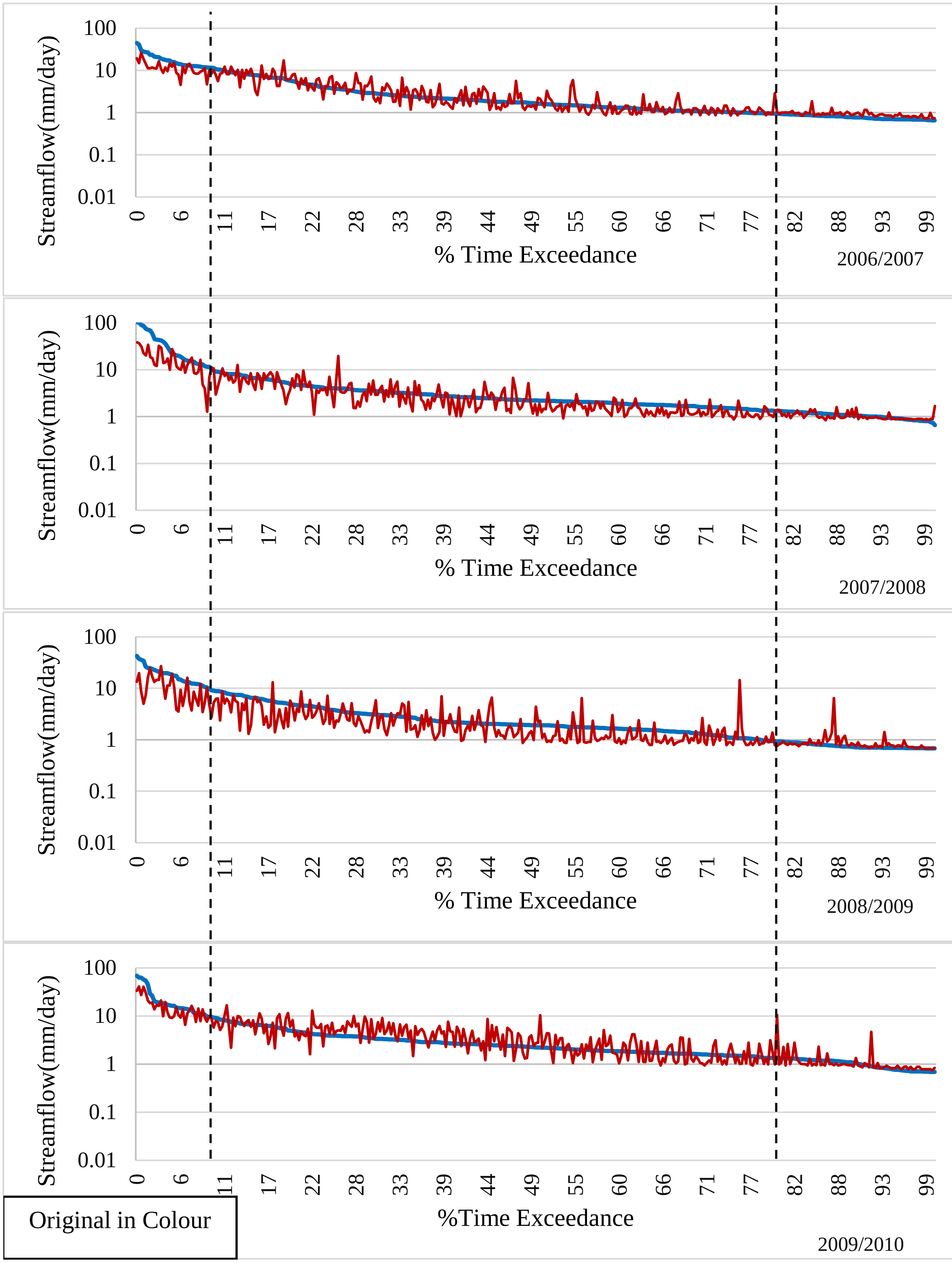

Figure 6-5 Flow duration curves of Ellagawa Lumped Model (Calibration)

Figure 6-4 shows the hydrographs matching of Ellagawa lumped model with observed flow of Ellagawa gauging station during calibration. Figure 6-5 shows the Flow Duration Curves (FDC) of the during model calibration where the variations in observed and modelled streamflows are plotted with respect to % time exceedance. The Flow duration curves are divided into three regions: High flow (0-10%), intermediate flow (10-80%) and low flow (80-100%). Overall simulated hydrograph and especially low flows of Ellagawa lumped model shows good match with that of observed streamflow. Normal plot of the Ellagawa lumped hydrographs during calibration and flow duration are given in Appendix D Figure D-2.

Table 6-7 Annual Water Balance of Ellagawa Lumped Model Calibration

Year (Oct-Sep)	Rainfall (mm)	Observed Streamflow (mm)	Modelled Streamflow (mm)	Observed Water Balance (mm)	Modelled Water Balance (mm)	Annual water balance error %
2006/2007	2756.1	1425.	1243.6	1330.6	1512.5	14
2007/2008	2971.6	2136	1383.5	835.6	1588.0	90
2008/2009	2445.8	1435.3	989.8	1011.3	1456.0	44
2009/2010	2445.8	1658	1580.3	1606.3	1684.0	5

Table 6-8 Annual Mass Balance of Ellagawa Lumped Model Calibration

Year (Oct-Sep)	Rainfall (mm)	Streamflow Observed (mm)	Streamflow Modelled (mm)	Runoff Coefficient (Observed)	Runoff Coefficient (Modelled)	Annual Mass balance error %
2006/2007	2756.1	1425.6	1243.6	0.52	0.45	12
2007/2008	2971.6	2136	1383.5	0.72	0.47	35
2008/2009	2445.8	1435.3	989.8	0.59	0.40	30
2009/2010	2445.8	1658	1580.3	0.68	0.65	4

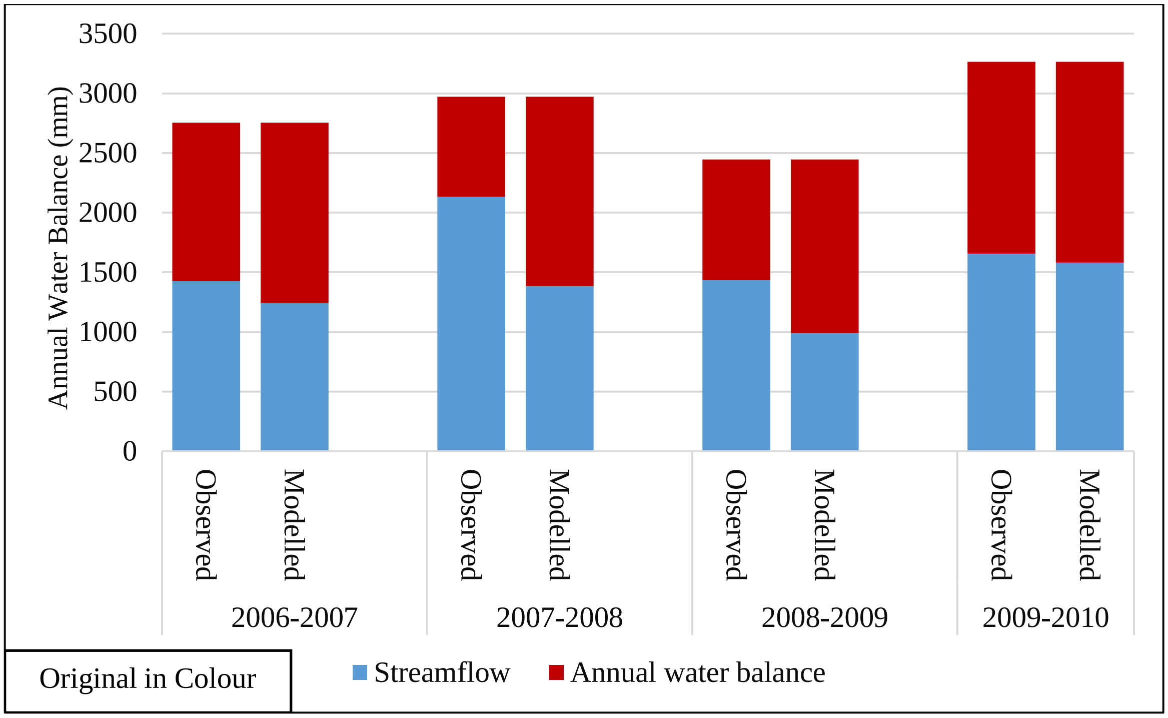

Figure 6-6 Annual Water Balance of Ellagawa Lumped Model (Calibration)

Table 6-7 and Figure 6-6 shows the annual water balance values of Ellagawa lumped model for the calibration period. 2007/2008 has higher annual water balance error of 90%. Whereas, 2006/2007 has moderate water balance error and 2009/2010 has lowest water balance error of 14% and 5% respectively. Furthermore, Table 6-8 shows annual mass balance and annual runoff coefficient Ellagawa lumped model during calibration. In the year 2007/2008 model deviates largely from observed annual streamflow. The runoff coefficient of observed streamflow was found inconsistent during calibration year 2007/2008. 2007/2008 have high observed runoff coefficient of 0.72 which is unusual value for rural watershed. However, runoff coefficient of modelled streamflow was found consistent throughout the calibration year. The runoff coefficient of modelled streamflow in 2007/2008 was 0.47 which is valid and reasonable runoff coefficient value for rural watersheds.

6.2. Lumped Model Validation

6.2.1. Ratnapura Lumped Model Validation

Ratnapura lumped model was validated with observed streamflow at Ratnapura gauging Station from 2010-2014. Table 6-9 shows Mean Ratio of Absolute Error (MRAE), Annual water balance error and MRAE for high, medium and low flows during the validation of Ratnapura lumped model. Mean Ratio of Absolute Error (MRAE) for overall hydrograph is 0.7843 and annual water balance error is 11 %. The MRAE for high medium and low flow are 0.46, 0.82 and 0.99 respectively.

Table 6-9 Validation Results of Ratnapura Lumped Model

Gauging Station	MRAE	Annual Water Balance Error (%)	Flow Duration Curve		
			High	Intermediate	Low
			MRAE	MRAE	MRAE
Ratnapura	0.784	11	0.468	0.829	0.990

Figure 6-7, shows the hydrographs matching of Ratnapura lumped model with observed flow of Ratnapura gauging station from the year 2010-2014. Fig 6-8 shows the Flow Duration Curves (FDC) of the during model validation where the variations in observed and modelled streamflows are plotted with respect to % time exceedance. The Flow duration curves are further divided into three regions: High flow (0-10 %), intermediate Flow (10-80%) and low flows (80 -100%). Normal plot of the Ratnapura lumped model hydrographs during validation are given in Appendix D Figure D-4.

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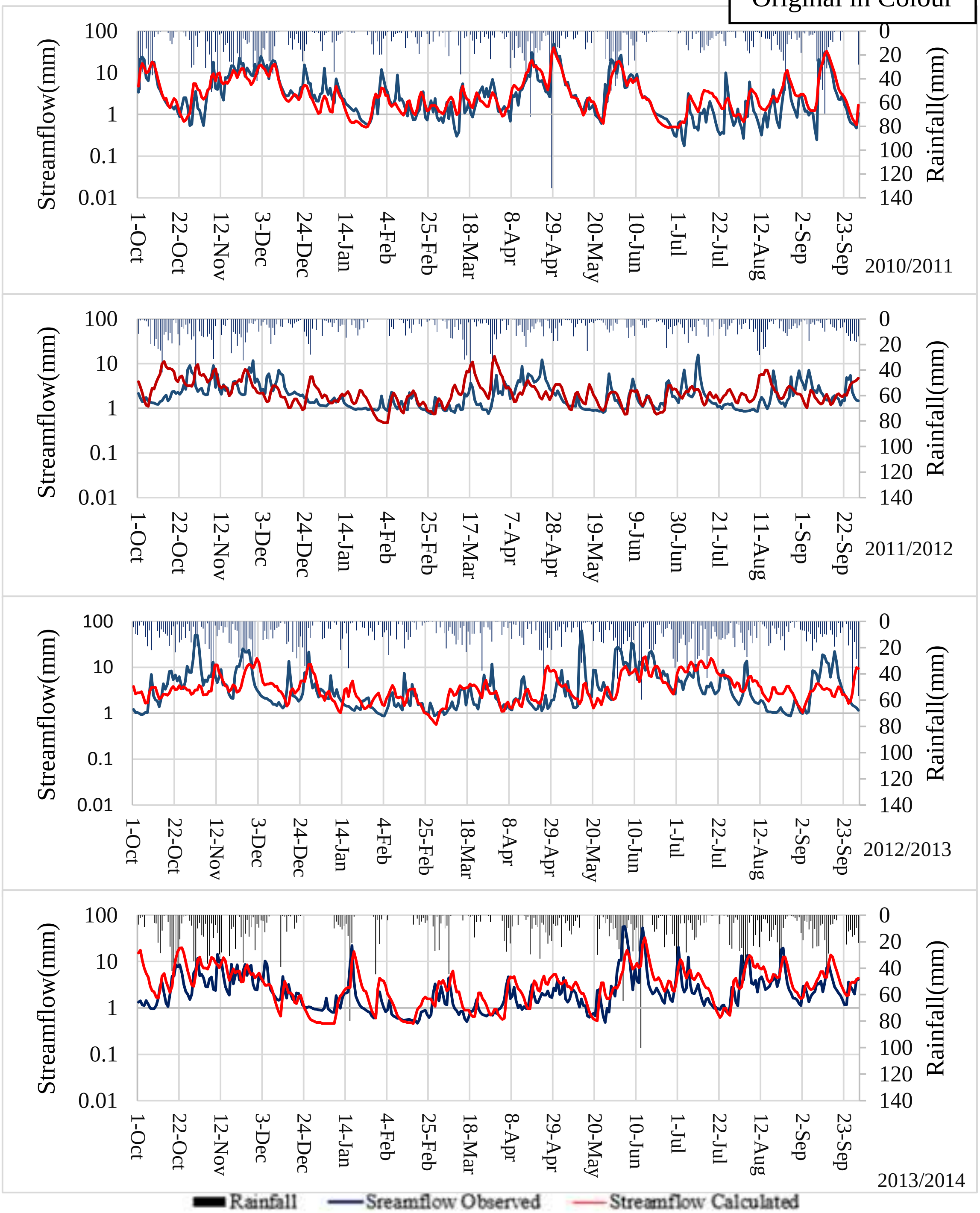

Figure 6-7 Hydrographs of Ratnapura Lumped Model (Validation)

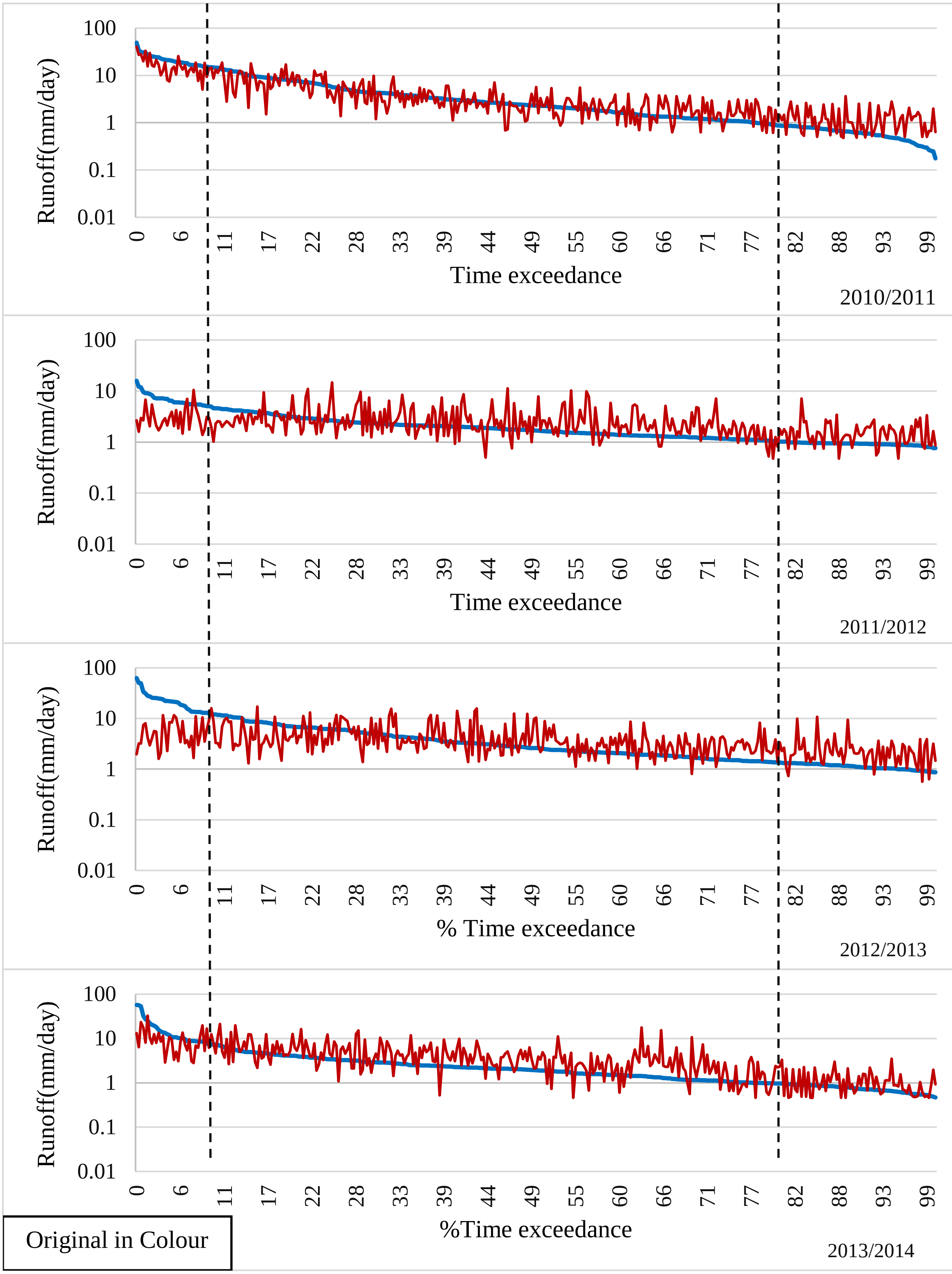

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Figure 6-8 Flow Duration curves of Ratnapura Lumped Model (Validation)

Table 6-10 Annual Water balance of Ratnapura Lumped Model Validation

Year (Oct-Sep)	Rainfall (mm)	Observed Streamflow (mm)	Modelled Streamflow (mm)	Observed Water Balance (mm)	Modelled Water Balance (mm)	Annual water balance error %
2010-2011	3490.0	1802.9	1692.8	1687.1	1797.2	6
2011-2012	2582.2	845.8	974.4	1736.4	1607.9	7
2012-2013	3845.2	1909.6	1537.4	1935.6	2307.8	19
2013-2014	3410.5	1275.2	1552.0	2135.3	1858.4	12

Table 6-11 Annual Mass Balance of Ratnapura Lumped Model Validation

Year (Oct-Sep)	Rainfall (mm)	Streamflow Observed (mm)	Streamflow Modelled (mm)	Runoff Coefficient (Observed)	Runoff Coefficient (Modelled)	Annual Mass balance error %
2010-2011	3490.0	1802.9	1692.8	0.52	0.49	6
2011-2012	2582.2	845.8	974.4	0.33	0.38	15
2012-2013	3845.2	1909.6	1537.4	0.56	0.40	19
2013-2014	3410.5	1275.2	1552.0	0.37	0.46	21

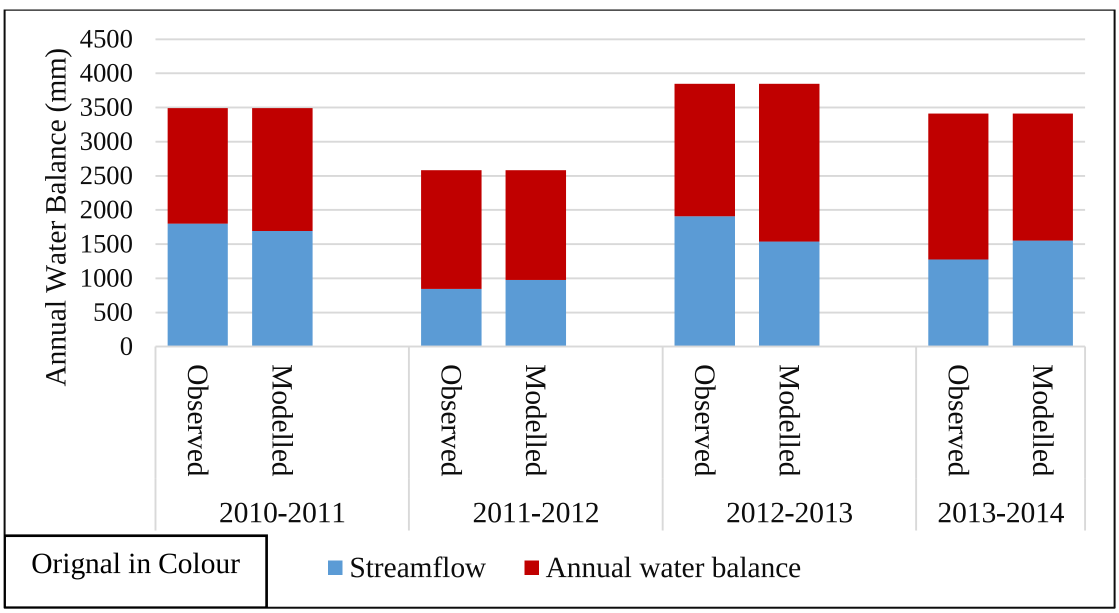

Figure 6-9 Annual Water Balance of Ratnapura Lumped Model (Validation)

Table 6-10 and Figure 6-9 shows the annual water balance values for the Ratnapura lumped model validation for the period 2010-2014. Similarly, Table 6-11 shows annual mass balance and annual runoff coefficient calculation for the observations. Annual water balance errors for all the validation year are satisfactory. Annual water balance error of the year 2010/2011 and 2011/2012 are 6 % and 7 % respectively. The annual water balance error of 2012/2013 and 2013/2014 are slightly higher in the range of 12%-19% respectively. The modelled runoff coefficient is in the range of 0.38- 0.46 which is valid value for rural watersheds.

6.2.2. Ellagawa Lumped Model Validation

Ellagawa lumped model was validated with observed streamflow at Ellagawa gauging station from 2010-/2014. Table 6-12 shows Mean Ratio of Absolute Error (MRAE), Annual water balance error and MRAE for high, medium and low flows during the Ellagawa lumped model validation. Mean Ratio of Absolute Error (MRAE) for overall hydrograph is 0.5865 and annual water balance error is 10.25%. The MRAE of high flow, intermediate flow and low flows are 0.4266, 0.6853 and 0.2939 respectively.

Table 6-12 Validation Results of Ellagawa Lumped Model

Gauging Station	MRAE	Annual Water Balance Error (%)	Flow Duration Curve		
			High	Intermediate	Low
			MRAE	MRAE	MRAE
Ellagawa	0.5865	10.25%	0.4266	0.6853	0.2939

Figure 6-10 shows the hydrographs matching of Ellagawa lumped model with observed flow at Ellagawa gauging station during validation. Figure 6-11 shows the Flow Duration Curves (FDC) during model validation where the variations in observed and modelled flow plotted with respect to % time exceedance. The Flow duration curves are further divided into three regions: High flow (0-10 %), Intermediate flow (10-80%) and low flow (80 -100%). Hydrographs of lumped model during validations in normal plot are given in Appendix D in Figure D-5.

