INVESTIGATION OF HEC-HMS MODEL PARAMETER TRANSFERABILITY FOR DAILY RAINFALL RUNOFF SIMULATION IN MAHA OYA BASIN

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Degree of Master of Science in Water Resources Engineering and Management

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

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DECLARATION

I declare that this is my own work and this thesis does not incorporate without acknowledgment any material previously submitted for a Degree or Diploma in any other University or Institute of higher learning and to the best of my knowledge and belief, it does not contain any material previously published or written by another person except where the acknowledgment is made in the text.

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The above candidate has researched for the Masters thesis under my supervision.

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Professor N.T.S.Wijesekera Date

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Investigation of HEC-HMS Model Parameter Transferability for Daily Rainfall Runoff Simulation in Maha Oya basin

Abstract

Water is an essential finite natural resource for the developing world, however water is under growing stress due to, increased water consumption resulting from rapid population growth, development activities and industrialization for economic prosperity. Therefore, considerable attention for water resource management and development activities are required. The main challenge in this context is the unavailability of observed flow data. To address the prevailing condition, it is necessary to understand the catchment behavior from the hydrological point of view. Therefore, water quantification with the aid of hydrological modeling is an essential requirement, to facilitate the water resource development in ungauged watersheds.

The objective of this work is to investigate the level of applicability of hydrological parameter transferability by using the HEC-HMS model for Badalgama and Giriulla catchments in the Maha Oya basin, for sustainable development and management of water Resources.

The HEC-HMS model has been developed for Giriulla and Badalgama watersheds in the Maha Oya basin with the use of hydro-meteorological data, climatic data, and topographical data. Then model development, parameter estimation and simulation of the model have been performed systematically. Thereafter model calibration and validation were carried out based on identified objective function as RMSE and model performance evaluation criteria as MRAE. Optimized parameters were transferred by deploying different approaches, including temporal, spatial, and spatiotemporal methods. Model performance evaluation was carried out by observing total flow hydrograph, annual and seasonal water balance, behavior of low, medium and high flow regimes in the flow duration curve.

Developed HEC-HMS models of Giriulla and Badalgama catchments were calibrated with 0.24 and 0.25 of MRAE values, while validated with 0.18 and 0.19 of MRAE value respectively. In addition to that, flow hydrographs and flow duration curves matched well with the observed data. According to the transferability results, it was revealed that best approach for reproducing streamflow in both catchments are temporal transferability, which showed approximately 80% accuracy level. The spatial and spatiotemporal transferability approaches were not capable enough to capture the streamflow in satisfactory accuracy level, as it was approximately less than 50% for both catchments. Further, based on model results, it shows good performance for high and medium flows when compared with low flows in both catchments. Accordingly, at Giriulla watershed high and medium flow prediction accuracy for temporal transferability are 76% and 85%, while same for Badalgama watershed are 89% and 84%. However low flow prediction accuracy maintained approximately less than 60%. Further, annual average water balance error at Giriulla is overestimated 20%, while indicating seasonal water balance errors are overestimated 23% (Maha) and 17% (Yala). Similarly, at Badalgama average water balance error is underestimated 11%, and seasonal water balance errors are underestimated 8% and 20% for Maha and Yala seasons respectively.

In the light of these findings, calibrated and validated HEC-HMS model can be utilized for water resources development activities in daily timescale with approximately 75% accuracy for both catchments. Further, low flow estimation with this model must be carried out with caution due to selection of one layer precipitation loss model. The temporal transferability could be done for the selected catchments with good level of confidence (80% for both catchments), while spatial transferability and spatiotemporal transferability cannot be done with acceptable accuracy, though both catchments are in the same river basin.