Original in colour

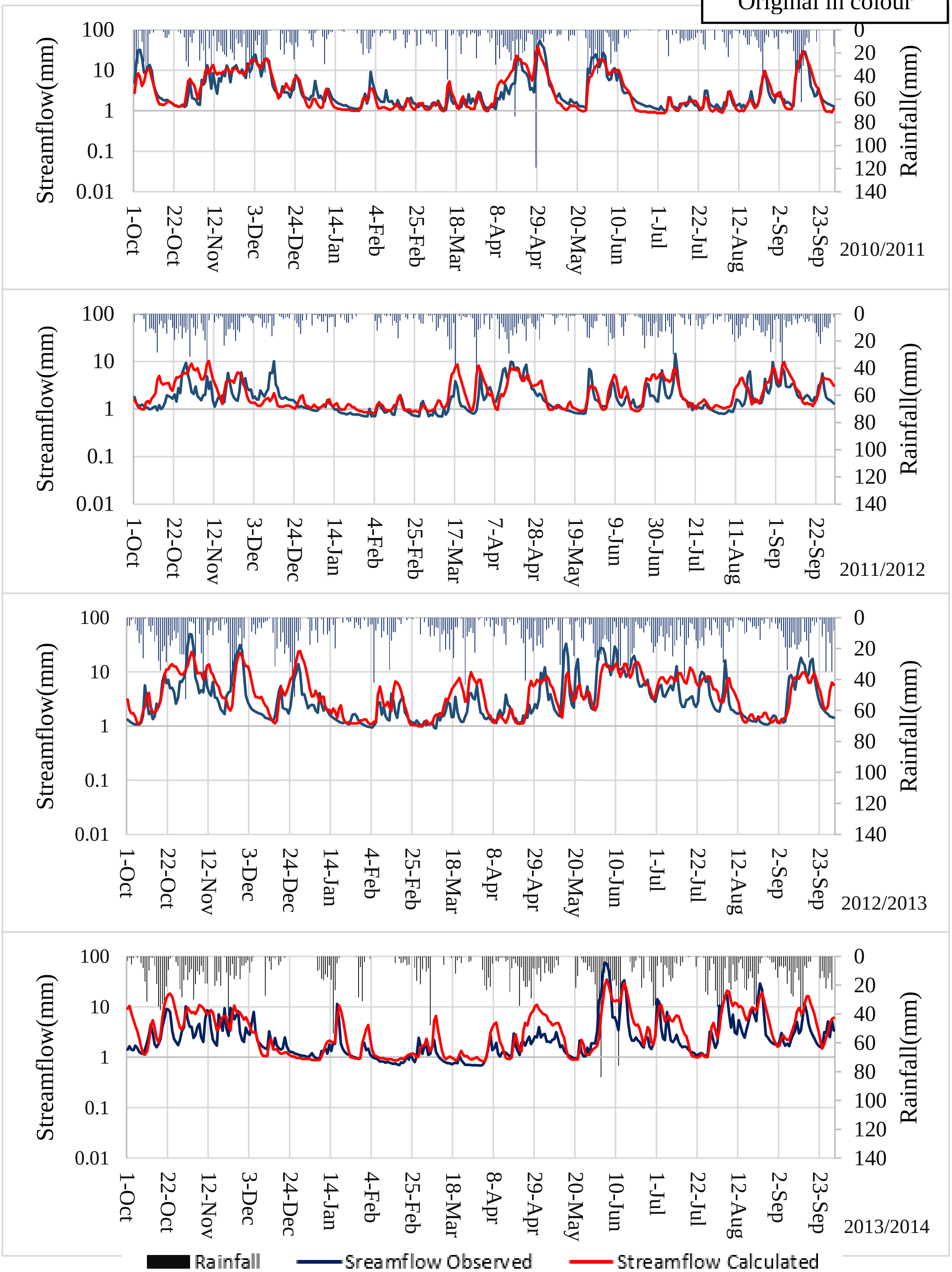

Figure 6-10 Hydrographs for Ellagawa lumped model (Validation)

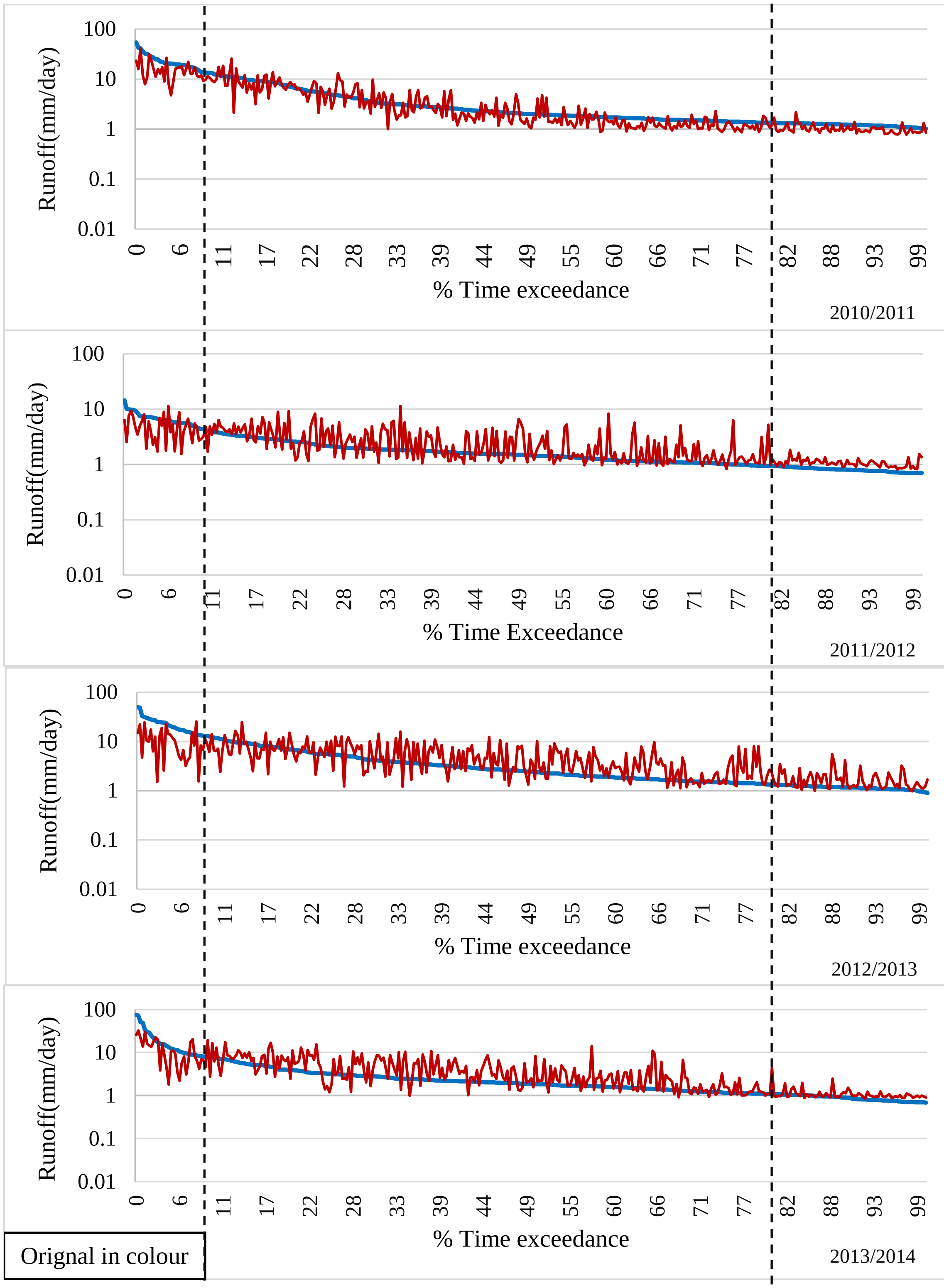

Figure 6-11 Flow duration curves of Ellagawa lumped model (Validation)

Table 6-13 Annual Water Balance of Ellagawa Lumped Model Validation

Year (Oct-Sep)	Rainfall (mm)	Observed Streamflow (mm)	Modelled Streamflow (mm)	Observed Water Balance (mm)	Modelled Water Balance (mm)	Annual water balance error %
2010-2011	3364	1810	1719	1554.5	1645.5	6
2011-2012	2536	764	937	1772.0	1598.7	10
2012-2013	3869	1801	1954	2068.4	1915.4	7
2013-2014	3413	1383	1754	2030.1	1665.2	18

Table 6-14 Annual Mass Balance of Ellagawa Lumped Model Validation

Year (Oct-Sep)	Rainfall (mm)	Streamflow Observed (mm)	Streamflow Modelled (mm)	Runoff Coefficient (Observed)	Runoff Coefficient (Modelled)	Annual Mass balance error %
2010-2011	3364	1810	1719	0.54	0.51	5
2011-2012	2536	764	937	0.30	0.37	22
2012-2013	3869	1801	1954	0.47	0.50	8
2013-2014	3413	1383	1754	0.41	0.51	26

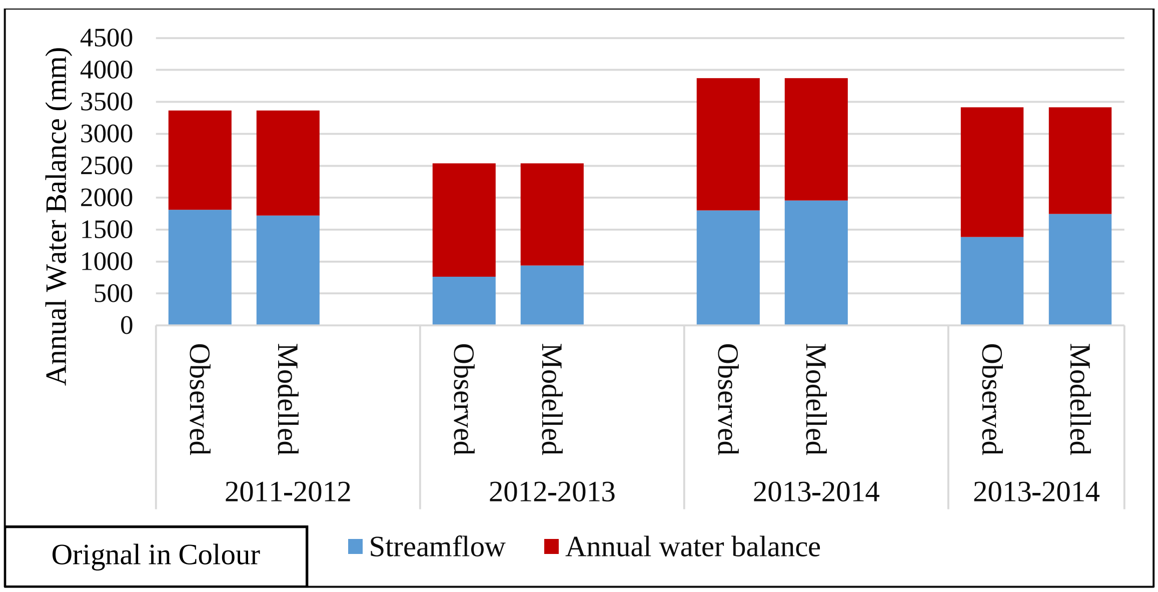

Figure 6-12 Annual water balance Ellagawa lumped model (Validation)

Table 6-13 and Figure 6-12 shows the annual water balance values for the Ellagawa Lumped model validation for the period 2010-2014. Table 6-14 shows the annual mass balance and annual runoff coefficients of Ellagawa lumped model during validation. Annual water balance error of the year 2010/2011, 2011/2012 and 2012/2013 are 6 %, 7 % and 10% respectively. Similarly, runoff coefficient of the validation also shows the satisfactory results. The modelled runoff coefficient is in the range of 0.37- 0.51 which is satisfactory value for rural watersheds.

6.3. Ellagawa Semi-Distributed Model Calibration

6.3.1. Modelling Scenario

Ellagawa semi-distributed model was calibrated for the purpose of comparison with Ellagawa lumped model. Ellagawa watershed was divided into three sub watersheds: Ratnapura, Lower Ellagawa and Upper Ellagawa shown in Figure 5-2 (Analysis section). Model was calibrated by optimizing hydrologic and hydraulic parameter for the streamflow at Ellagawa gauging station from 2006-2010. Routing time step was set 3600 seconds and conduit roughness was calibrated to 0.09. Table shows the calibrated parameter of Ellagawa semi-distributed model.

Table 6-15 Calibrated Parameter of Ellagawa Semi-Distributed Model

Parameters	Units	Ratnapura	Lower Ellagawa	Upper Ellagawa
		Values		
Surface Runoff				
N-Pervious	$s/m^{1/3}$	0.018	0.20	0.20
D-storage Pervious	mm	2.5	2.5	2.5
Infiltration				
Suction head	mm	270	270	270
Saturated Hydraulic Conductivity	Mm/hrs.	0.315	0.315	0.315
Initial Deficit	fraction	0.5	0.5	0.5
Ground Water				
GW lateral Discharge coefficient (A)	-	0.001793	0.001793	0.001793
Deep Percolation coefficient (B)	-	5	4	4

6.3.2. Model Calibration

Ellagawa semi-distributed model was calibrated with observed streamflow at Ellagawa gauging station from 2006-2010. Table 6-16 shows Mean Ratio of Absolute Error (MRAE), Annual water balance error and MRAE for high, medium and low flows of Ellagawa semi-distributed model during calibration. The Mean Ratio of Absolute Error (MRAE) for overall hydrograph is 0.2912 and annual water balance error 35.5%. Results shows good match in high, intermediate and low flow regions with MRAE 0.3615, 0.3055 and 0.1766. There was a significant improvement in statistical measure of goodness of fit for overall hydrograph and all flow regions compared to Ellagawa lumped model can be noticed.

Table 6-16 Calibration Results of Ellagawa Semi-Distributed Model

Gauging Station	MRAE	Annual Water Balance Error (%)	Flow Duration Curve		
			High	Intermediate	Low
			MRAE	MRAE	MRAE
Ellagawa	0.2912	35.5 %	0.3615	0.3055	0.1766

Figure 6-13 shows the hydrographs matching of Ellagawa semi-distributed model with observed flow of Ellagawa gauging station from the 2006-2010. Hydrographs matching during calibration is satisfactory and significantly improved from lumped model. Figure 6-14 shows the Flow Duration Curves (FDC) during model calibration where the variations in observed and modelled streamflows are plotted with respect to % time exceedance. The Flow duration curve are divided into three regions: high flow (0-10 %), intermediate flow (10-80%) and low flow (80 -100%). Normal plot of the Ellagawa semi-distributed model hydrographs are given in Appendix D in Figure D-3.

Original in Colour

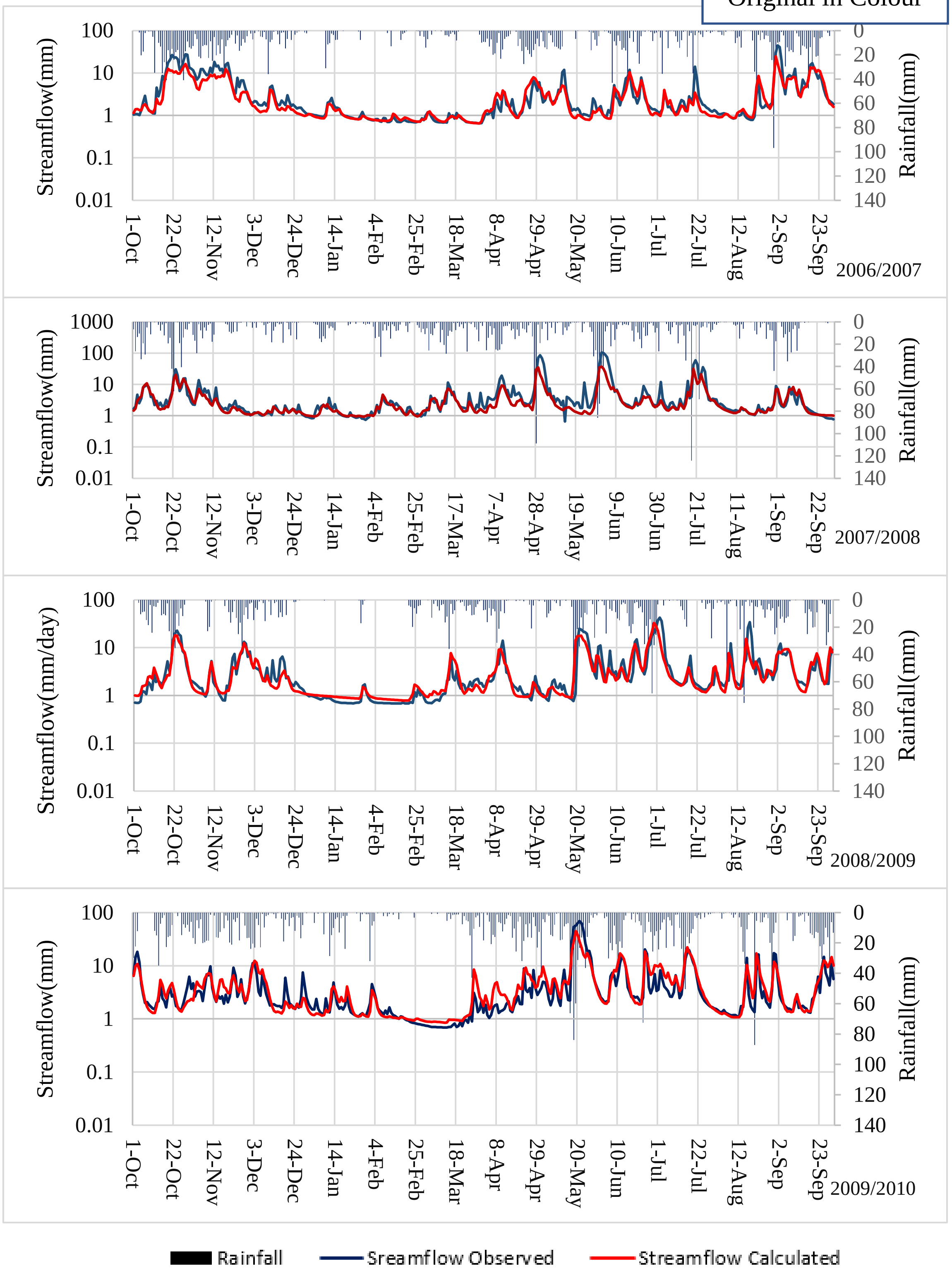

Table 6-13 Hydrographs of Ellagawa Semi-Distributed Model (Calibration)

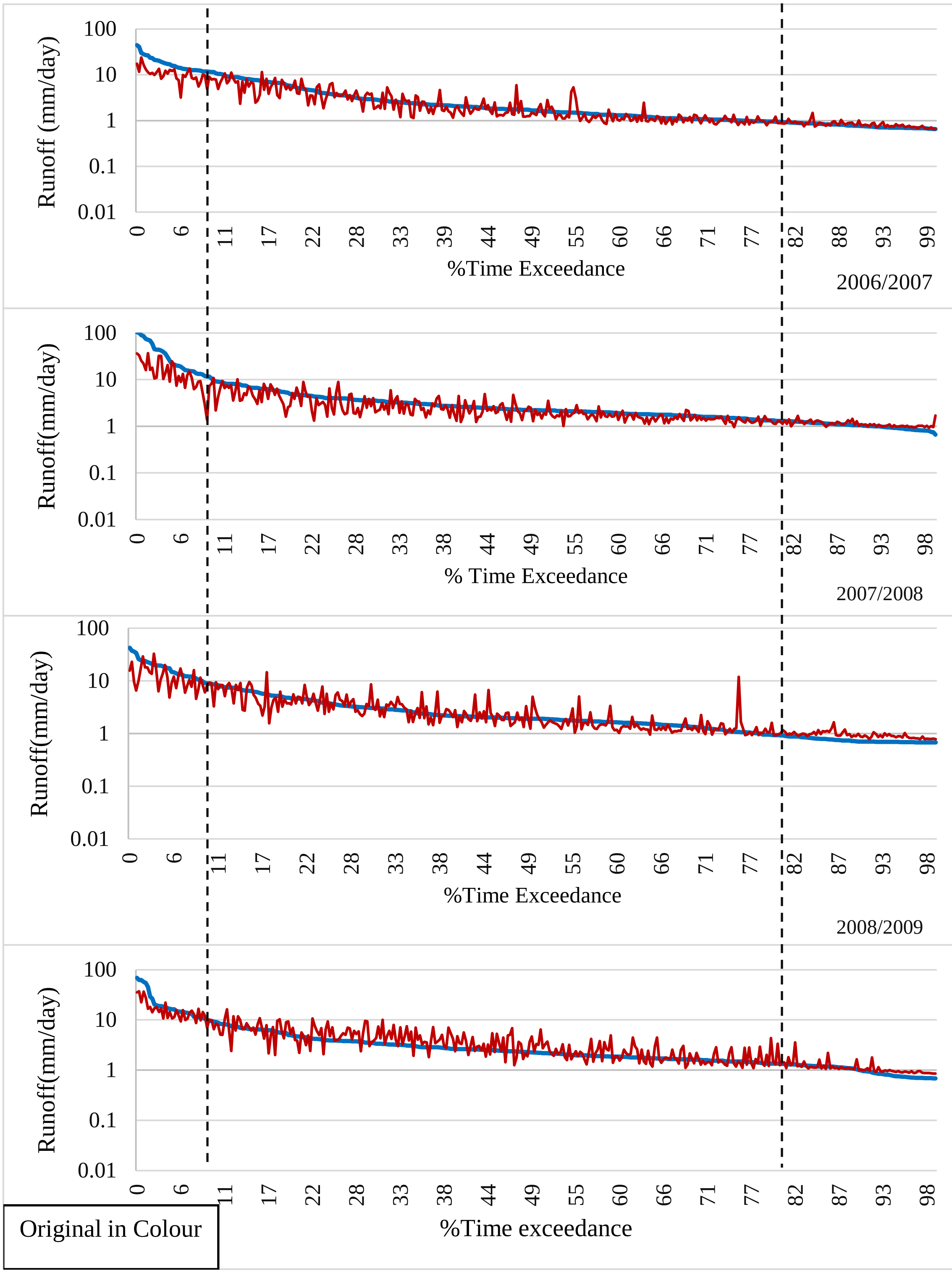

Figure 6-14 Flow Duration Curves of Ellagawa Semi-Distributed Model (Calibration)

Table 6-17 Annual Water Balance of Ellagawa Semi-Distributed Model Calibration

Year (Oct-Sep)	Rainfall (mm)	Observed Streamflow (mm)	Modelled Streamflow (mm)	Observed Water Balance (mm)	Modelled Water Balance (mm)	Annual water balance error %
2006-2007	2756.1	1425.6	1096.6	1330.5	1659.5	25
2007-2008	2971.6	2135.2	1303.3	836.3	1668.2	99
2008-2009	2445.8	1434.5	1262.1	1011.3	1183.7	17
2009-2010	3264.38	1658.0	1639.8	1606.3	1624.5	1

Table 6-18 Annual Mass Balance of Ellagawa Semi-Distributed Model Calibration

Year (Oct-Sep)	Rainfall (mm)	Streamflow Observed (mm)	Streamflow Modelled (mm)	Runoff Coefficient (Observed)	Runoff Coefficient (Modelled)	Annual Mass balance error %
2006-2007	2756.1	1425.6	1096.6	0.52	0.40	20
2007-2008	2971.6	2135.2	1303.3	0.72	0.44	38
2008-2009	2445.8	1434.5	1262.1	0.59	0.52	12
2009-2010	3264.38	1658.0	1639.8	0.51	0.50	1

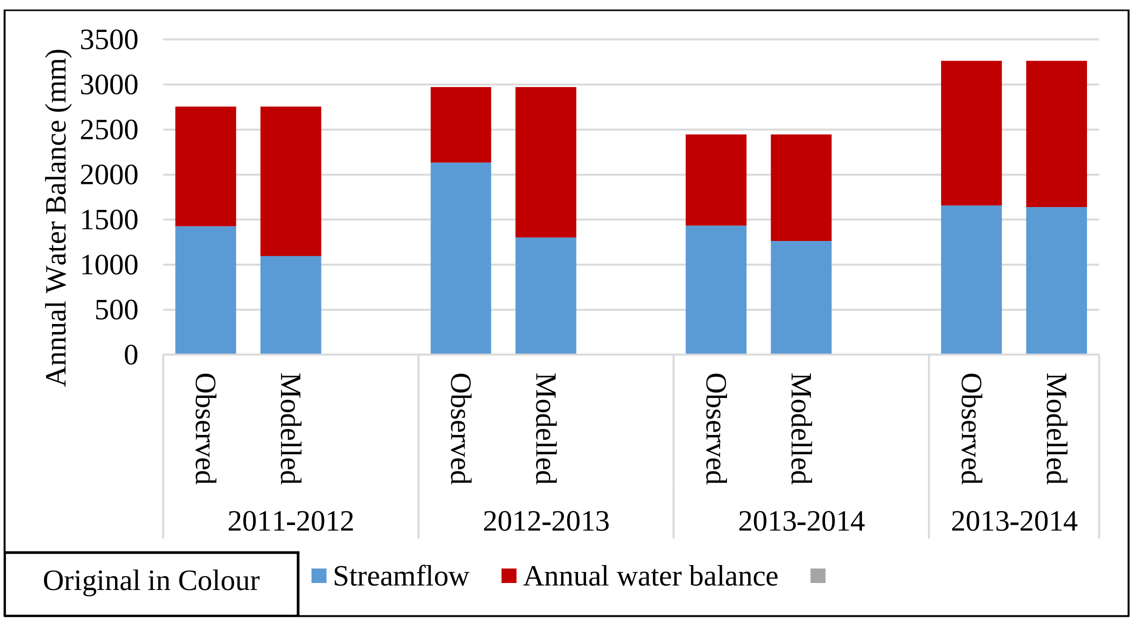

Figure 6-15 Annual Water Balance of Ellagawa Semi-Distributed Model (Calibration)

Table 6-17 and Figure 6-15 shows the Annual water balance values of Ellagawa lumped model for the calibration period 2006-2010. 2007/2008 has higher annual water balance error of 99%. Whereas, 2006/2007 and 2008/2009 have moderate water balance error 0f 25% and 17 % respectively. 2009/2010 has lowest water balance error of 1%. Furthermore, Table 6-18 shows annual mass balance and annual runoff coefficient calculation of Ellagawa lumped model during calibration. In the year 2007/2008 model deviates largely from observed annual streamflow. The runoff coefficient of observed streamflow was found inconsistent during calibration year 2007/2008. 2007/2008 have high observed runoff coefficient of 0.72 which is unusual value for rural watershed. However, runoff coefficient of modelled streamflow was found consistent throughout the calibration year. The runoff coefficient of modelled streamflow in 2007/2008 was 0.44 which is valid and reasonable runoff coefficient value for rural watersheds.

6.4. Ellagawa Semi-Distributed Model Validation

Ellagawa semi-distributed model was validated with observed flow at Ellagawa gauging Station from 2010-2014. Table 6-14 shows Mean Ratio of Absolute Error (MRAE), Annual Water Balance Error and MRAE for high, medium and low flows of Ellagawa semi-distributed model during validation. Mean Ratio of Absolute Error (MRAE) for overall hydrograph is 0.571 and annual water balance error is 10%. Results shows satisfactory matching in high, intermediate and low flow regions with MRAE are 0.3742, 0.6421 and 0.4089.

Table 6-19 Validation Results of Ellagawa Semi-Distributed Model

Gauging Station	MRAE	Annual Water Balance Error (%)	Flow Duration Curve		
			High	Intermediate	Low
			MRAE	MRAE	MRAE
Ellagawa	0.5761	10%	0.3742	0.6421	0.4089

Original in Colour

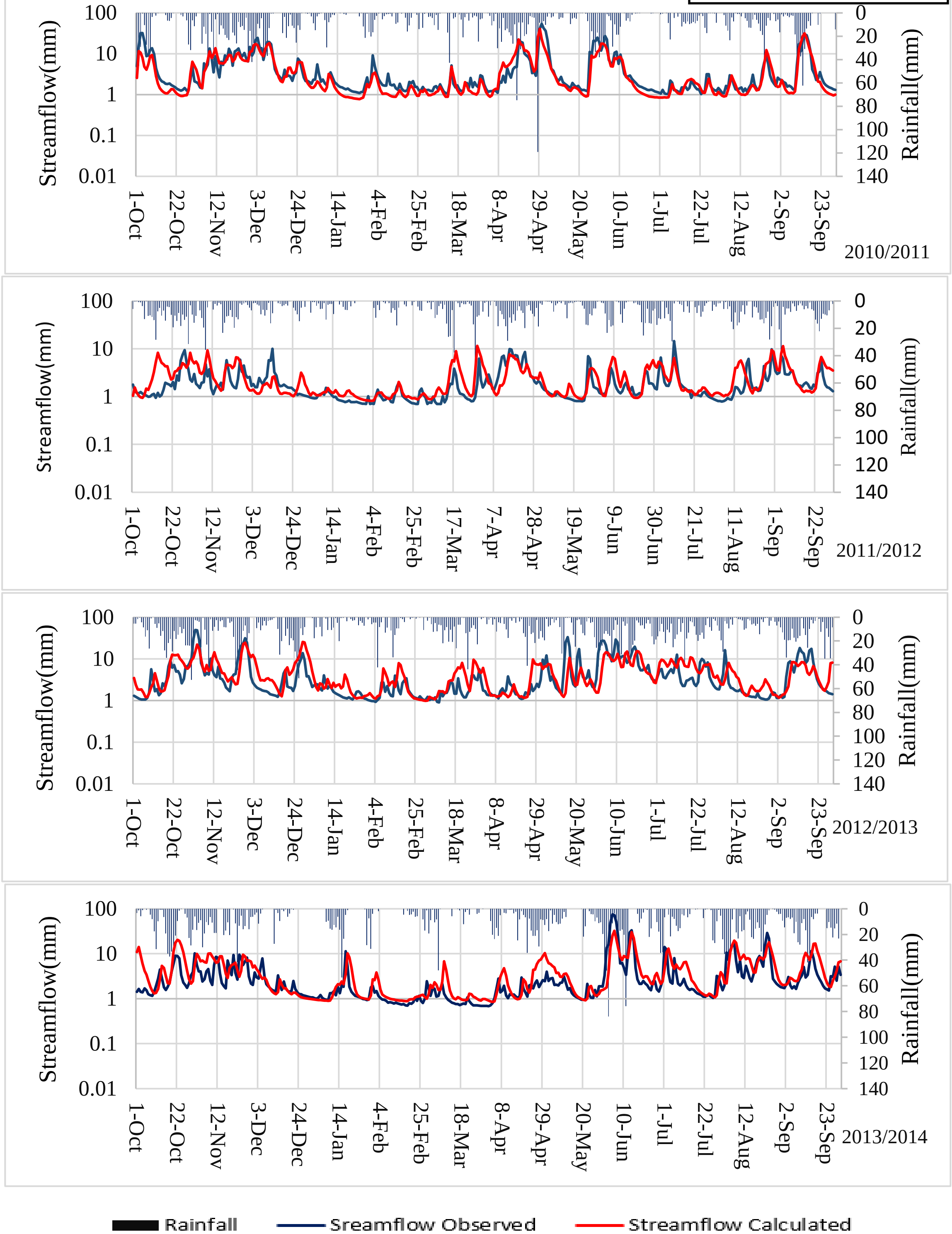

Figure 6-16 Hydrographs of Ellagawa Semi-Distributed Model (Validation)

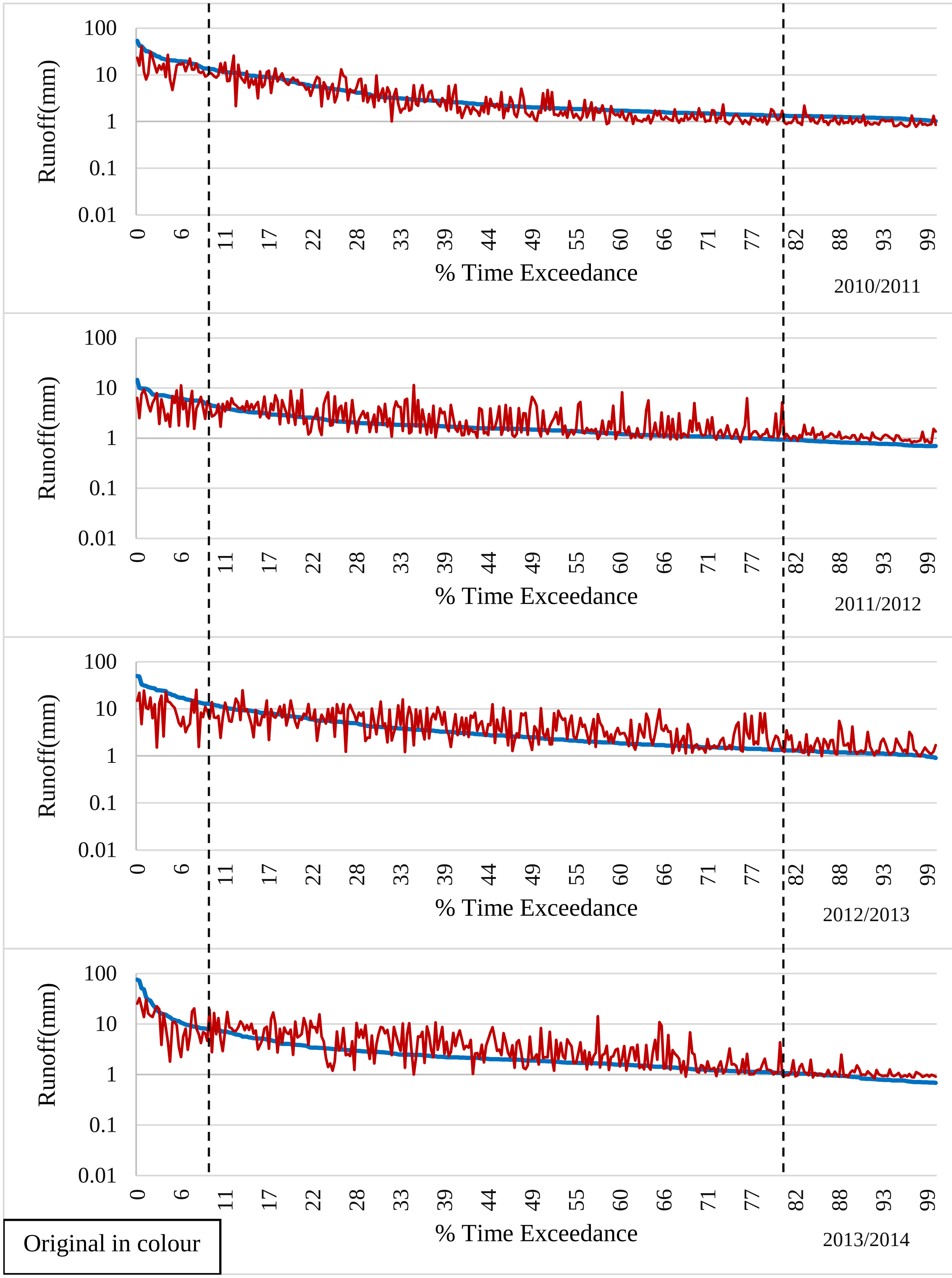

Figure 6-17 Flow Duration Curves of Ellagawa Semi-Distributed Model (Validation)

Figure 6-16, shows the hydrographs matching of Ellagawa semi-distributed model with observed flow at Ellagawa gauging station during validation. Hydrograph matching during the year of validation is satisfactory and significantly improved from lumped model. Figure 6-17, shows the Flow Duration Curves (FDC) during model validation where the variations in observed and modelled streamflows are plotted with respect to % time exceedance.. The Flow duration curves are divided into three regions: High flow (0-10%), Intermediate flow (10-80%) and low flow (80 -100%). Normal plot of the Ellagawa lumped hydrographs are given in Appendix D in Figure D-6.

Table 6-20 Annual Water Balance of Ellagawa Semi-Distributed Model Validation

Year (Oct-Sep)	Rainfall (mm)	Observed Streamflow (mm)	Modelled Streamflow (mm)	Observed Water Balance (mm)	Modelled Water Balance (mm)	Annual water balance error %
2010-2011	3364.6	1810.1	1524.5	1554.5	1840.1	18
2011-2012	2536.6	764.8	933.4	1771.8	1603.1	9.5
2012-2013	3869.4	1801.0	1832.0	2068.4	2037.4	1.5
2013-2014	3413.1	1383.0	1603.1	2030.1	1810.0	10.8

Table 6-21 Annual Mass Balance of Ellagawa semi-Distributed Model Validation

Year (Oct-Sep)	Rainfall (mm)	Streamflow Observed (mm)	Streamflow Modelled (mm)	Runoff Coefficient (Observed)	Runoff Coefficient (Modelled)	Annual Mass balance error %
2010-2011	3364	1810	1524.5	0.54	0.45	15
2011-2012	2536	764	933.4	0.30	0.37	22
2012-2013	3869	1801	1832.0	0.47	0.47	1
2013-2014	3413	1383	1603.1	0.41	0.47	15

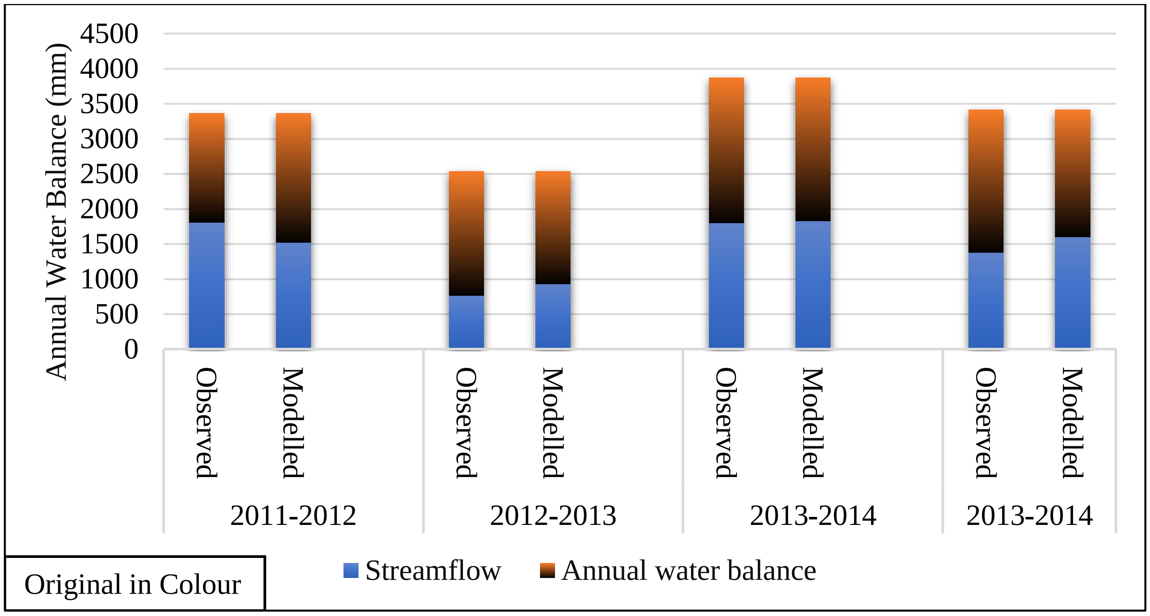

Figure 6-18 Annual Water Balance of Ellagawa Semi-Distributed Model (Validation)

Table 6-20 and Figure 6-18 shows the annual water balance values for the Ellagawa semi-distributed model during validation. Table 6-21 shows the annual mass balance and annual Runoff coefficient calculation for observation during validation. Annual water balance error for all the validation year is satisfactory. Annual water balance error of the year 2010/2011, 2011/2012, 2012/2013 and 2013/2014 are 18%, 9.5%, 1.5% and 10.8% respectively. Similarly, runoff coefficient of the validation also shows the satisfactory results. The modelled runoff coefficient is in the range of 0.37- 0.51 which is satisfactory value for rural watersheds.

7. DISCUSSION

7.1. Model Components

Model components of SWMM can be broadly classified into (i) Surface runoff (ii) groundwater. The infiltration compartment of SWMM can be referred as an intermediate component which plays the role of a bridge between aforementioned two components. Surface runoff and groundwater are responsible for generating total hydrograph at the outlet. Whereas, Infiltration compartment supplies the remaining water to the groundwater depending upon the nature and characteristics of the surface.

SWMM gives its user a wide range of options to select the models within these components. Available models in SWMM within surface runoff, groundwater and infiltration components are given in the Table 7-1 below.

Table 7-1 Available Models within the various Components of SWMM

S.N	Model Component	Models
1	Surface runoff	Nonlinear reservoir model
		Unit Hydrograph Method
2	Infiltration	Curve number
		Horton's and Modified Horton's
		Green-Ampt and Modified Green Ampt
3	Groundwater	SWMM standard groundwater model (lateral flow per horizontal area of the groundwater region)
		User-Defined Flux Equations (two-stage linear reservoir model for lateral groundwater outflow)

Nonlinear reservoir model was chosen over the unit hydrograph method for surface runoff component. Among the various reasons for selecting the nonlinear reservoir model over unit hydrograph, some are listed below.

1. The Nonlinear reservoir model is a preferred surface runoff model in general practice
2. A few literatures can be found where the unit hydrograph method is chosen for surface runoff modelling in SWMM.
3. Unit hydrograph approach in SWMM is to model surface runoff empirically where it needs observed rainfall-runoff records within a specific watershed or be chosen from a number of synthetic unit hydrographs.
4. Unit hydrograph method in SWMM is only designed to generate direct hydrograph at the outlet so it can be coupled with groundwater model to generate total hydrograph.

In case, of Infiltration component, modified Green-Ampt method was selected. Use of CN number method becomes obsolete when it comes to long-term simulation or continuous modelling. Horton’s and Green-Ampt method were characterized and ranked based on the model complexity, data requirement and performance. The Green-Ampt method was favoured compared to Horton’s method. While on groundwater component, user-defined flux equations (two-stage linear reservoir model for lateral groundwater outflow) was selected since parameters on SWMM standard groundwater model needs observed data which were unavailable in case of the Sri Lankan context. SWMM standard groundwater model deals with the large number of parameters which makes it a more complex model to be incorporated. In addition to these hydrological model component, there is a hydraulic model component namely conveyance compartment in SWMM. Conveyance compartment is responsible to transport the generated flow from the point of flow accumulation to the sub-watershed outlet. Conveyance compartment deals with a number of parameters which can be physically determined: conduit shape, conduit length, node invert elevation and some calibration parameters: conduit roughness coefficient which can be easily estimated.

7.2. Optimization

The process of the optimization started with the sorting out sensitive parameters. Since, long term continuous simulation of total hydrograph in SWMM deals with the large set of parameters, all of them cannot be optimized. Therefore, it is needed to identify sensitive parameters. N-pervious in surface runoff compartment, saturated hydraulic conductivity in infiltration compartment and groundwater discharge coefficient in groundwater compartment were found most sensitive parameters. Table 7-2 shows parameters of different model components were subjected to the optimization exercise based on the parameter sensitivity analysis.

Table 7-2 Parameters Subjected to Optimization

Parameters	Units
Surface Runoff	
N-Pervious	seconds/meters$^{1/3}$
Depression storage Pervious	millimeters
Infiltration	
Suction head	millimeters
Saturated Hydraulic Conductivity	millimeters/hour
Initial Deficit	Fraction
Groundwater	
GW lateral Discharge coefficient (a)	meters/sec
Deep Percolation coefficient (b)	meters/sec

The main problem with SWMM was unavailability of automatic parameter an optimization tool. The set of parameters to be optimized was reduced to seven (7). The optimization process was using combinations of parameters within a certain model component. First, parameters of surface runoff compartment namely N-pervious and D-storage pervious were optimized. Then parameter of infiltration compartment namely Suction head, saturated hydraulic conductivity and initial deficit were optimized. Finally, groundwater parameters a. GW lateral Discharge coefficient b. Deep Percolation coefficient was optimized. Mean Ratio of Absolute Error (MRAE) was chosen as the objective function for the optimization. Although the objective of the study was not flood modelling (matching of the peaks are a not necessity), Nash efficiency which is proven as a good objective function for peak discharge simulation was also computed to avoid undesirable peaks in the hydrograph. Annual water balance error was also used to evaluate model performance. The overall performance was thus evaluated by MRAE of the overall hydrograph, annual water balance error and the MRAE of high, intermediate and low flows. The details of systematic optimization of the parameters corresponding to different model components are given in Figure E-1, Figure E-2 and Figure E-3 of APPENDIX E. The manual optimization technique is a rigorous and a time-consuming process effort and was not efficient. Models dealing large set of parameters may need to look at automatic optimization. The absence of automatic optimization and to optimize the large set of parameters manually is a point of concern in this study.

7.3. Lumped Model

7.3.1. Comparison of Calibration Results

Table 7-3 Comparison of Results of Lumped Models (Calibration)

Gauging Station	MRAE	Annual Water Balance Error (%)	Flow Duration Curve		
			High	Intermediate	Low
			MRAE	MRAE	MRAE
Ratnapura	0.4531	31	0.38	0.37	0.77
Ellagawa	0.3634	38	0.36	0.40	0.20

Table 7-3 shows the results of lumped model calibration. Result for both lumped models showed satisfactory performances in terms of MRAE, MRAE in flow duration curve (High flows, Intermediate Flow and low flows) and annual water balance errors. Mean Ratio of Absolute Error (MRAE) for Ratnapura lumped model for overall hydrograph (0.4531) is slightly higher than that of Ellagawa (0.3634). The MRAE value high flows and intermediate flows for Ratnapura Lumped model are 0.38 and 0.37 respectively whilst MRAE for high and intermediate flows for Ellagawa Lumped model are 0.36 and 0.40 respectively. Therefore it can be said that, the high flow and intermediate flow simulation in both lumped models are satisfactory good. Although, MRAE for low flows region showed very good matching in Ellagawa lumped model, it is not so in the case of low flows region of Ratnapura. Similarly, Annual water balance error for Ratnapura and Ellagawa lumped models are 31% and 38% respectively which can be considered as well satisfactory result.

Table 7-4 Comparison of Runoff coefficients of Lumped Models (Calibration)

Runoff coefficient (Simulated hydrograph)	Lumped model	Calibration data period			
		2006/2007	2007/2008	2008/2009	2009/2010
	Ratnapura	0.43	0.45	0.44	0.46
	Ellagawa	0.45	0.47	0.40	0.65

Comparison of annual runoff coefficient of simulated hydrograph during calibration is shown in Table 7-4. Annual runoff coefficient for Ratnapura is consistent in rage of 0.43-0.46 while it varied in wider range (0.40-0.65) in the case of Ellagawa. However, both the models are showing a reasonable value of runoff coefficient acceptable for rural watersheds. Therefore, the results of calibration in terms of simulated annual runoff coefficients can be considered satisfactory.

7.3.2. Comparison of Validation Results

Table 7-5 Comparison of Results of Lumped Models (Validation)

Gauging Station	MRAE	Annual Water Balance Error (%)	Flow Duration Curve		
			High	Intermediate	Low
			MRAE	MRAE	MRAE
Ratnapura	0.7843	11	0.4685	0.8295	0.9905
Ellagawa	0.5865	10.25	0.4266	0.6853	0.2939

Table 7-5 shows the results of lumped models validation. Compared to validation results of Ellagawa lumped model Ratnapura shows very poor results for overall hydrograph and for intermediate and low flows. Mean Ratio of Absolute Error (MRAE) for Ratnapura lumped model for overall hydrograph (0.7843) is much higher than that of

Ellagawa (0.5865). Both models performed well in terms of annual water balance error and high flow simulations. Annual water balance error of Ratnapura and Ellagawa lumped model are 11% and 10.25% respectively. Similarly, MRAE of Ratnapura and Ellagawa lumped models in high flow region are 0.4685 and 0.4266 respectively. Furthermore, Ellagawa lumped model is validated with minimum MRAE (0.2939) in low flows region while, MRAE of low flow region of Ratnapura is the maximum among the flow types. In addition to that, simulation errors on intermediate flows of Ratnapura lumped model is much higher than Ellagawa lumped model.