Key Words:

HEC-HMS, Hydrological Model, parameter transferability, Calibration, and Validation, Maha Oya Basin

INVESTIGATION OF HEC HMS MODEL PARAMETER TRANSFERABILITY FOR DAILY RAINFALL RUNOFF SIMULATION IN MAHA OYA BASIN

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ABBREVIATIONS

2-P	- Two Parameter
4-P	- Four Parameter
AMC	- Antecedent Moisture Condition
AMSL	- At Mean Sea Level
ANN	- Artificial Neural Network
CN	- Curve Number
ET	- Evapotranspiration
FDC	- Flow Duration Curve
GIS	- Geographic Information System
GW	- Ground Water
HEC-HMS	- Hydrological Engineering Center-Hydrological Modeling System
IDW	- Inverse Distance Weighted
ID	- Irrigation Deparment
L	- Stream Length
MRAE	- Mean Ratio of Absolute Error
MSL	- Mean Sea Level
MSE	- Mean Square Error
NASH	- Nash Sutcliffe
PoR	- Period of Record
RF	- Rainfall
RMSE	- Root Mean Square Error
RR	- Rainfall-Runoff
SCS	- Soil Conservation Service
SD	- Survey Department
SF	- Stream Flow
SMA	- Soil Moisture Accounting
SWAT	- Soil Water Allocation Model
WMO	- World Meteorological Organization

1 INTRODUCTION

1.1 General

Water is an indispensable for human survival, hence it is a fundamental natural resource for all human activities. Therefore, from the time of ancient civilizations, mankind had been searching for water systems to fulfill their requirements. However, around the world, water has become scarce in quantity and poor in quality. This has been mainly due to increased water consumption resulting from rapid population growth, development activities and industrialization for economic prosperity (Mahmoud Abu-Zeid, Shiklomanov, 2004). The situation will be severely affected by impacts of evolution of climate change (Hijioka, et al., 2014). Hence, scarcity for clean water is being increased rapidly ever before. As a result, systematic planning tool and management techniques for water resources is critical to address the growing water resources scarcity.

Sri Lanka is a humid tropical country in the Indian Ocean, having three distinguishable elevation zones as, coastal belt, plains, and central hills. All major perennial rivers started from the central hills and drain radially towards the coast. There are three major zones based on amount of rainfall distribution, including Dry zone, Wet zone, and Intermediate zone (Jayawardena et al., 2011). The main two monsoons provide rainfall to Sri Lanka which are named as the northeast monsoon (October to March - Maha season) and the southwest monsoon (April to September -Yala Season), based on Ponrajah 1984. Meteorologically four seasons have been recognized as two monsoons and two inter-monsoons (Wickramagamage, 2009).

1.2 Sustainable Water Resources Developments and associated challenges

According to the UNESCO, 1999, sustainable water resources developments are designed to serve the community now and in the future, while balancing the environmental, ecological and hydrological integrity. However, water managers face many difficulties when managing water, hence systematic approaches are essential to develop the water resources in the local and national scale (Loucks, 2000).

In that context, accurate and precise water quantity estimation is essential, for water resources planning activities, including irrigation projects, water supply projects, hydropower projects, etc.. (Coulibaly, 2013). But due to unavailability or inadequate data availability would exaggerate the prevailing challenges. To address the situation, new methodologies have to be developed while evaluating the applicability of existing methodologies for interested areas. According to several researchers, the most sophisticated technology is the development of hydrological models (Arnold et al., 1998; Hunter et al., 2007; Magnusson Jan, Yang Xue, 2018).

1.3 Hydrological Modeling and Importance

It can be used hydrological modeling as a tool, to solve problems related to sustainable planning and management of water resources (Devia et al., 2015). Predicting river flow discrepancies in poorly-gauged/ungauged watersheds is major challenge in rainfall-runoff modelling, which can be especially seen in data scare situations and areas with considerable spatial variation in hydrological heterogeneity (Abimbola et al., 2017).

Rainfall-runoff models facilitate to simulate the hydrological behaviors in the Catchments (Sampath et al., 2015). The common practice is to use the models with lesser complexity and minor parameter requirement to reproduce the results close to reality (Devia et al., 2015). Most of the hydrological models such as HEC, SWAT, SWMM etc.. have been developed considering various hydrological processes and the three main inputs other than the topography, used to describe and understand those processes are rainfall, streamflow, and evaporation. To represent the reality, watershed characteristics, soil properties, land use coverage, topographical details, groundwater aquifer details are also introduced.