Table 7-6 Comparison of Runoff Coefficients of Lumped Model (Validation)

Runoff coefficient (Simulated hydrograph)	Lumped model	Validation data period			
		2010/2011	2011/2012	2012/2013	2013/2014
	Ratnapura	0.49	0.38	0.40	0.46
	Ellagawa	0.51	0.37	0.50	0.51

Comparison of annual runoff coefficient of simulated hydrograph during validation is shown in Table 7-6. The annual runoff coefficient for Ratnapura is in rage of 0.38-0.49 while it showed a wider range (0.37-0.51) in the case of Ellagawa. 2011/2012 is marked by low runoff year in both models. Although, variation of annual runoff coefficient is higher in both Ellagawa and Ratnapura lumped models, both the models are showing a reasonable value of runoff coefficient for rural catchments. In that sense, the results of validation in terms of annual runoff coefficient of simulated hydrograph can also be considered satisfactory.

7.4. Semi-Distributed Modeling

7.4.1. Semi-Distributed Modelling (SWMM)

Storm Water Management Model (SWMM) is basically a semi-distributed conceptual rainfall-runoff model. It is based on the definition of sub-watershed units delineated upon analysis of the areas draining towards a given discharge point. This discharge point which is referred generally as outlet is termed as outfall in SWMM. The outfall is represented by a computational node and usually corresponds to the node of the system.

Each sub-watershed unit is approximated by a regularly shaped surface to which uniform morphological and hydrological characteristics are assigned. A spatially uniform rainfall input is assigned to each sub-watershed. Unlike lumped models where there is a single outlet and precipitation input, distributed models with a number sub-watershed need to have several gauges and stream gauge. The runoff generated from each sub-watershed should be routed to final outfall node to obtain total hydrograph of the basin. Runoff volumes estimated for the sub-watersheds are routed to the sub-watershed outlet and finally to the outfall. Nodes should be placed on the sub-watershed outlet and at the junction point. Those nodes should be further linked by conduits for the passage of the flow. Node elevation, conduit geometry, conduit roughness, routing time step are some additional parameters to define in distributed modelling. An appropriate routing process should be selected based on the nature of the flow and watershed physical properties. Dynamic wave routing was selected for the purpose of this study.

7.4.2. Calibration Procedure

Calibration procedure adopted for this study is one-at-a-time calibration of sub-watersheds model. In distributed models, each sub-watershed is an independent unit with separate input parameters which give specific output for the sub-watershed. Since outlets of all three catchments are not gauged; calibration was done with reference to the observed streamflow at the main outfall. Calibration of the Ellagawa distributed model started with the estimation of the hydraulic parameters such as nodes, conduits properties and routing time steps. Among the numbers of the parameter in the hydraulic model, routing time steps and conduit roughness were the parameters to be optimized. This is because parameters like conduit geometry, conduit length, and node elevation are the parameter which could be physically determined. Those parameters (routing time steps and conduit roughness) were optimized using rational trail value range closer to the initial estimation. The routing time step is chosen to be uniform in all three sub-watersheds. Optimized parameters of the Ellagawa and Ratnapura lumped model were inserted as the initial estimations for the calibration of distributed sub-watershed models.

Therefore, only fine tuning of those sub-watershed models was needed rather than optimizing the whole set of the parameters.

7.4.3. Improvement of model performance

Table 7-7 Comparison of Ellagawa Lumped and Semi-Distributed Model (Calibration)

Gauging Station	MRAE	Annual Water Balance Error (%)	Flow Duration Curve		
			High	Intermediate	Low
			MRAE	MRAE	MRAE
Ellagawa lumped model	0.3634	38%	0.3658	0.4030	0.2007
Ellagawa semi-distributed model	0.2912	35.5%	0.3615	0.3055	0.1766

Table 7-8 Comparison of Ellagawa Lumped and Semi-Distributed Model (Validation)

Gauging Station	MRAE	Annual Water Balance Error (%)	Flow Duration Curve		
			High	Intermediate	Low
			MRAE	MRAE	MRAE
Ellagawa lumped model	0.5865	10.25	0.4266	0.6853	0.2939
Ellagawa semi-distributed model	0.5761	9.95	0.3742	0.6421	0.4089

Improvement of the model performance of Ellagawa semi-distributed parameter model can be evaluated once it is compared with the Ellagawa lumped model. The comparison of model performances of lumped and the semi-distributed model during calibration and validation is given in Table 7-7 and Table 7-8. MRAE of overall hydrograph, Annual Water Balance Error and MRAE of low, intermediate and high flows showed good results during the calibration of distributed model. MRAE of overall hydrograph was reduced to 0.2912 from 0.3634, a 19% reduction on errors. The MRAE for overall hydrograph 0.2912 in the semi-distributed model can be considered to be in the minimum range of errors. Similarly, MRAE has been reduced in all flow regions. Low flow from 0.2007 to 0.1766, intermediate flow from 0.4030 to 0.3055 and high flows from 0.3658 to 0.3615. In addition, annual balance error has also shown a decent improvement by reducing from 38% to 33.5%. The reduced errors are not only good when compared to the lumped model but also indicates a minimum range of errors that are expected in modelling practices. For Example MRAE for low flow region of distributed model is 0.1766 which falls in the best range of errors in continuous modelling. Therefore it can be said that there has been a significant improvement on model performance during calibration of the semi-distributed model as compared to the calibration of the lumped model. Similar to calibration, validation of the semi-distributed model also showed satisfactory improvement in the model performance when compared with the validation of the lumped model. MRAE of the overall hydrograph is reduced to 0.5761 from 0.5865. In addition, Annual water balance error showed a good improvement by reducing from 10.25% to 9.95%. The high and intermediate flow showed fair improvement as they reduced from 0.4266 to 0.3742 and 0.6853 to 0.6421 respectively.

The result showed considerable improvement of performance in terms of MRAE of the overall hydrograph, high flow, intermediate flow and low flow with the inclusion of sub-watersheds. This could be easily attributed to the increased number of parameter. However, the increase of parameter with sub-watershed is different to increase of parameter in a single lumped model. This permits flexibility and meaningfulness to incorporate distributed physical characteristics and also the inclusion of meaningful flow routing.

7.5. Comparison of Parameters

7.5.1. Physical Parameters

Physical parameters are derived from physical characteristics of the watershed. The physical parameters are closely related to the geometrical shape and topographical condition of the watershed. These parameters are obtained by combining DEM with spatial information of watersheds based on geometrical analysis in ArcGIS. Physical properties of watershed like watershed area, width and slope are physical parameters of the model.

Table 7-9 Comparison of Physical Parameters of the Models

Parameters	Ratnapura Lumped	Ellagawa lumped	Ellagawa semi-distributed		
			Ratnapura	Upper Ellagawa	Lower Ellagawa
Area (Hectares)	65300	134200	65300	29800	39100
Width (meters)	15000	26000	15000	12000	750
Slope (m/m)	0.01	0.01	0.01	0.02	0.01

Table 7-9 shows the physical parameters of Ratnapura lumped, Ellagawa lumped and Ellagawa semi-distributed model. The width of the watershed can be defined as area of watershed divided by length of the longest overland flow path. Similarly, slope of the watershed is defined as ratio of difference of elevations to the length of the longest overland flow path. Area of the watershed is directly proportional to the runoff volume. Similarly, Slope of the watershed is directly proportional to runoff peak and width of the watershed is inversely proportional to runoff peak. Watershed area of Ratnapura, Ellagawa, Upper Ellagawa and Lower Ellagawa are 65300 ha, 134200 ha, 29800 ha and 39100 ha respectively. This implies runoff volume generated by Ellagawa watershed highest and runoff volume generated by Upper Ellagawa is lowest. Watershed width of Ratnapura, Upper Ellagawa and Lower Ellagawa are 1500m, 26000m, 12000m and 750m. This signifies runoff peaks corresponding to the watershed width is higher in Lower Ellagawa watershed compared to other watersheds. Similarly, Watershed slope of Ratnapura, Ellagawa and Lower Ellagawa are 0.01 whereas watershed slope of Upper Ellagawa is 0.02. This signifies runoff peaks corresponding slope of the watershed is higher in Upper Ellagawa watershed compared. However, in real scenario combination of all these parameters are responsible shape, volume and peaks of output hydrograph.

7.5.2. Calibration Parameters

Values of the calibration parameters depend upon the land cover types in the watershed. Therefore, values of such parameters are estimated from literatures.

Table 7-10 Comparison of Calibration Parameters

Parameters	Ratnapura Lumped	Ellagawa Lumped	Ellagawa Semi-distributed				Remarks
			Ratnapura	Upper Ellagawa	Lower Ellagawa	Average	
N-pervious ($s/m^{1/3}$)	0.028	0.02	0.018	0.02	0.2	0.08	A change in the order of magnitude can be seen at the Lower Ellagawa Watershed
N-impervious ($s/m^{1/3}$)	0.013	0.013	0.011	0.11	0.11	0.08	A change in the order of magnitude can be seen at the upper and Lower Ellagawa Watershed
D-Store Pervious (mm)	1.2	2.5	2.5	2.5	2.5	2.5	Ratnapura Lumped and Ellagawa has a difference but sub watershed and main watershed has the same values
D-Store Impervious (mm)	1.1	1.1	1.1	1.1	1.1	1.1	No change in Values
Suction head (mm)	270	270	270	270	270	270	No change in Values
Conductivity (mm/hr.)	0.672	0.3	0.315	0.315	0.315	0.315	Ratnapura Lumped and Ellagawa has a difference but sub watershed and main watershed has the same values
Initial deficit	0.46	0.2	0.5	0.5	0.5	0.5	Ratnapura Lumped, Ellagawa Lumped and Ellagawa Semi Distributed has a difference
Lateral discharge coefficient	0.002581	0.001793	0.001793	0.001793	0.001793	0.001793	Similar order of magnitude
Deep percolation coefficient	4	5	5	4	4	4	Similar order of magnitude

Table 7.10 shows the calibrated parameters of Ratnapura lumped, Ellagawa lumped and Ellagawa semi-distributed model. There is significant variation in between parameters of Ratnapura lumped model and Ellagawa lumped whereas parameters of Ellagawa lumped model and Ellagawa distributed model remains closely similar. N-pervious of Ratnapura lumped, Ellagawa lumped model and Ratnapura sub-watershed of Ellagawa semi-distributed model were calibrated to 0.028, 0.02 and 0.018. Similarly, depression storage of pervious layers of Ratnapura lumped model and Ellagawa lumped model are 1.2 mm and 2.5mm. Similarly, saturated hydraulic conductivity of Ratnapura lumped model, Ellagawa lumped model and Ellagawa semi-distributed model varies to each other. Values of saturated hydraulic conductivity was 0.67, 0.3 and 0.315 for Ratnapura lumped model, Ellagawa lumped model and Ellagawa semi-distributed model respectively. Similarly, in the lateral discharge coefficient of ground water model for Ratnapura lumped model and Ellagawa Lumped model were 0.00258 and 0.001793 respectively.

7.5.2.1.Calibrated Parameter Value

Manning's roughness coefficient of pervious layer varied in the range 0.02-0.18 whereas Manning's roughness coefficient of impervious layer varied in the range 0.11-0.13. Rossman & Huber, (2016) have listed Manning's roughness coefficient value SWMM reference manual. Manning's roughness 0.02 represents the landcover of bare clay loom whereas 0.2 represents landcover of short grasses. Similarly, Manning's roughness coefficient of the range 0.10-0.13 represents the concrete and asphalt surface. The Manning's roughness coefficient is inversely proportional to the runoff. This implies runoff corresponding to Manning's roughness is higher in Ellagawa, Ratnapura and Upper Ellagawa watershed and lower in Lower Ellagawa watershed. Similarly, Depression storage of impervious layer was calibrated to 1.1 mm and depression storage of pervious storage layer was calibrated to 2.5 mm. The depression storage of impervious layer is much lesser than depressions storage of pervious layer because water retention capacity of pervious layer is lesser than that of pervious layer. Variation of depression storage value among the watershed is negligible because the influence of the spatial distribution of depression storage in the watershed is insignificant. There is no definite range of depression storage provided in literature. The saturated hydraulic conductivity is one of the sensitive parameters. Saturated hydraulic conductivity varied in the range (0.3mm/hr.-0.67mm/hr.) According to Rawls et al., (1983) hydraulic conductivity value range from 0.254 mm/hr. to 0.67 mm/hr. represents the soil type of silty clay loam soil, silty clay and clay soil type. Although the details of soil types of the watershed are not available, it is known that Sri Lankan highland has brownish loam (Clay loam) type of soil. The saturated hydraulic conductivity is inversely proportional to the surface discharge. The rate of infiltration (K=0.675) in Ratnapura lumped model is much higher than other models which implies runoff corresponding to hydraulic conductivity is lesser in Ratnapura lumped model than other models. The suction head value is an insensitive parameter thus did not varied at all. The calibrated value of suction head was 270 mm which represent silty clay loom type of soil. Similarly, initial moisture deficit varied in the range of 0.2-0.5 which is dimensionless value and does not represent any specific soil type or landuse. Initial moisture deficit is the amount of moisture needed to soil for surface runoff to happen. Hence, the value of initial moisture deficit is inversely proportional to the runoff. The Ellagawa lumped model has the lesser initial moisture deficit (0.2) compared to other models which imply that the runoff corresponding to initial moisture deficit is higher in Ellagawa lumped model than other models. The value of the initial moisture deficit can be only derived from calibration. Furthermore, two parameters namely lateral discharge coefficient and deep percolation coefficient of groundwater model were calibrated. These parameters are responsible for baseflow in the hydrograph. Lateral discharge coefficient is responsible for immediate baseflow whereas deep percolation coefficient is responsible for lagged time baseflow. Lateral discharge coefficient value is calibrated in the range of 0.1793-0.02581 and value of deep percolation coefficient is calibrated in the range of 4-5. The values of these coefficients cannot be found any literature. Hence, the groundwater parameter value should be validated with similar studies future in other watersheds.

7.6. Comparison of Water Quantity Estimations

Water quantity estimation for three models: Ratnapura lumped, Ellagawa lumped and Ellagawa semi-distributed for different temporal scale are calculated and compared Table 7-11.

Table 7-11 Comparison of Water Quantity Estimation

Watershed model	Rainfall	Observed Streamflow	Modelled Streamflow	Streamflow Estimation Difference	% Difference
Annual (mm/year/mm^2)					
Ratnapura Lumped	3179	1588	1392	196	12.3
Ellagawa Lumped	3078	1552	1445	107	6.9
Ellagawa Semi-Distributed	3078	1552	1399	153	9.9
Maha Season (mm/season/mm^2)					
Ratnapura Lumped	1407	669	598	71	10.6
Ellagawa Lumped	1618	743	736	7	0.9
Ellagawa Semi-Distributed	1618	743	535	208	28.0
Yala Season (mm/season/mm^2)					
Ratnapura Lumped	1772	918	793	125	13.6
Ellagawa Lumped	2002	1075	981	94	8.7
Ellagawa Semi-Distributed	2002	1075	833	242	22.5
Monthly (mm/month/mm^2)					
Ratnapura Lumped	265	132	116	16	12.1
Ellagawa Lumped	298	150	142	8	5.3
Ellagawa Semi-Distributed	298	150	116	34	22.7

Ratnapura lumped model estimated annual streamflow with maximum error (10.6%) whereas Ellagawa lumped model estimated annual streamflow with minimum error (6.9%). Similarly, Ellagawa semi-distributed model estimated seasonal streamflow with maximum error (28% in Maha and 22.5% in Yala) whereas Ellagawa lumped model estimated seasonal streamflow with minimum error (0.9% in Maha and 8.7% in Yala). Furthermore, Ellagawa semi-distributed model estimated monthly streamflow with maximum error (22.7%) whereas Ellagawa lumped model estimated monthly streamflow with minimum error (5.3%). Comparing the streamflow estimation of Ellagawa lumped model and Ellagawa semi-distributed model it was found that Ellagawa Lumped model estimated better annual, seasonal and monthly streamflow than Ellagawa semi-distributed model. Although annual, seasonal and monthly streamflow estimations have greater significance for water resources management. The result showed there is no considerable improvement in estimation of streamflows with the inclusion of sub-watersheds. Hence, distributed sub-watershed model cannot be considered better and meaningful modelling option for water resources management.

7.7. Hydro-Meteorological Data

7.7.1. Selection of Data Period

Continuous rainfall-runoff modelling requires at least 8-10-years of daily resolution data. These data should be further divided into calibration and validation data. The long (4-5-year) data set is expected to model the watershed with longer period validity. Kalu Ganga basin consisted of two gauging stations. They are Ratnapura and Ellagawa gauging station. Ratnapura gauging station has not been functioning from 1998 to 2006. Since 2006 both gauging station were functioning therefore, the period of 2006-2014 was selected. It is better to select the recent years for the modelling because it would have more validity for forthcoming years. There is the need of existence of extreme years in terms of rainfall and streamflow. 20011/2012 was noted as the driest year and 2012/2013 and 2013/2014 were noted as the wet years. The existence of contrasting weather conditions in a data set makes model more robust.

7.7.2. Data Error

Errors in data have been noted through annual water balance. Though 2006/2007 and 2007/2008 had similar amounts of rainfall, the streamflow had increased in 2007/2008. The annual runoff coefficient of 2007/2008 year was found to be 0.75 which felt as an unrealistic value for a rural watershed. Similarly, in the year 2011/2012 streamflow does not seem to respond to rainfall. The issue indicates that either there is inconsistency in the streamflow data or because the Theissen average is not representing the actual situation. Due to difficulty in availability of long term continuous data, the available data with discrepancies were adopted for the study. Number of the sharp peaks without rainfall signals and flat hydrograph during the rain has been noted in visual observation of daily hydrographs which presented in data checking section 4-7.

7.8. Uncertainty in Groundwater Model

SWMM has been widely used as an urban drainage model and its application to rural water is a new investigation. Urban sewerage and drainage systems are generally lined concrete where groundwater recharge is negligible. Outflow from urban watersheds is generally equivalent to surface runoff. Due to these reasons, though there was adequate literature on SWMM, no reference has cited continuous simulation with groundwater. SWMM 5.1 reference manual 2016, has updated the groundwater modelling techniques It has given user two option on the selection of the groundwater model: (i). SWMM standard ground model ii. User-defined custom equation. The SWMM standard groundwater model needs physical data which cannot be estimated manually and on the other hand, it deals with many parameters. User defined custom equation is a linear reservoir model which is much simpler compared to standard groundwater equations and deals fewer number of parameters. Parameters of the linear reservoirs groundwater model deal with (a) groundwater recharge coefficient (b) deep percolation coefficient. SWMM groundwater model was simulated by observing the base flow of the hydrograph and adjusting the groundwater recharge coefficient and deep percolation coefficient simultaneously. Even with no literature support and references available the groundwater model was calibrated satisfactorily. The groundwater simulation in SWMM carried in this study is unique in its type because no literature for similar studies can be found. As such there can be some inherent uncertainties in the groundwater models which should be studied separately future research. Groundwater model cannot validate from observed surface runoff data, groundwater flows are not generally monitored in Sri Lanka. Therefore, it is recommended to carry out further similar studies improve and validate the groundwater model of SWMM.

8. CONCLUSIONS

1. Continuous modelling of rural watersheds can be satisfactorily carried out in SWMM and was demonstrated with both lumped and semi-distributed application.
2. Ellagawa lumped model and Ratnapura lumped model were calibrated and validated with the acceptable value of MRAE. MRAE for Ellagawa lumped and Ratnapura lumped model were 0.45, 0.36 respectively during calibration and were 0.58, 0.78 respectively during validation.
3. Lumped models in SWMM showed water resources assessment capability with good high and intermediate flow estimations. Ellagawa and Ratnapura lumped models calibrated high flow with MRAE 0.38 and 0.36 respectively and intermediate flow with MRAE 0.40 and 0.37 respectively.
4. Manning's roughness coefficient (pervious), Depression Storage (pervious), saturated hydraulic conductivity, initial deficit were most sensitive calibration parameters. Manning's roughness coefficient (pervious) was optimized in the range (0.02 $s/m^{1/3}$-0.028 $s/m^{1/3}$), depression storage (pervious) was optimized in the range (1.2mm-2.5 mm), and saturated hydraulic conductivity was optimized in the range of (0.3 mm/hr-0.67 mm/hr.). Similarly, initial moisture deficit varied in the range of (0.2-0.5).
5. Ellagawa semi-distributed model showed some improvements in MRAE for overall and intermediate daily flow compared to Ellagawa lumped model. MRAE for overall flow and intermediate flow reduced from 0.36 to 0.29 and 0.40 to 0.30 respectively during calibration and 0.58 to 57 and 0.68 to 0.64 respectively during validation. However, Ellagawa semi-distributed model showed poor estimations of annual, seasonal and monthly streamflow compared to Ellagawa lumped model. Therefore, the semi-distributed model with single gauging cannot be considered as better and meaningful modelling option in SWMM with certainty.

9. RECOMMENDATIONS

1. More application of SWMM for continuous modelling of streamflow in monsoon regions is recommended.
2. More research on automatic optimization and objective function is recommended.
3. More study on groundwater parameters estimation is recommended.
4. Good quality of rainfall and streamflow data should be available for better quality of modelling work in the future.
5. Streamflows should be better gauged at watersheds and subwatersheds for future challenges such as flood, drought and water resources management.

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REFERENCES

Acharya, A. (2018). Evaluating the Suitability of Application of Hydrological Models in a Mixed Land Use Watershed. *Journal of Water Management Modeling*, 26 (C456).

Addor, N., & Melsen, L. A.(2019). Legacy, Rather Than Adequacy, Drives the Selection of Hydrological Models. *Water Resources Research*, 55(1), 378–390.

Akdogan, Z., & Guven, B. (2016). Assessing the Sensitivity of the SWMM to Variation in Hydrological and Hydraulic Parameters. A Case Study for the City of Istanbul.18 (4), 831 - 841

Arcement, G. J., & Scheider, V.(1989). Guide for Selecting Manning’s Roughness Coefficients for Natural Channels and Flood Plains. USGS.

Askari, K., & Shayannejad, M. (2016). Flood Routing in Rivers by Muskingum's with new Adjusted Coefficients. *International Water Technology*, 6(3).

Barati, R., Rahimi, S., & Akbari, G. H. (2012). Analysis of Dynamic Wave Model for Flood Routing in Natural Rivers. *Water Science and Engineering*, 5(3), 243–258.

Barco, J., Wong, K. M., & Stenstrom, M. K. (2008). Automatic Calibration of the U.S. EPA SWMM Model for a Large Urban Catchment. *Journal of Hydraulic Engineering*, 134(4), 466–474.

Barco Janet, Wong Kenneth M., & Stenstrom Michael K. (2008). Automatic Calibration of the U.S. EPA SWMM Model for a Large Urban Catchment. *Journal of Hydraulic Engineering*, 134(4), 466–474.

Baumbach, T., Burckhard, S. R., & Kant, J. (2015). Watershed Modeling Using Arc Hydro Tools. GeoHMS, and HEC-HMS.

Beling, F. A., Garcia, J. I. B., Paiva, E., Bastos, G. A. P., & Paiva, J. B. D. (2011). Analysis of the SWMM Model Parameters for Runoff Evaluation in Periurban Basins from Southern Brazil. 12nd International Conference on Urban Drainage, 11–16.

Beven, K. (1997). TOPMODEL: A Critique. Hydrological Processes, 11(9), 1069–1085.

Biancamaria, S., Bates, P. D., Boone, A., & Mognard, N. M. (2009). Large-scale coupled hydrologic and hydraulic modelling of the Ob river in Siberia. *Journal of Hydrology*, 379(1), 136–150.

Blazkova, S., Beven, K. J., & Kulasova, A. (2002). On constraining TOPMODEL hydrograph simulations using partial saturated area information. *Hydrological Processes*, 16(2), 441–458.

Boithias, L., Sauvage, S., Lenica, A., Roux, H., Abbaspour, K., Larnier, K., Sánchez-Pérez, J. (2017). Simulating Flash Floods at Hourly Time-Step Using the SWAT Model. Water, 9(12), 929.

Borah Deva K., Arnold Jeffrey G., Bera Maitreyee, Krug Edward C., & Liang Xin-Zhong. (2007). Storm Event and Continuous Hydrologic Modeling for Comprehensive and Efficient Watershed Simulations. *Journal of Hydrologic Engineering*, 12(6), 605–616.

Bravo J. M., Allasia D., Paz A. R., Collischonn W., & Tucci C. E. M. (2012). Coupled Hydrologic-Hydraulic Modeling of the Upper Paraguay River Basin. *Journal of Hydrologic Engineering*, 17(5), 635–646.

Butt, M. J., Umar, M., & Qamar, R. (2013). Landslide dam and subsequent dam-break flood estimation using HEC-RAS model in Northern Pakistan. *Natural Hazards*, 65(1), 241–254.

Cambez, M., & David, L. (2008). Using SWMM 5 in the continuous modelling of stormwater hydraulics and quality. Presented at the 11th International Conference on Urban Drainage.

Chaudhry, M. H., & SpringerLink. (2008). Open-channel flow. New York: Springer.

Chen, Y., Li, J., Wang, H., Qin, J., & Dong, L. (2017). Large-watershed flood forecasting with high-resolution distributed hydrological model. *Hydrology and Earth System Sciences*, 21(2), 735–749.

Chow, V. T., Maidment, D. R., & Mays, L. W. (1988). Applied Hydrology. McGraw-Hill.

Clarke, R. T. (1973). A review of some mathematical models used in hydrology, with observations on their calibration and use. *Journal of Hydrology*, 19(1), 1–20.

Clilverd, H. M., Thompson, J. R., Heppell, C. M., Sayer, C. D., & Axmacher, J. C. (2016). Coupled Hydrological/Hydraulic Modelling of River Restoration Impacts and Floodplain Hydrodynamics: Modelling of River Restoration Impacts. *River Research and Applications*, 32(9), 1927–1948.

Cranmer, A. J., Kouwen, N., & Mousavi, S. F. (2001). Proving WATFLOOD: modelling the nonlinearities of hydrologic response to storm intensities. *Canadian Journal of Civil Engineering,* 28(5), 837–855.

Cunderlink, J. (2003). Hydrologic model selection for the CFCAS project: Assessment of Water Resources Risk and Vulnerabilty to changing climatic conditions (No. 046). The University of Western Ontario Department of Civil and Environmental Engineering.

D. N. Moriasi, J. G. Arnold, M. W. Van Liew, R. L. Bingner, R. D. Harmel, & T. L. Veith. (2007). Model Evaluation Guidelines for Systematic Quantification of Accuracy in Watershed Simulations. Transactions of the ASABE, 50(3), 885–900.

Danish Hydraulic Institute. (2006). MIKE SHE User Manual: Reference Guide.

Demirel, M. C., Booij, M. J., Cluckie, I., Yangbo Chen, Babovic, V., Konikow, L., Savic, D. A. (2009). Identification of an appropriate low flow forecast model for the Meuse River. *Hydroinformatics in Hydrology, Hydrogeology and Water Resources*. IAHS Publ. 331, 296-303.

Devia, G. K., Ganasri, B. P., & Dwarakish, G. S. (2015). A Review on Hydrological Models. *Aquatic Procedia*, 4, 1001–1007.

Diskin, M. H., & Simon, E. (1977). A procedure for the selection of objective functions for hydrologic simulation models. *Journal of Hydrology,* 34(1–2), 129–149.

F. H. Jaber, & S. Shukla. (2012). MIKE SHE: Model Use, Calibration, and Validation. *Transactions of the ASABE,* 55(4), 1479–1489.

Feldman, A. (2010). Hydrologic Modelling System HEC-HMS Technical Reference Manual. Retrieved from US Army Corps of Army Engineers, Hydrologic Engineering Center HEC

Galván, L., Olías, M., Izquierdo, T., Cerón, J. C., & Fernández de Villarán, R. (2014). Rainfall estimation in SWAT: An alternative method to simulate orographic precipitation. *Journal of Hydrology*, 509, 257–265.

Gao, J., Holden, J., & Kirkby, M. (2015). A distributed TOPMODEL for modelling impacts of land-cover change on river flow in upland peatland catchments: A Distributed TOPMODEL to Support Landcover Change Studies. *Hydrological Processes*, 29(13), 2867–2879.

Garrote, L., & Bras, R. L. (1995). A distributed model for real-time flood forecasting using digital elevation models. *Journal of Hydrology*, 167(1–4), 279–306. h

Geetha, K., Mishra, S. K., Eldho, T. I., Rastogi, A. K., & Pandey, R. P. (2008). SCS-CN-based Continuous Simulation Model for Hydrologic Forecasting. *Water Resources Management*, 22(2), 165–190.

Gholami, V., & Mohseni Saravi, M. (2010). Effects of impervious surfaces and urban development on runoff generation and flood hazard in the Hajighoshan watershed. *Caspian Journal of Environmental Sciences*, 8(1), 1–12.

Gironás, J., Roesner, L. A., Rossman, L. A., & Davis, J. (2010). A new applications manual for the Storm Water Management Model (SWMM). *Environmental Modelling & Software*, 25(6), 813–814.

Goff, K. M., & Gentry, R. W. (2006). The Influence of Watershed and Development Characteristics on the Cumulative Impacts of Stormwater Detention Ponds. *Water Resources Management*, 20(6), 829–860.

Grey, O. P., Webber, D. F. S. G., Setegn, S. G., & Melesse, A. M. (2014). Application of the Soil and Water Assessment Tool (SWAT Model) on a small tropical island (Great River Watershed, Jamaica) as a tool in Integrated Watershed and Coastal Zone Management. *Revista de Biología Tropical*, 62, 293–305.

Grillakis, M. G., Tsanis, I. K., & Koutroulis, A. G. (2010). Application of the HBV hydrological model in a flash flood case in Slovenia. *Natural Hazards and Earth System Science*, 10(12), 2713–2725.

Guo, S., Guo, J., Zhang, J., & Chen, H. (2009). VIC distributed hydrological model to predict climate change impact in the Hanjiang basin. Science in China Series E: *Technological Sciences*, 52(11), 3234.

Halwatura, D., & Najim, M. M. M. (2013). Application of the HEC-HMS model for runoff simulation in a tropical catchment. *Environmental Modelling & Software*, 46, 155–162.

Hamby, D. M. (1994). A review of techniques for parameter sensitivity analysis of environmental models. *Environmental Monitoring and Assessment*, 32(2), 135–154.

Holko, L., & Lepistö, A. (1997). Modelling the hydrological behaviour of a mountain catchment using TOPMODEL. *Journal of Hydrology*, 196(1), 361–377.

Hromadka T. V., & DeVries J. J. (1988). Kinematic Wave Routing and Computational Error. *Journal of Hydraulic Engineering*, 114(2), 207–217.

Hsu, S. M., Ni, C.-F., & Hung, P.-F. (2002). Assessment of Three Infiltration Formulas based on Model Fitting on Richards Equation. *Journal of Hydrologic Engineering*, 7(5), 373–379.

Hwang, S. H., Ham, D. H., & Kim, J. H. (2012). A new measure for assessing the efficiency of hydrological data-driven forecasting models. *Hydrological Sciences Journal*, 57(7), 1257–1274.

Jajarmizad, M., Harun, S., & Salarpour, M. (2012). A Review on Theoretical Consideration and Types of Models in Hydrology. *Journal of Environmental Science and Technology*, 5, 249–261.

Jayadeera, P. M. (2017). Development of a rainfall runoff model for Kalu ganga basin of Sri Lanka using HEC-HMS model. Retrieved http://dl.lib.mrt.ac.lk/handle/123/12800

K. W. King, J. G. Arnold, & R. L. Bingner. (1999). Comparison of Green-Ampt and Curve Number methods on Goodwin Creek Watershed using SWAT. *Transactions of the ASAE*, 42(4), 919–926.

Kamali, B., Mousavi, S. J., & Abbaspour, K. C. (2013). Automatic calibration of HEC-HMS using single-objective and multi-objective PSO algorithms. *Hydrological Processes*, 27(26), 4028–4042.

Kanchanamala, D. P. H. M., Herath, H. M. H. K., & Nandalal, K. D. W. (2016). Impact of Catchment Scale on Rainfall Runoff Modeling: Kalu Ganga River Catchment upto Ratnapura. Engineer: *Journal of the Institution of Engineers*, Sri Lanka, 49(2), 1.

Kandel, D. D., Western, A. W., & Grayson, R. B. (2005). Scaling from process timescales to daily time steps: A distribution function approach. *Water Resources Research*, 41(2).

Kannan, N., Santhi, C., Williams, J. R., & Arnold, J. G. (2008). Development of a continuous soil moisture accounting procedure for curve number methodology and its behaviour with different evapotranspiration methods. *Hydrological Processes*, 22(13), 2114–2121.

Kavuncuoglu, H., Kavuncuoglu, E., Karatas, S. M., Benli, B., Sagdic, O., & Yalcin, H. (2018). Prediction of the antimicrobial activity of walnut (Juglans regia L.) kernel aqueous extracts using artificial neural network and multiple linear regression. *Journal of Microbiological Methods*, 148, 78–86.

Keig, G., & Mcalpine, J. R. (1969). Watbal: a computer system for the estimation and analysis of soil moisture regimes from simple climatic data.

Kiesel, J., Schmalz, B., Brown, G. L., & Fohrer, N. (2013). Application of a hydrological-hydraulic modelling cascade in lowlands for investigating water and sediment fluxes in catchment, channel and reach. *Journal of Hydrology and Hydromechanics*, 61(4), 334–346.

Kobold, M., & Brilly, M. (2006). The use of HBV model for flash flood forecasting. *Natural Hazards and Earth System Science*, 6(3), 407–417.

Koch, R. W., & Kekhia, F. (1987). Effect of rainfall intensity distribution on excess precipitation. Presented at the Engineering Hydrology Conference, A Symposium, Williamsburg Hilton National Conference Center, Williamsburg, Virginia, United States, ASCE.

Komi, Kossi, Neal, J., Trigg, M., & Diekruger, B. (2017). Modelling of flood hazard extent in data sparse areas: a case study of the Oti River basin, West Africa. *Journal of Hydrology: Regional Studies*, 10, 122–132.

Kouwen, N. (2014). WATFLOOD / WATROUTE Hydrological Model Routing & Flow Forecasting System. Ontario, Canada: University of Waterloo.

Krause, P., Boyle, D. P., & Bäse, F. (2005). Comparison of different efficiency criteria for hydrological model assessment. *Advances in Geosciences*, 5, 89–97.

Krishnaveni, M., & Rajeswari, A. (2019). Flow Routing and Surface Water Balance Simulation of a Tank Cascaded Catchment Using Coupled MIKE SHE/MIKE 11 Modeling. *Journal of The Institution of Engineers* (India): Series A, 100(1), 65–74.

Lenhart, T., Eckhardt, K., Fohrer, N., & Frede, H.-G. (2002). Comparison of two different approaches of sensitivity analysis. *Physics and Chemistry of the Earth*, Parts A/B/C, 27(9–10), 645–654.

LéVesque, éTienne, Anctil, F., Van Griensven, A., & Beauchamp, N. (2008). Evaluation of streamflow simulation by SWAT model for two small watersheds under snowmelt and rainfall. *Hydrological Sciences Journl*, 53(5), 961–976.

Li, C., Qi, J., Feng, Z., Yin, R., Zou, S., & Zhang, F. (2010). Parameters optimization based on the combination of localization and auto-calibration of SWAT model in a small watershed in Chinese Loess Plateau. *Frontiers of Earth Science in China*, 4(3), 296–310.

Li, J. (2017). Assessing the accuracy of predictive models for numerical data, 12(8).

Li, Z., Liu, H.-Y., & Li, Y. (2012).Review on HSPF model for simulation of hydrology and water quality processes, 33(7), 2217–2223.

Liebmann, B., & Allured, D. (2005). Daily Precipitation Grids for South America. Bulletin of the American Meteorological Society, 86(11), 1567–1570.

Lin, S.-S., Liao, Y.-P., Hsieh, S.-H., Kuo, J.-T., & Chen, Y.-C. (2010). A pattern-oriented approach to development of a real-time storm sewer simulation system with an SWMM model. *Journal of Hydroinformatics*, 12(4), 408–423.

Lohmann, D., Raschke, E., Nijssen, B., & Lettenmaier, D. P. (1998). Regional scale hydrology: I. Formulation of the VIC-2L model coupled to a routing model. *Hydrological Sciences Journal*, 43(1), 131–141.

Madsen, H. (2000). Automatic calibration of a conceptual rainfall–runoff model using multiple objectives. *Journal of Hydrology*, 235(3–4), 276–288.

Marshall, L., Nott, D., & Sharma, A. (2005). Hydrological model selection: A Bayesian alternative: Hydrological model selection. *Water Resources Research*, 41(10).

Masih, I., Maskey, S., Uhlenbrook, S., & Smakhtin, V. (2011). Assessing the Impact of Areal Precipitation Input on Streamflow Simulations Using the SWAT Model1. JAWRA *Journal of the American Water Resources Association*, 47(1), 179–195.

McCuen, R. H. (1973). The role of sensitivity analysis in hydrologic modeling. *Journal of Hydrology*, 18(1), 37–53.

McCuen, R. H. (2016). Hydrologic Analysis and Design (4 edition). Boston: Pearson.

Mishra, A., Kar, S., & Singh, V. P. (2007). Determination of runoff and sediment yield from a small watershed in sub-humid subtropics using the HSPF model. *Hydrological Processes*, 21(22), 3035–3045.

Mishra, S. K., Tyagi, J. V., & Singh, V. P. (2003). Comparison of infiltration models. *Hydrological Processes*, 17(13), 2629–2652.

Monte, B., Costa, D., Chaves, M., Magalhães, L., & Uvo, C. (2016). Hydrological and hydraulic modelling applied to the mapping of flood-prone areas, 21(1), 152–167.

Moradkhani, H., & Sorooshian, S. (2009). General Review of Rainfall-Runoff Modeling: Model Calibration, Data Assimilation, and Uncertainty Analysis. In Water Science and Technology Library. *Hydrological Modelling and the Water Cycle* (pp. 1–24).

Moynihan, K., & Vasconcelos, J. (2014). SWMM Modeling of a Rural Watershed in the Lower Coastal Plains of the United States. *Journal of Water Management Modeling*.

Mwendera, E. J., & Feyen, J. (1992). Estimation of depression storage and Manning's resistance coefficient from random roughness measurements. Geoderma, 52(3–4), 235–250.

Nash, J. E., & Sutcliffe, J. V. (1970). River flow forecasting through conceptual models part I — A discussion of principles. *Journal of Hydrology*, 10(3), 282–290.

Neitsch, S. L., Arnold, J. G., Kiriny, J. R., Srinivasan, R., & Williams, J. R. (2002). Soil and Water Assesment Tool User Manual [Manual]. USDA Agricultural Research Service.

Nicolle, P., Pushpalatha, R., Perrin, C., François, D., Thiéry, D., Mathevet, T., … Morice, E. (2014). Benchmarking hydrological models for low-flow simulation and forecasting on French catchments. *Hydrology and Earth System Sciences*, 18(8), 2829–2857.

Nishat, S., Guo, Y., & Baetz, B. W. (2007). Development of a simplified continuous simulation model for investigating long-term soil moisture fluctuations. *Agricultural Water Management*, 92(1–2), 53–63.

Oleyiblo, J. O., & Li, Z. (2010). Application of HEC-HMS for flood forecasting in Misai and Wan'an catchments in China. *Water Science and Engineering*, 3(1), 14–22.

Olivera, F., Valenzuela, M., Srinivasan, R., Choi, J., Cho, H., Koka, S., & Agrawal, A. (2006). Arcgis-Swat: A Geodata Model and Gis Interface for Swat1. JAWRA *Journal of the American Water Resources Association*, 42(2), 295–309.

Onyutha, C. (2016). Influence of Hydrological Model Selection on Simulation of Moderate and Extreme Flow Events: A Case Study of the Blue Nile Basin.

Ozdemir, A., & Leloglu, U. M. (2018). A fast and automated hydrologic calibration tool for SWAT. Water and Environment Journal.

Perry, M., & Hollis, D. (2005). The generation of monthly gridded datasets for a range of climatic variables over the UK. *International Journal of Climatology*, 25(8),

Ponce Victor M. (1991). Kinematic Wave Controversy. *Journal of Hydraulic Engineering*, 117(4), 511–525.

Ramesh, R., Datta, B., Bhallamudi, S. M., & Narayana, A. (2000). Optimal Estimation of Roughness in Open-Channel Flows. *Journal of Hydraulic Engineering*, 126(4), 299–303.

Rawls, W. (1976). Calibration of selected infiltration equations for the Georgia Coastal Plain. *Agricultural Research Service*, U.S. Dept. of Agriculture.

Risley, J., Stonewall, A., & Haluska, T. (2009). Estimating Flow-Duration and Low-Flow Frequency Statistics for Unregulated Streams in Oregon .

Rosa, D. J., Clausen, J. C., & Dietz, M. E. (2015). Calibration and Verification of SWMM for Low Impact Development. J*AWRA Journal of the American Water Resources Association*, 51(3), 746–757.

Rossman, L. A., & Huber, W. (2016a). Storm Water Management Model Reference Manual Volume I, Hydrology.

Sandu, M.-A., & Virsta, A. (2015). Applicability of MIKE SHE to Simulate Hydrology in Argesel River Catchment. Agriculture and Agricultural Science Procedia, 6, 517–524.

Singh, V. P., & McCann, R. C. (1980). Some notes on Muskingum method of flood routing. *Journal of Hydrology*, 48(3), 343–361.

Skhakhfa, I. D., & Ouerdachi, L. (2016). Hydrological modelling of wadi Ressoul watershed, Algeria, by HEC-HMS model. *Journal of Water and Land Development*, 31.

Skotnicki, M., & Sowiński, M. (2015). The influence of depression storage on runoff from impervious surface of urban catchment. *Urban Water Journal*, 12(3), 207–218.

Şorman, A. A., Şensoy, A., Tekeli, A. E., Şorman, A. Ü., & Akyürek, Z. (2009). Modelling and forecasting snowmelt runoff process using the HBV model in the eastern part of Turkey. *Hydrological Processes*, 23(7), 1031–1040.

Soulis, K. X., & Valiantzas, J. D. (2012). SCS-CN parameter determination using rainfall-runoff data in heterogeneous watersheds – the two-CN system approach. *Hydrology and Earth System Sciences*, 16(3), 1001–1015.

Surfleet, C. G., Tullos, D., Chang, H., & Jung, I.-W. (2012). Selection of hydrologic modeling approaches for climate change assessment: A comparison of model scale and structures. *Journal of Hydrology,* 464–465, 233–248.

Suriya, S., & Mudgal, B. V. (2012). Impact of urbanization on flooding: The Thirusoolam sub watershed – A case study. *Journal of Hydrology,* 412–413, 210–219.

Thakur Balbhadra, Parajuli Ranjan, Kalra Ajay, Ahmad Sajjad, & Gupta Ritu. (2017). Coupling HEC-RAS and HEC-HMS in Precipitation Runoff Modelling and Evaluating Flood Plain Inundation Map. World Environmental and Water Resources Congress 2017, 240–251.

Thapa, G., & Wijeskera, S. (2016). Computation and Optimization of Snyder's Synthetic Unit Hydrograph Parameters.

Thompson, J. R., Sørenson, H. R., Gavin, H., & Refsgaard, A. (2004). Application of the coupled MIKE SHE/MIKE 11 modelling system to a lowland wet grassland in southeast England. *Journal of Hydrology*, 293(1), 151–179.

Tscheikner-Gratl, F., Zeisl, P., Kinzel, C., Leimgruber, J., Ertl, T., Rauch, W., & Kleidorfer, M. (2016). Lost in calibration: why people still do not calibrate their models, and why they still should – a case study from urban drainage modelling. *Water Science and Technology*, 74(10), 2337–2348.

Tsihrintzis, V. A., & Hamid, R. (1998). Runoff quality prediction from small urban catchments using SWMM. *Hydrological Processes*, 12(2), 311–329.

Tuo, Y., Duan, Z., Disse, M., & Chiogna, G. (2016). Evaluation of precipitation input for SWAT modeling in Alpine catchment: A case study in the Adige river basin (Italy). Science of The Total Environment, 573, 66–82.

Unduche, F., Tolossa, H., Senbeta, D., & Zhu, E. (2018). Evaluation of four hydrological models for operational flood forecasting in a Canadian Prairie watershed. *Hydrological Sciences Journal*, 63(8), 1133–1149.

Wanniarachchi, S. S. (2013). Mathematical Modelling of Watershed Runoff Coefficient for Reliable Estimations to meet the Future Challenges of Water Resources Development in Sri Lanka. Engineer: *Journal of the Institution of Engineers*, Sri Lanka, 46(2).

Warwick, J. J., & Tadepalli, P. (1991). Efficacy of SWMM Application. *Journal of Water Resources Planning and Management*, 117(3), 352–366.

Weinman, P., & Laurensen, M. (1979). Approximate Flood Routing Methods: A Review. *ASCE*, 105(12), 1521–1536.

Wijesekera, N. T. S., & Rajapakse, R. L. H. L. (2013). Mathematical modelling of watershed wetland crossings for flood mitigation and groundwater enhancement – case of the Attanagalu Oya river basin. Engineer: *Journal of the Institution of Engineers, Sri Lanka*, 46(3).

Wijesekera, S. N. (2018). Classification of Streamflow Observations for Water Management.

WMO. (1965). Guide to Hydrometeorological Practices. Secretariat of the World Meteorological Organization.

Xi Jin, Wenyan Wu, Ying-he Jiang, & Jian-hua Jin. (2011, May). Automatic calibration of SWMM model with adaptive genetic algorithm. 891–895.

Xia, Y., Mocko, D. M., Wang, S., Pan, M., Kumar, S. V., Peters-Lidard, C. D., … Ek, M. B. (2018). Comprehensive Evaluation of the Variable Infiltration Capacity (VIC) Model in the North American Land Data Assimilation System. *Journal of Hydrometeorology*, 19(11), 1853–1879.

Yapo, P. O., Gupta, H. V., & Sorooshian, S. (1998). Multi-objective global optimization for hydrologic models. *Journal of Hydrology*, 204(1), 83–97.

Yatagai, A., Xie, P., & Alpert, P. (2008). Development of a daily gridded precipitation data set for the Middle East. *Advances in Geosciences*, 12, 165–170.

Yates, D. N. (1996). WatBal: An Integrated Water Balance Model for Climate Impact Assessment of River Basin Runoff. International *Journal of Water Resources Development*, 12(2), 121–140.

Zaghloul, N. A. (1983). Sensitivity analysis of the SWMM Runoff-Transport parameters and the effects of catchment discretisation. *Advances in Water Resources*, 6(4), 214–223.

Zhang, X., & Bao, W. (2012). Modified Saint-Venant equations for flow simulation in tidal rivers. *Water Science and Engineering*, 5(1), 34–45.

Zhang, Y. (2005). Simulation of open channel network flows using finite element approach. Communications in Nonlinear Science and Numerical Simulation, 10(5), 467–478.

APPENDIX A: MASS CURVE ANALYSIS

Table A-0-1. Average annual precipitation of rainfall stations

Year	Halwathura	Ratnapura	Alupola	Pelmadula	Nivithigala
2006/2007	3276.5	3345.4	3852.6	1415.48	1838
2007/2008	2041.1	3855.5	4519.77	1610.3	2093.5
2008/2009	3291.8	3409.1	3772.5	2169	1722
2009/2010	4000.5	3940.6	4482.3	2687.5	1653.5
2010/2011	3217.5	4276.8	4283.96	2753.9	1484.9
2011/2012	4350.8	1946	3059.6	2784.6	1273
2012/2013	5727	4236	5899.7	2246.5	2132.9
2013/2014	4223	3762	4132.3	2841.7	2155.5

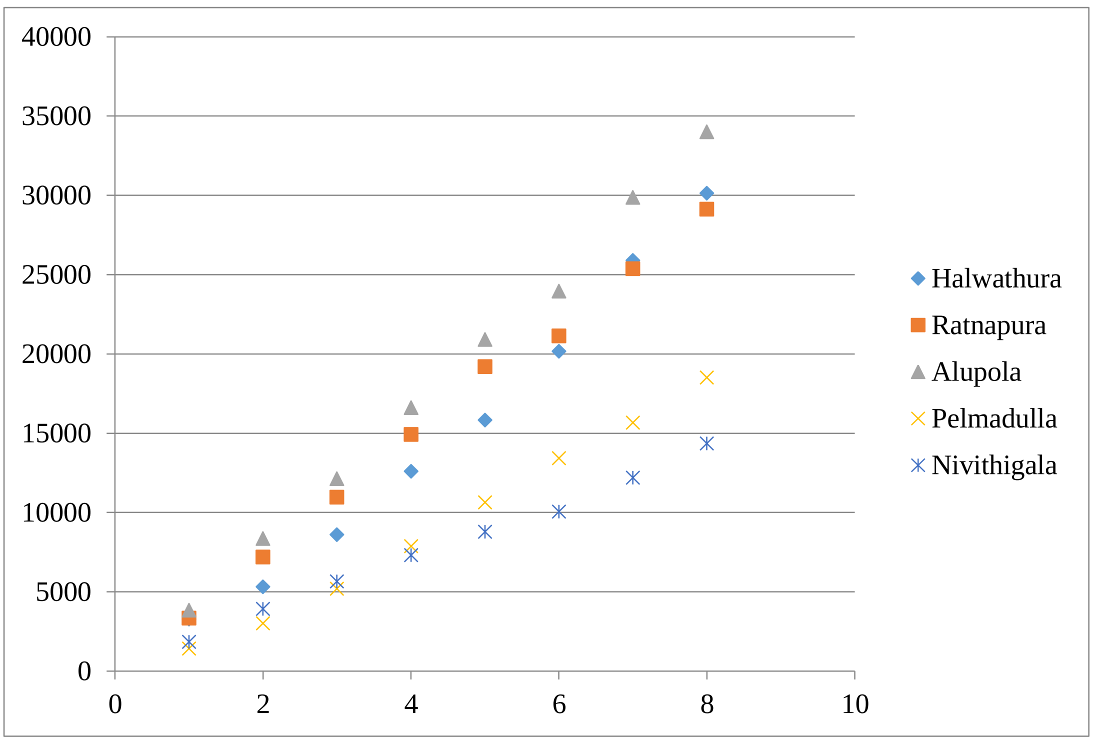

Figure A-1. Single mass curve for all rainfall stations

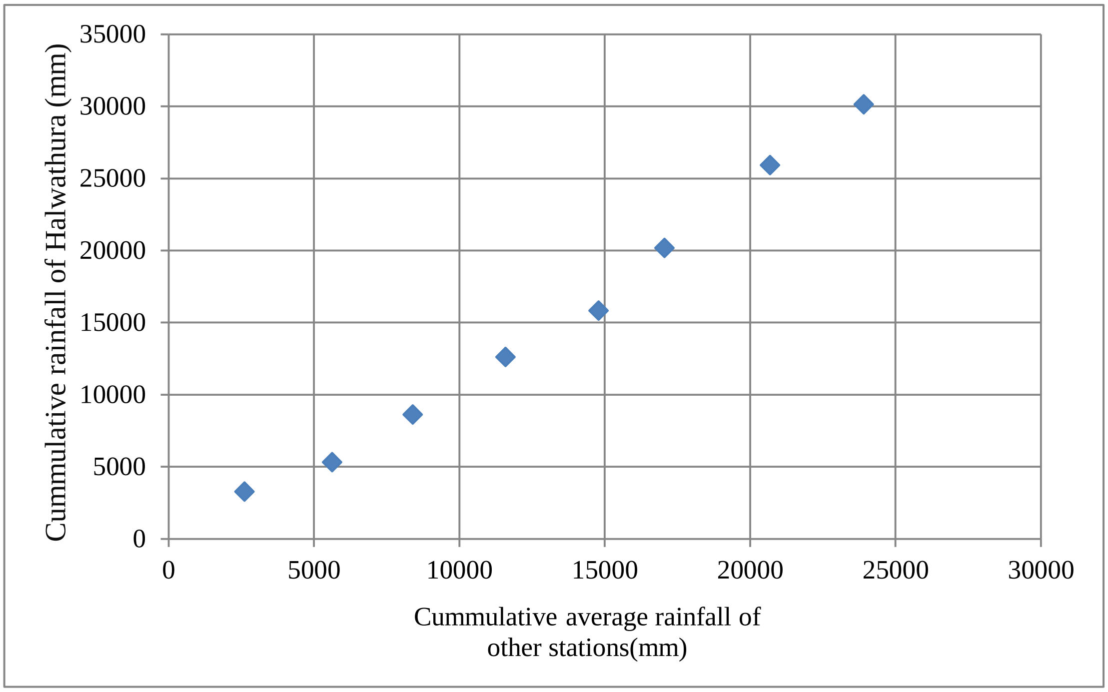

Figure A-2. Double Mass Curve for Halwathura station

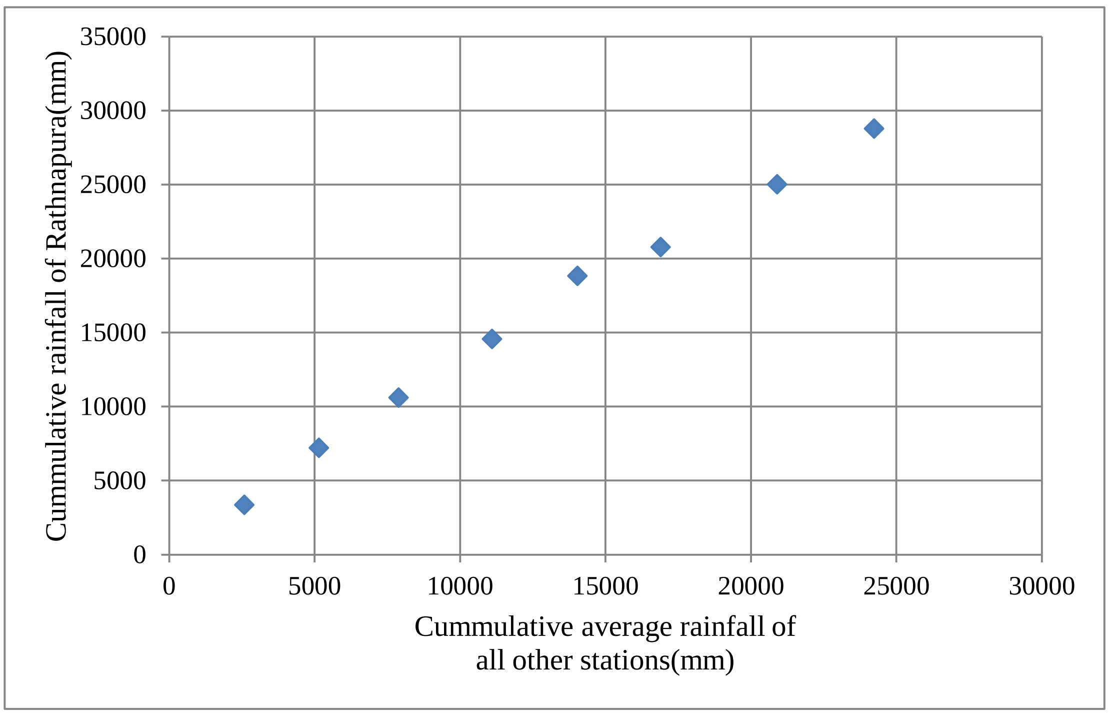

Figure A-3. Double Mass curve for Ratnapura station

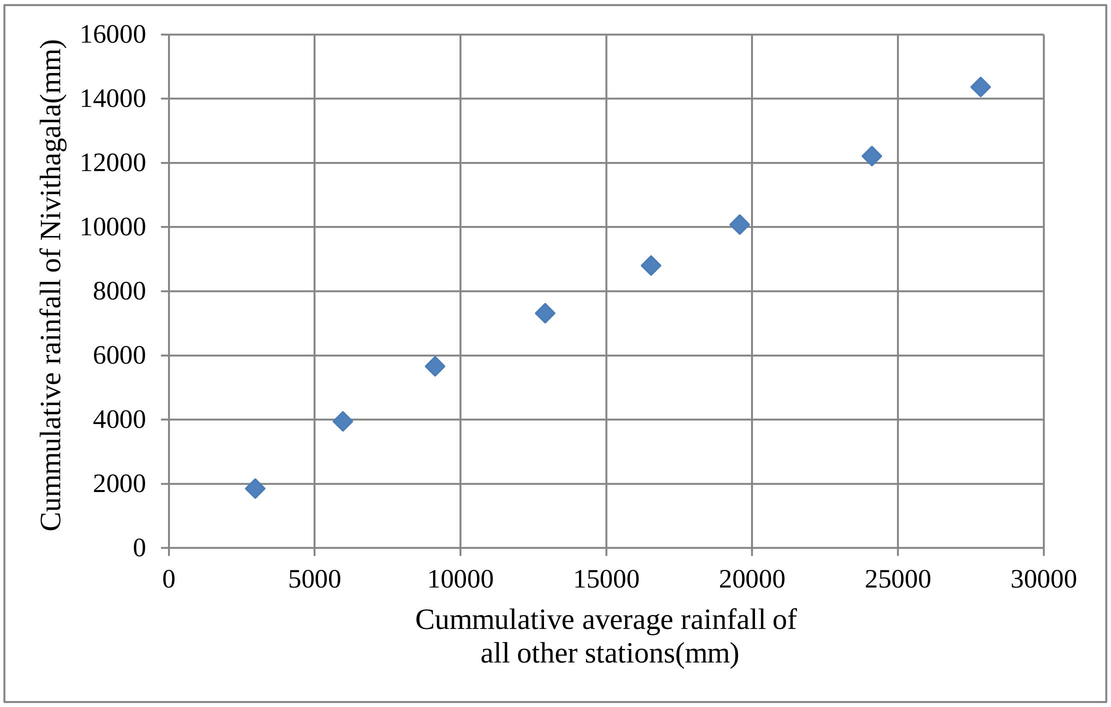

Figure A-4 Double Mass curve for Nivithagala stations

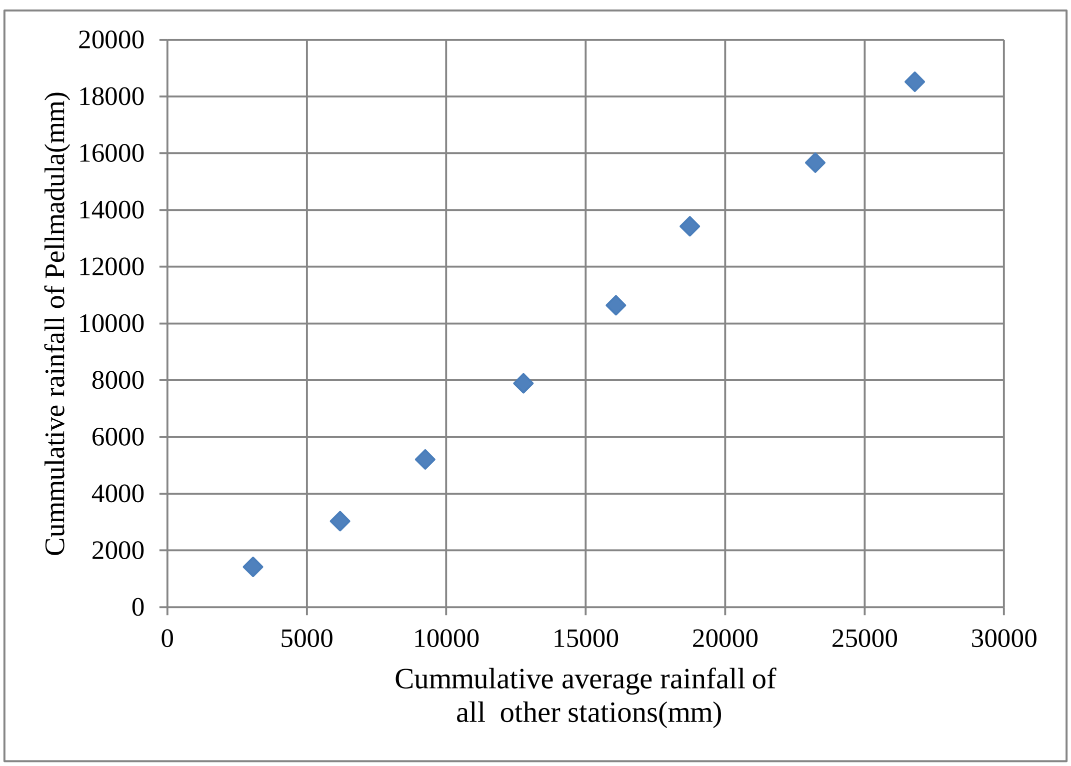

Figure A-5 Double Mass curve for Pelmadula station

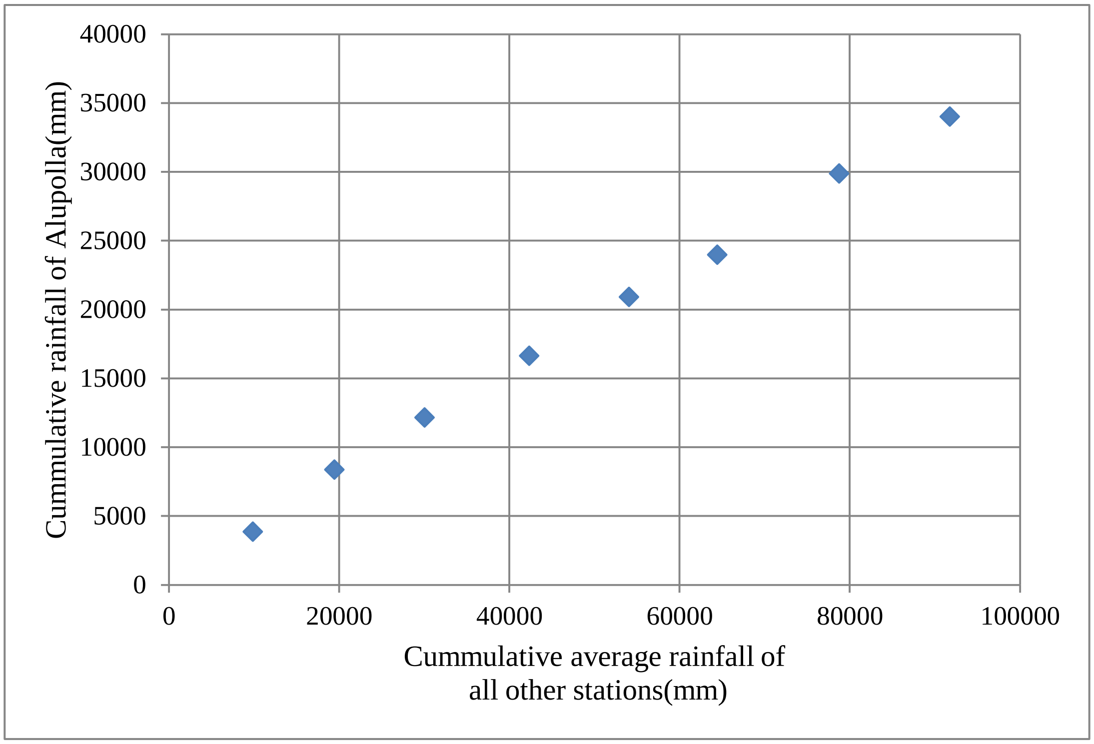

Figure A-6 Double Mass curve for Alupola station

APENDIX B: STREAMFLOW RESPONSE WITH RAINFALL

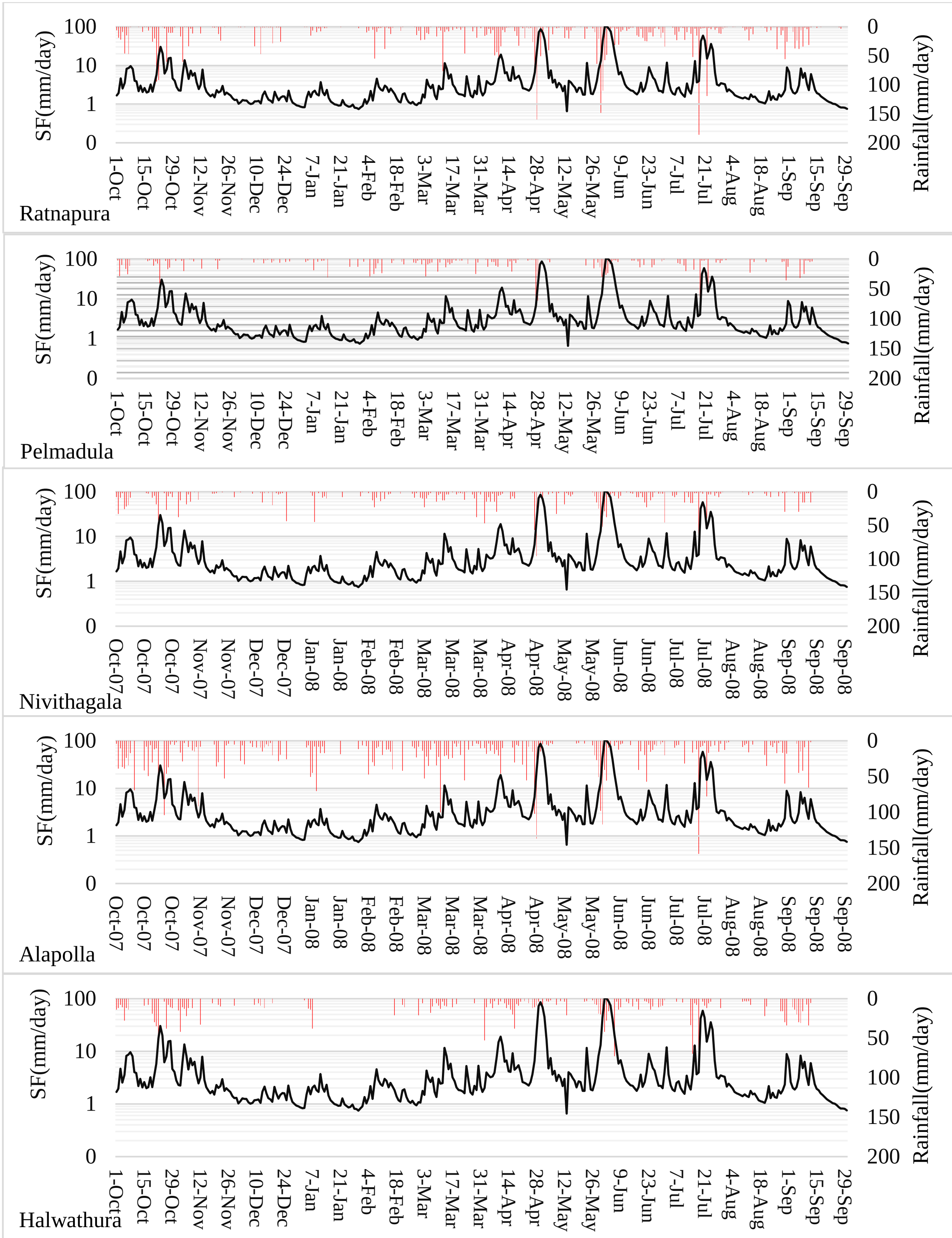

Figure B-1. Ellagawa Streamflow Response to Daily Rainfall 2007-2008

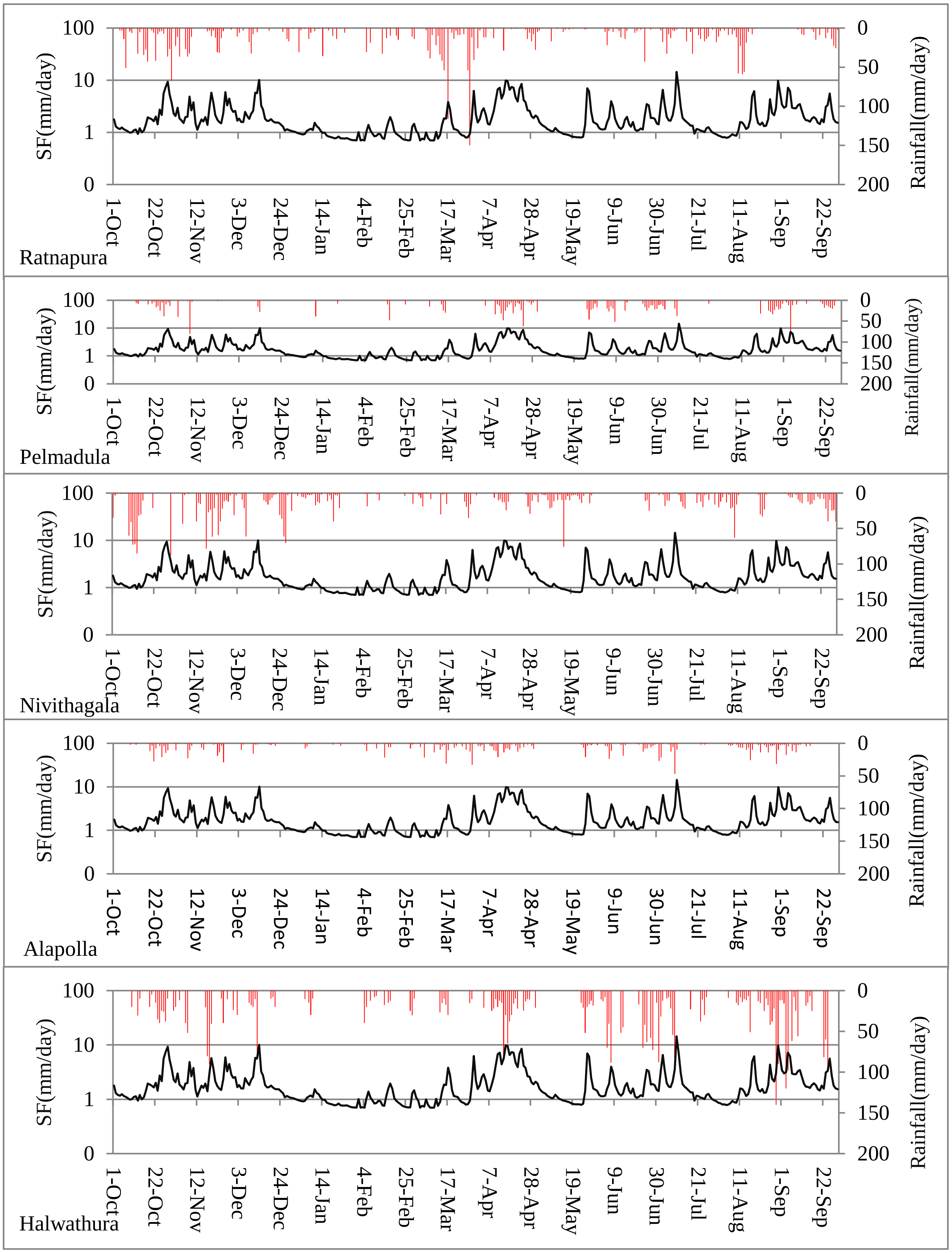

Figure B-2. Ellagawa Streamflow Response to Daily Rainfall 20011-20112

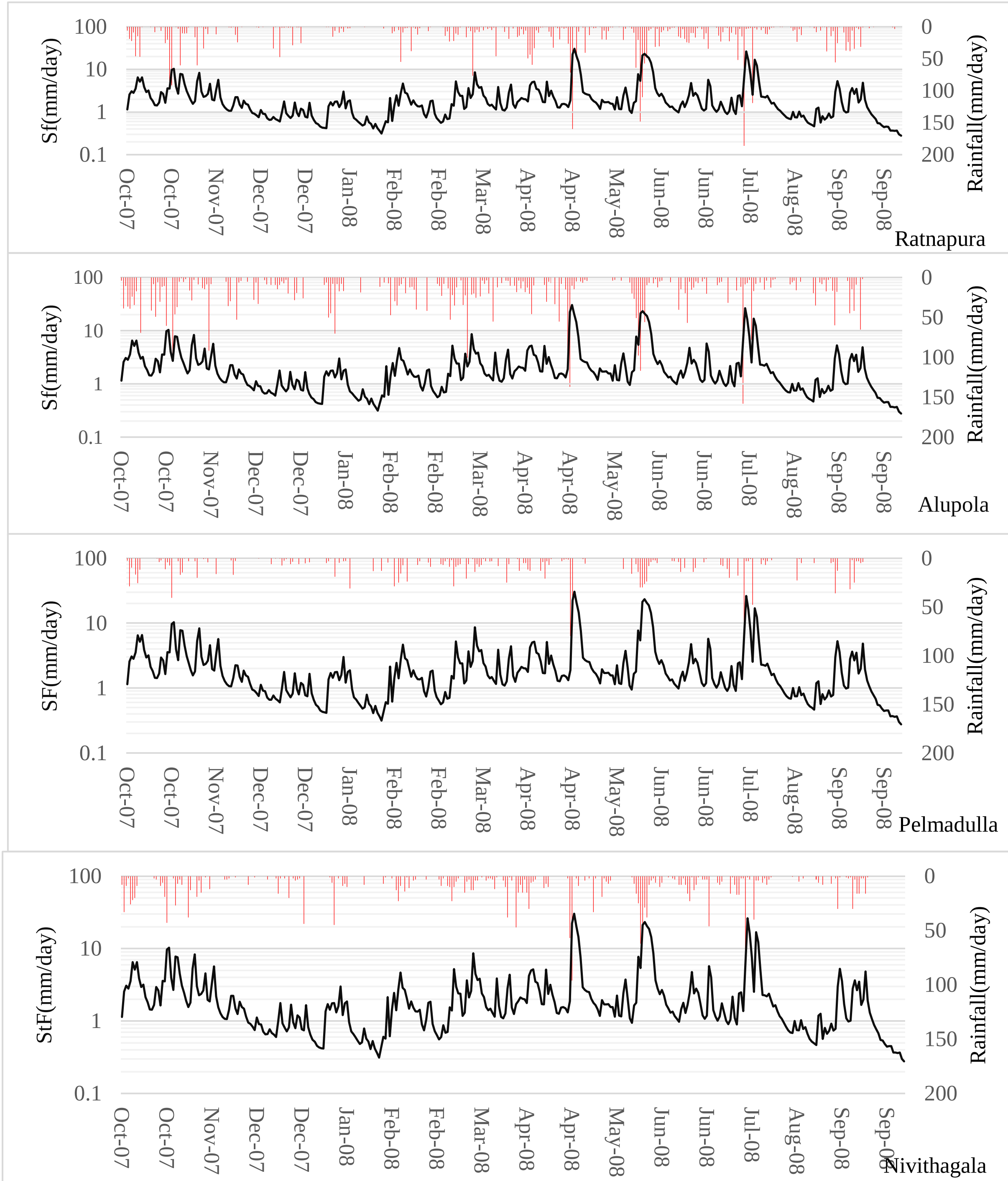

Figure B-3. Ratnapura Streamflow Response to Daily Rainfall 2007-2008

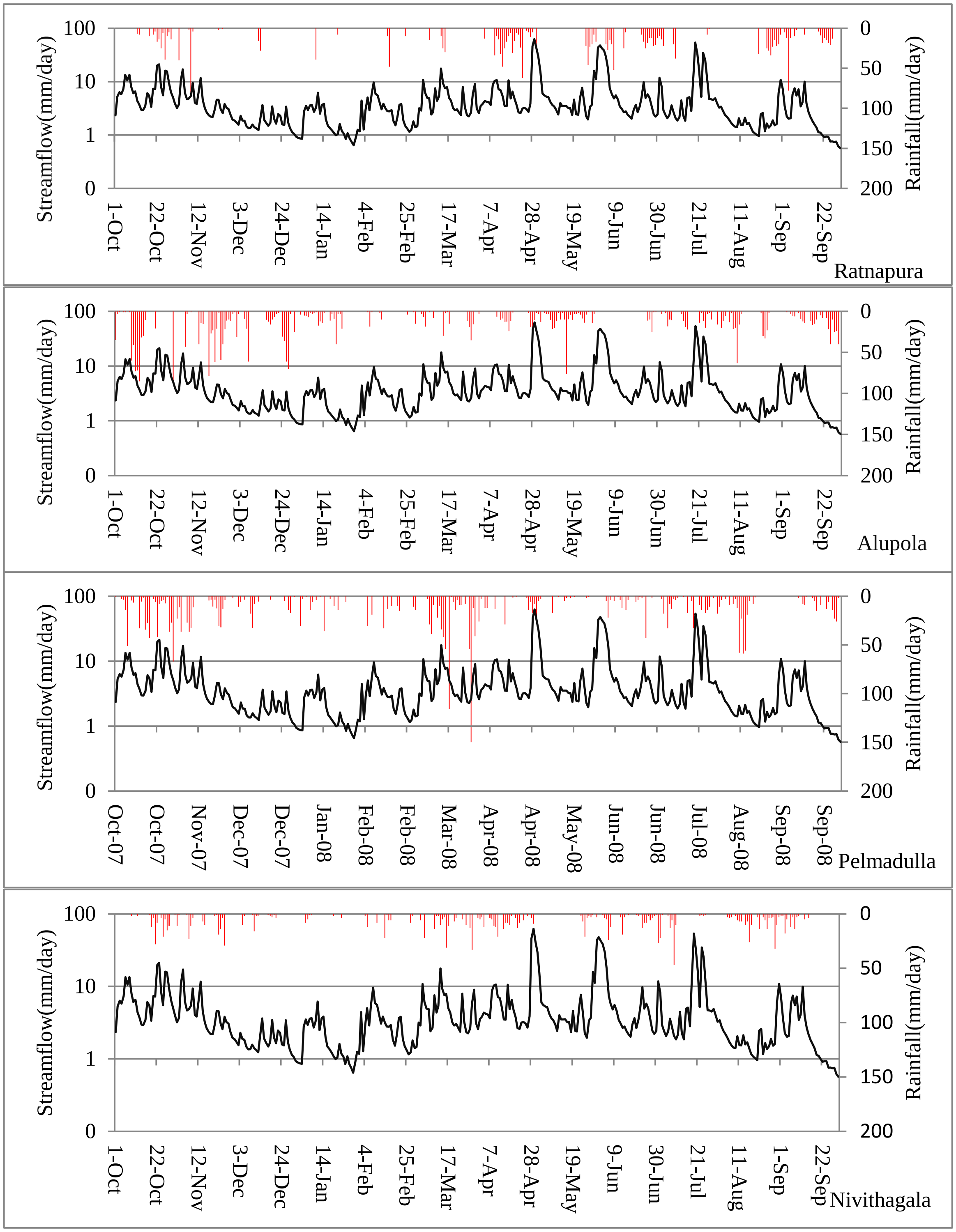

Figure B-4. Ratnapura Streamflow Response to Daily Rainfall 20011-2012

APPENDIX C: PARAMETER SENSITIVITY

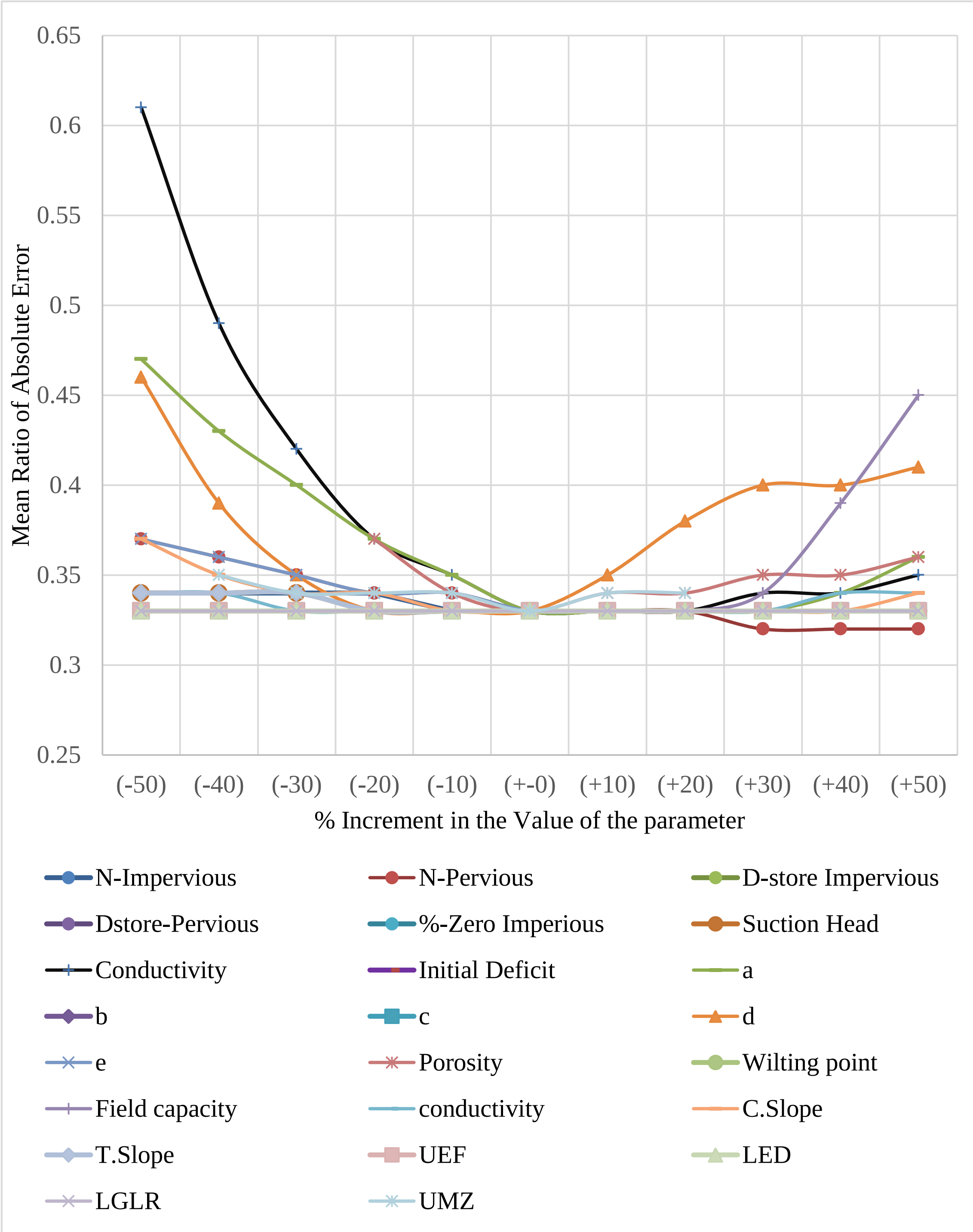

Figure C-1. Parameter Sensitivity to MRAE

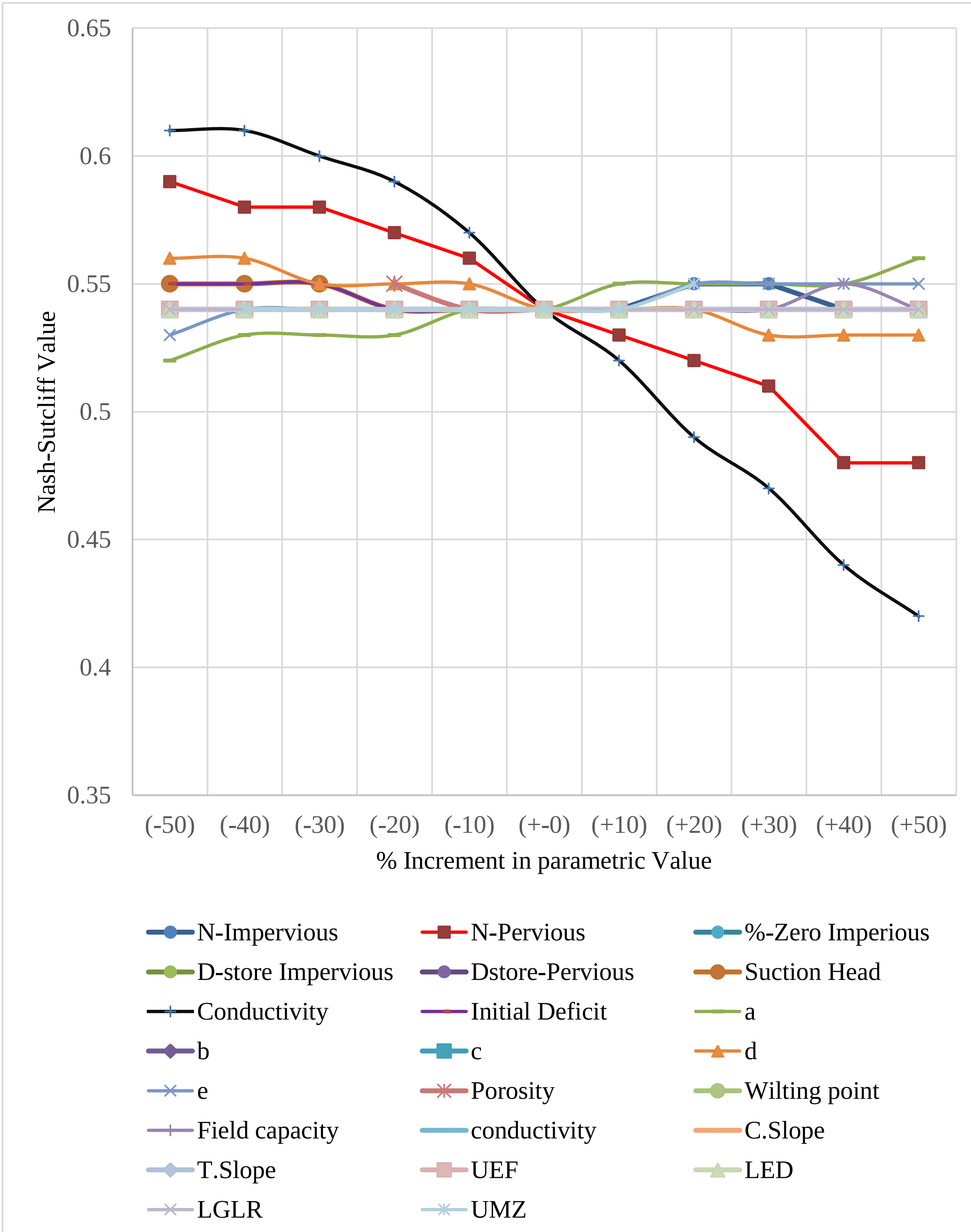

Figure C-2. Parameter Sensitive to NASH

APPENDIX D: MATCHING OF HYDROGRAPH IN NORMAL PLOT

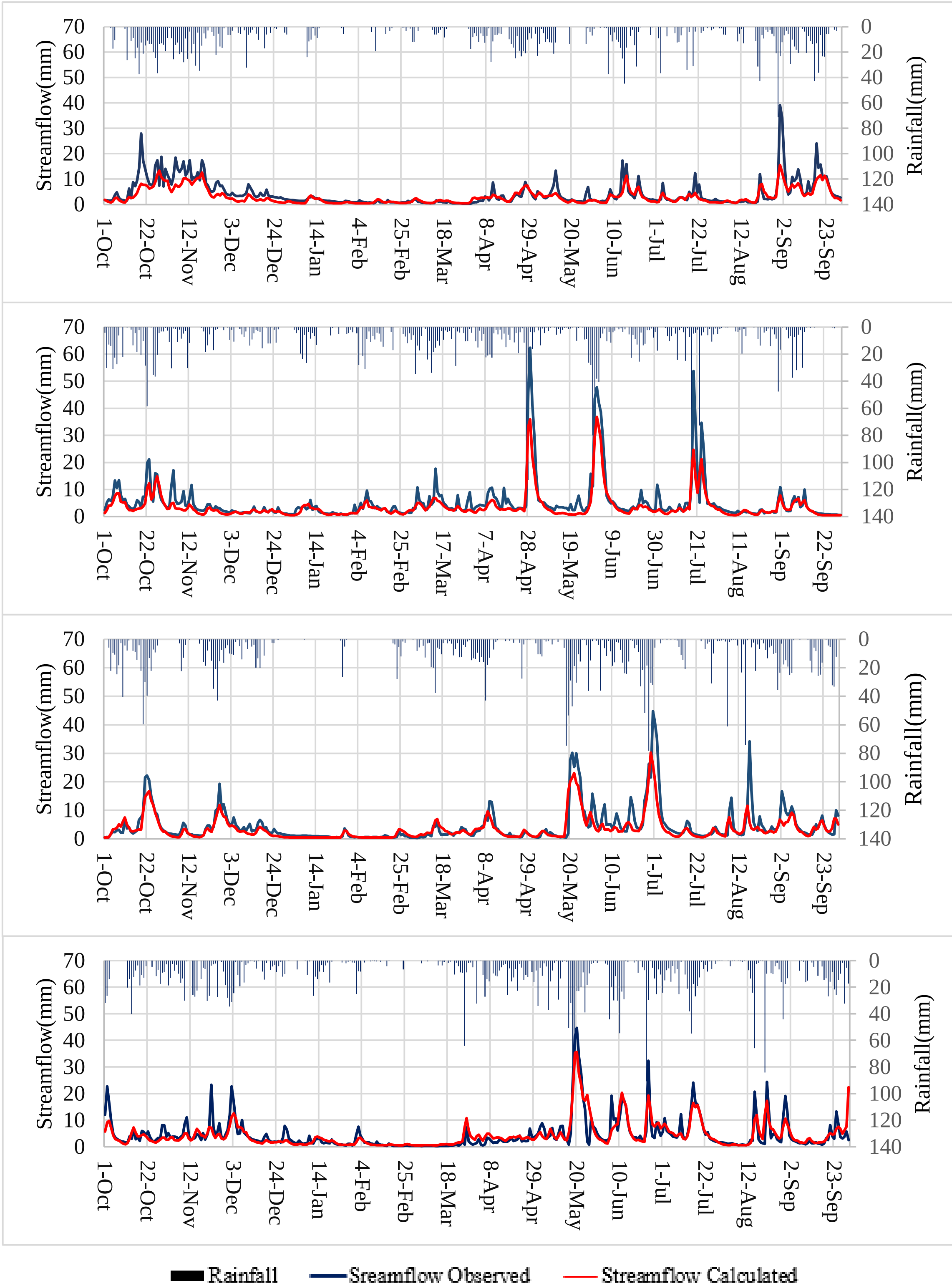

Figure D-1. Performance of Ratnapura Lumped model during Calibration

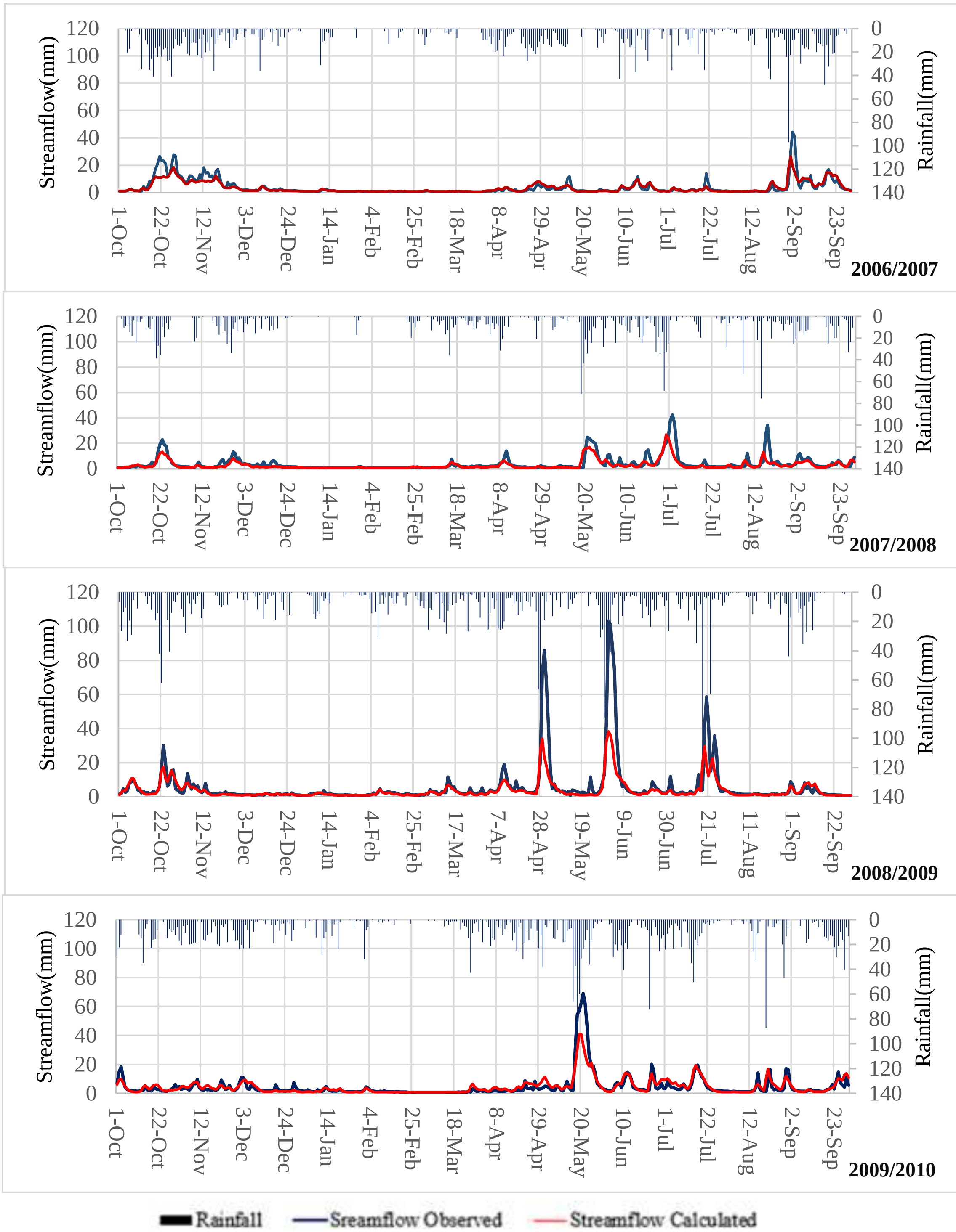

Figure D-2. Performance of Ellagawa Lumped During Calibration

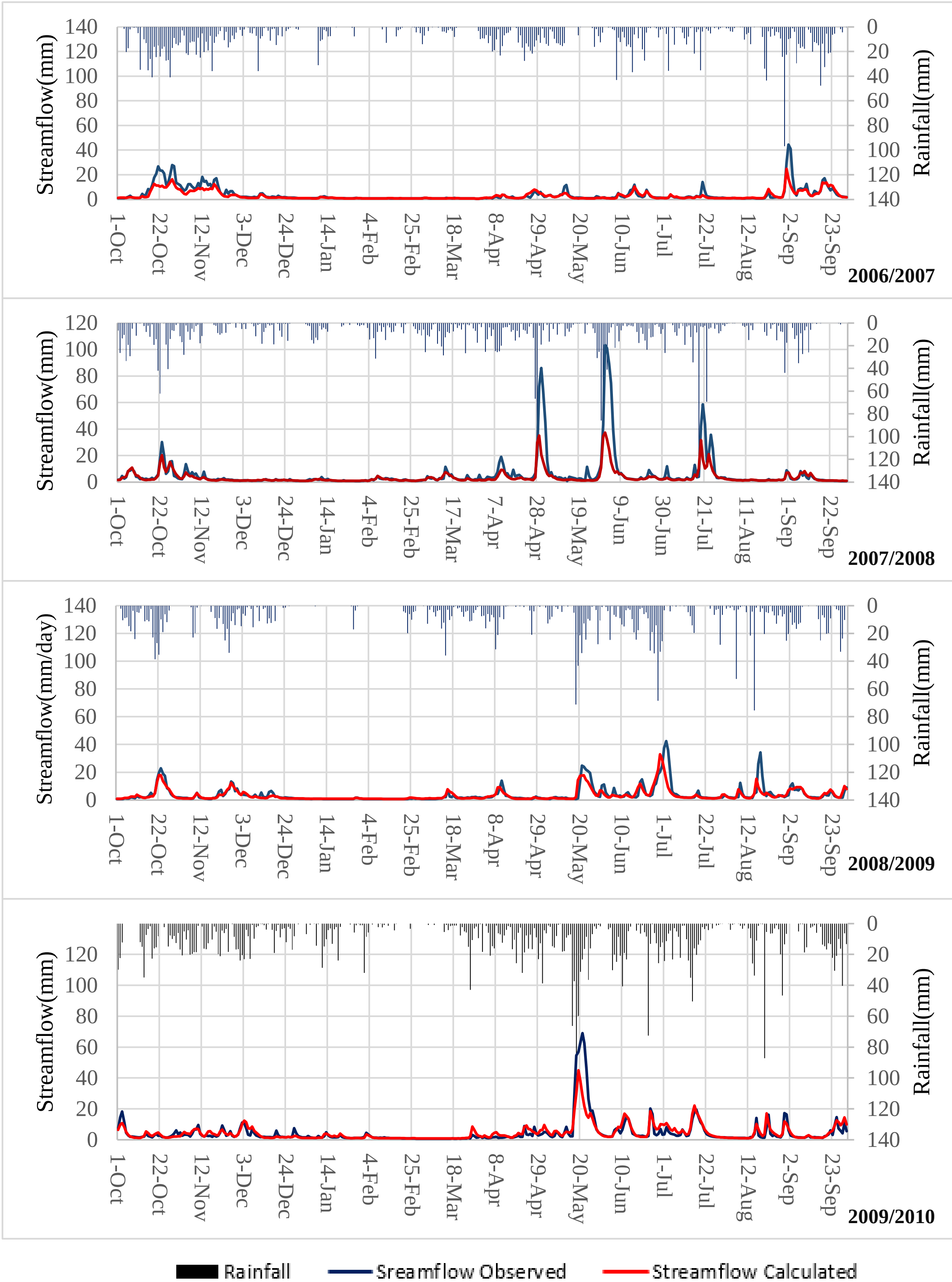

Figure D-3. Performance of Ellagawa Distributed model during Calibration

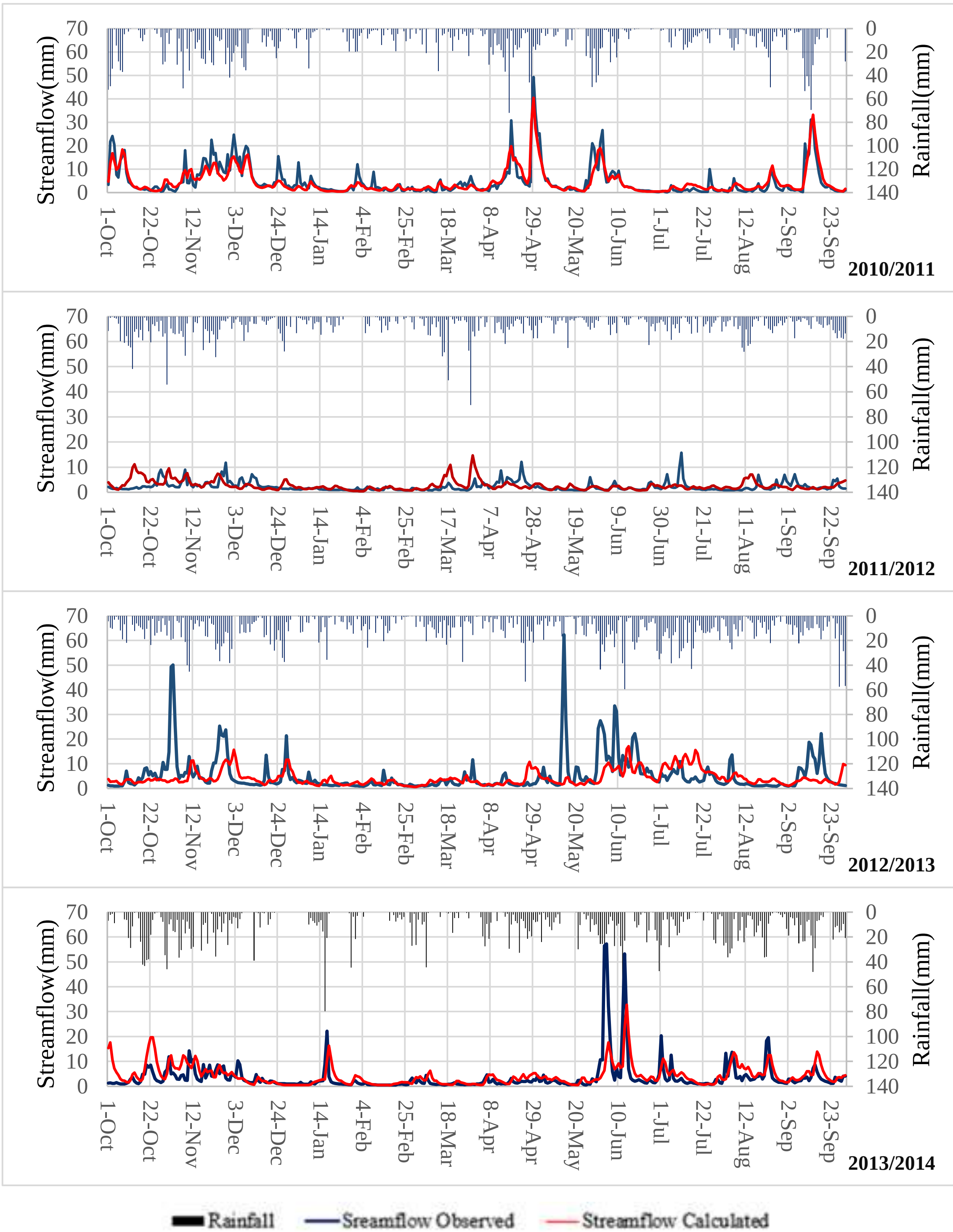

Figure D-4. Performance of Ratnapura model during Validation

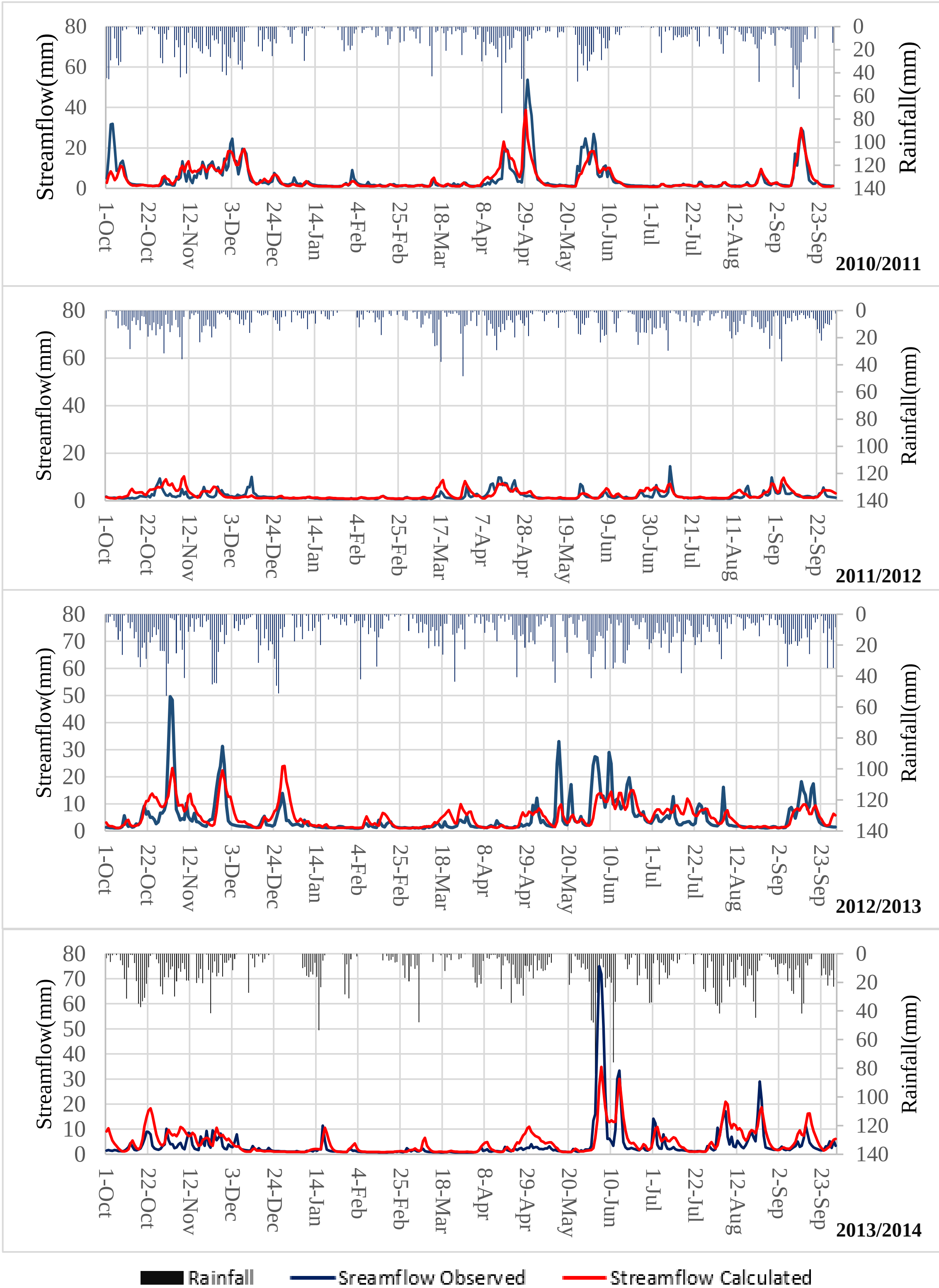

Figure D-5. Performance of Ellagawa Lumped model during Validation

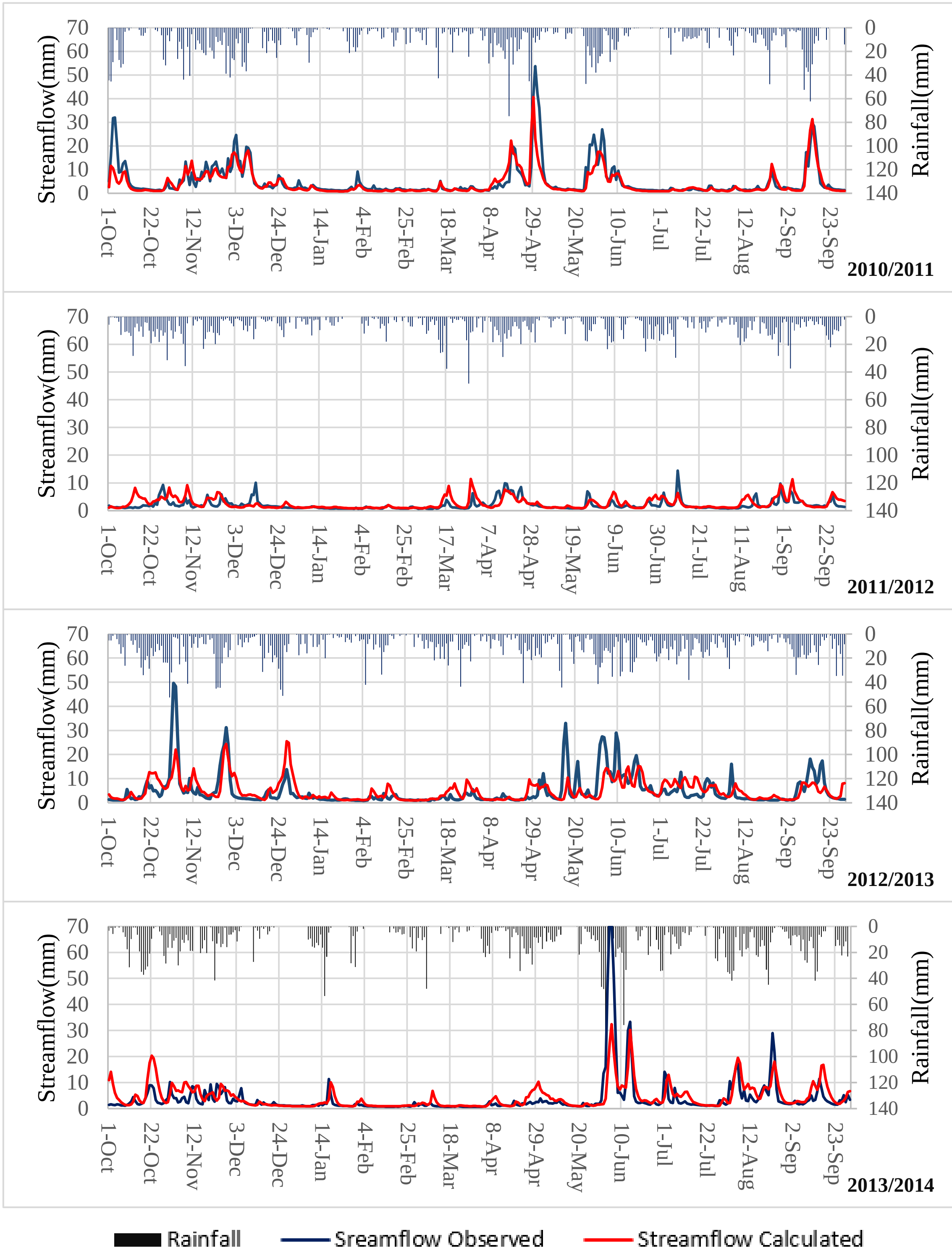

Figure D-6. Performance of Ellagawa distributed model during Validation

APPENDIX E: PARAMETER OPTIMIZATION

Table F-1. Optimization of surface runoff parameter (N-pervious) of Ellagawa catchment

Optimization of N-Pervious					
Parameter range	MRAE	Nash	Parameter range	MRAE	Nash
0.0175	0.3526	0.58	0.05	0.3177	0.43
0.02	0.3443	0.57	0.0525	0.317	0.43
0.0225	0.3386	0.55	0.055	0.3171	0.42
0.025	0.334	0.54	0.0575	0.3173	0.41
0.0275	0.3303	0.53	0.06	0.317	0.4
0.03	0.3266	0.52	0.0625	0.3181	0.4
0.0325	0.3256	0.5	0.065	0.3179	0.39
0.035	0.323	0.49	0.0675	0.3181	0.38
0.0375	0.322	0.49	0.07	0.3183	0.38
0.04	0.3201	0.47	0.0725	0.3188	0.37
0.0425	0.3193	0.46	0.075	0.3186	0.37
0.045	0.319	0.45	0.0775	0.3196	0.36
0.0475	0.3179	0.44	0.08	0.3201	0.35

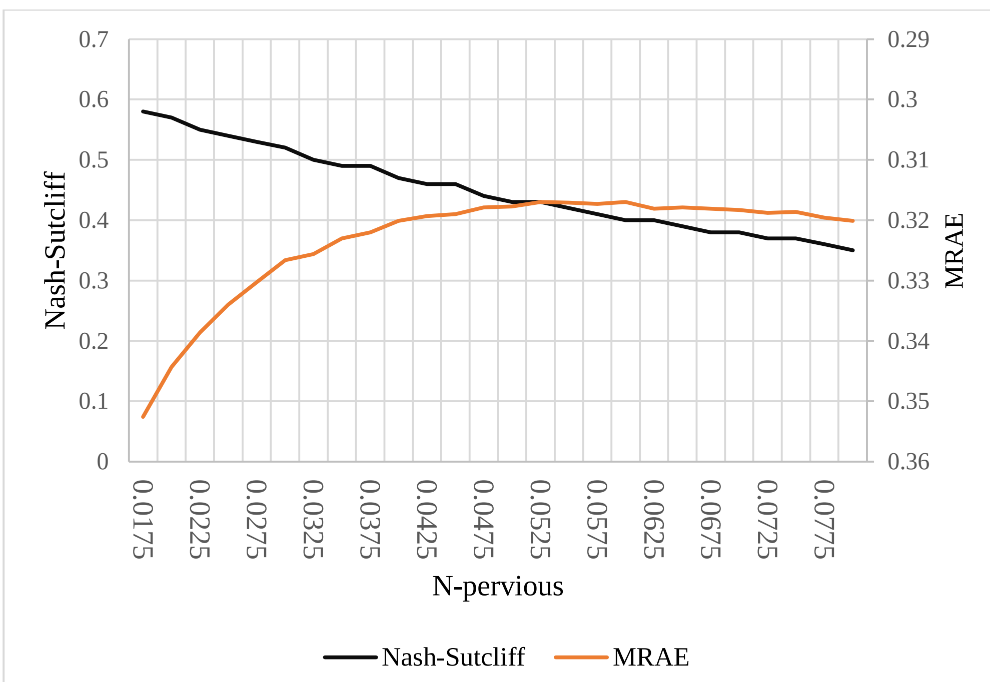

Figure F-1 Optimization of surface runoff parameter (N-pervious) of Ellagawa catchment

Table F-2 Optimization of infiltration parameter (saturated hydraulic conductivity K) of Ellagawa catchment

Parameter	Nash	MRAE	Parameter	Nash	MRAE
0.105	0.57	0.9229	0.525	0.40	0.3501
0.21	0.59	0.4866	0.56	0.37	0.3562
0.245	0.58	0.409	0.595	0.35	0.3626
0.28	0.57	0.359	0.63	0.33	0.3657
0.315	0.54	0.341	0.665	0.32	0.3683
0.35	0.52	0.3266	0.7	0.30	0.3711
0.385	0.49	0.3253	0.735	0.28	0.3722
0.42	0.47	0.3295	0.77	0.27	0.3731
0.455	0.44	0.33	0.805	0.25	0.3747
0.49	0.42	0.3426	0.84	0.24	0.3749

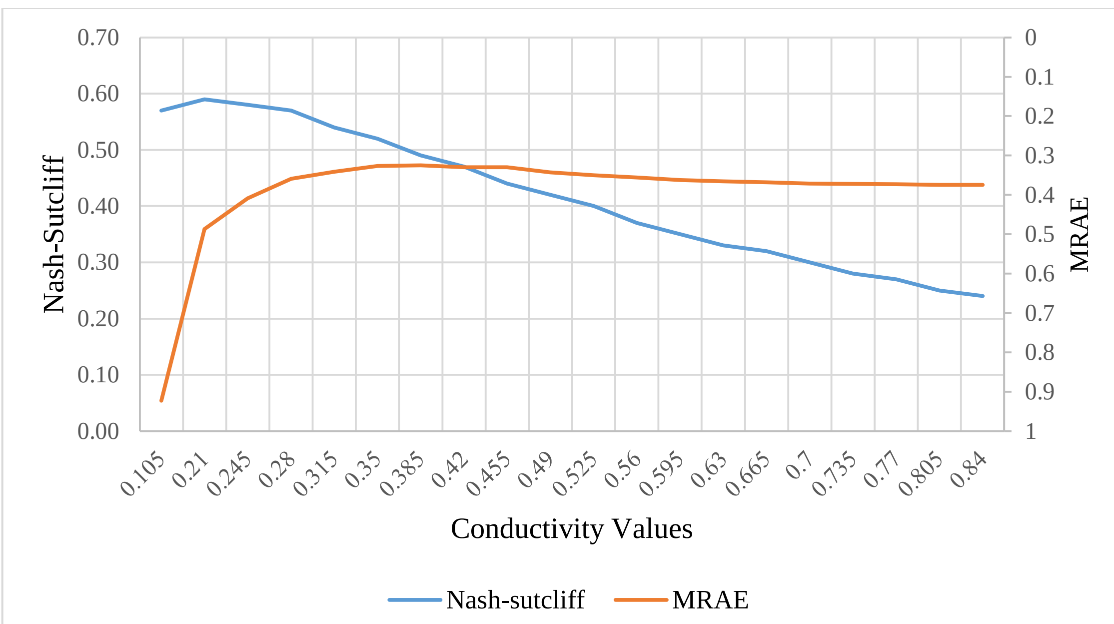

Figure F-2 Optimization of infiltration parameter (Saturated hydraulic conductivity K) of Ellagawa catchment

Table F-3 Optimization of groundwater parameter (a and b) of Ellagawa catchment

MRAE		Deep percolation coefficient (b)				
		1	**3**	**5**	**7**	**9**
Groundwater discharge coefficient (a)	**0.000815**	0.722974	0.3567	0.4591	0.52123	0.543636
	0.000978	0.5938	0.32719	0.4246	0.48	0.5216
	0.001141	0.8477	0.3244	0.3936	0.4589	0.5
	0.001304	0.96	0.3379	0.3649	0.4347	0.4788
	0.001467	1.0738	0.36	0.341203	0.4108	0.4585
	0.00163	1.1759	0.39	0.3266	0.38939	0.4399
	0.001793	1.2718	0.4269	0.3236	0.36718	0.4216
	0.001956	1.3613	0.46	0.32618	0.3511	0.4
	0.002119	1.4434	0.5	0.335	0.3363	0.3865
	0.002282	1.5226	0.549	0.34	0.3271	0.3705
	0.002445	1.5064	0.5934	0.3608	0.3245	0.3561

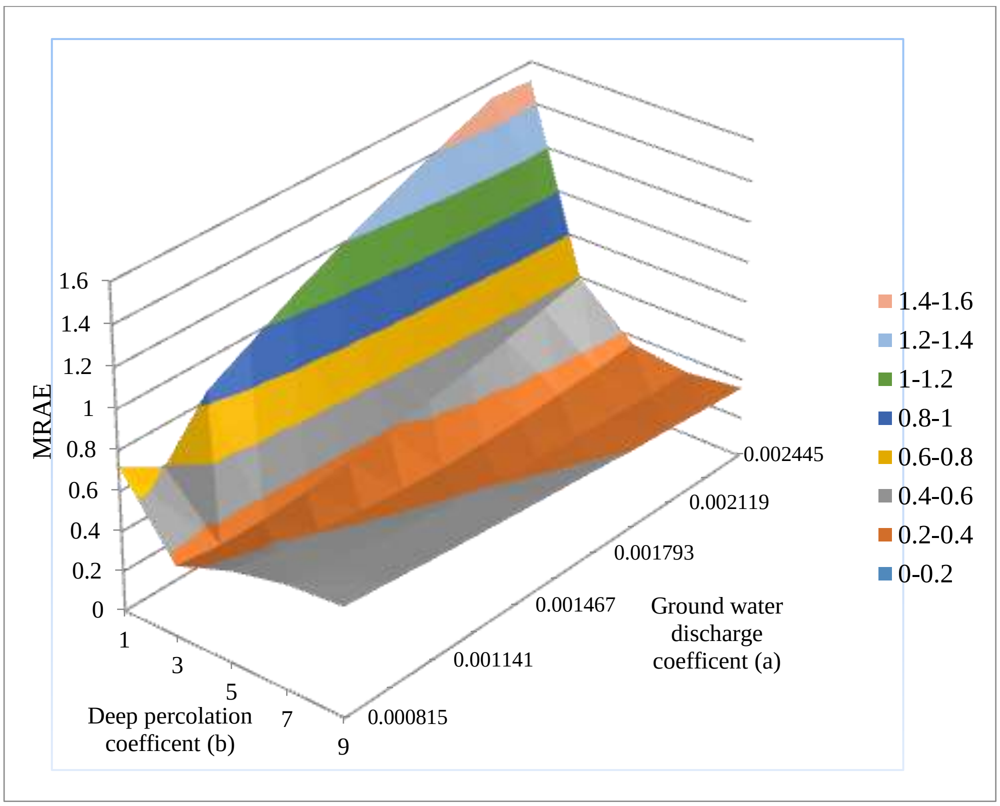

Figure E-3 Optimization of groundwater parameter of Ellagawa catchment1