There are different ways to classify mathematical models considering spatial resolution, input-output parameters, model simplicity, etc. One example is the classification as empirical, conceptual and physical. Another is the one based on the spatial interpretation as distributed, semi-distributed and lumped (Sitterson et al., 2017). Empirical models, which sometimes referred as data-driven models, and non-linear statistical relationships between inputs and outputs has been used. Conceptual models represent the runoff process by connecting overall hydrological process in a simplified way, by providing a conceptual idea of behavior in the catchment (Devia et al, 2015; Vaze, 2012). Furthermore, models are representing the water balance equation for the conversion of rainfall to runoff by considering evaporation, groundwater, etc… Physical models, which also known as mechanistic or process-based model, are based hydrological processes related to physics, and are based on governing equations represent different hydrological processes (Sitterson et al., 2017).

The catchment area is considered as a one identical unit in the lumped models, and spatial variation of watershed parameters has not been considered in this model (Moradkhani & Sorooshian, 2008; Singh, 1995). Semi-distributed models are combination of lumped model structures, and distributed model features, which contained a series of localized parameters applied almost spatially (Sitterson et al., 2017). The most complex models are the distributed hydrological models because they take into account the spatial heterogeneity of the inputs (Sitterson et al., 2017).

Some of the hydrological modeling tools commonly used in the water resources management sector are Two Parameter Model (2-P), Tank Model, TOPMODEL, HEC-HMS, SWAT, MIKE-SHE, SOBEK, HBV etc.. (Devia et al., 2015), (Silberstein, 2006a).

1.4 Temporal and Spatial resolution of Rainfall-Runoff Modeling

The Hydrological models have been developed in different time resolutions including annually, seasonally, monthly, and daily. However, common practice in planning and managing the water resource sector to develop rainfall runoff models on a monthly basis (Ponrajah 1984; and Mouelhi, Michel, Perrin, & Andréassian, 2006), since it is less data and parameter intensive with respect to the models with finer timesteps (Xu & Singh, 1998). According to literature, the use of finer temporal resolution data in hydrological models, would able to represent the catchment hydrological processes very precisely. Further, when considering the situation in Sri Lanka most of the hydrological and meteorological data recorded daily (Department of Meteorology and the Department of Irrigation in Sri Lanka).

However in case of flood mitigation, it is focused on specific events and daily finer time resolutions would be much preferable in those cases (Xu & Singh, 1998). In most of the developing countries, major challengers are caused due to sparse data. Therefore, some assumptions have to make in poorly gauged or ungauged catchments, which leads to an increase in the level of uncertainties. Moreover, the most accurate and reliable method is to develop physically-based distributed models, though it required a high number of parameters. Accordingly, model selection would be highly dependent on the availability of continuous data series with good spatial distribution.

1.5 Transferability of Streamflow

As mentioned above, the main challenge in water resource development is the unavailability of adequate and reliable streamflow measurements. It was revealed that the number of methods has been utilized by the hydrological communities to handle this situation.

In 2013, Wijesekara has carried out a study by extrapolating streamflow data to ungauged catchment called Bopath Ella from the adjacent gauged catchment called, Deraniyagala, due to lack of availability of streamflow records at Bopath Ella. The primary aim of this study was the development of mini-hydropower system at Bopath Ella.

Further Patil & Stieglitz, 2015, have emphasized the importance of transfer of parameters (calibrated) with the use of hydrological models, especially either in time or space or both. According to him, even though the number of individual researches have been done in parameter transferability for streamflow prediction, these approaches are much less documented. In this research they have focus on three different schemes of parameter transfer including, temporal, spatial and spatiotemporal.

1.6 Hydrological Modeling in Maha Oya basin

Maha Oya is 11th largest river basins (National Atlas Sri Lanka), which is located in the west part of the wet zone in Sri Lanka. This river basin is vulnerable for flooding as well as for drought regularly. Although, topographically there is a greater potential of water resources development in this basin, a limited number of researches have been carried out in this basin.

In 2018, researched to investigate model performance with the effect of watershed subdivision within the Maha Oya basin. It was used antecedent moisture condition (AMC) to obtain good model performance. Nash–Sutcliffe (NASH) coefficient and Mean Ratio of Absolute Error (MRAE) were used to assess model performance in this research. According to the results, it shows minor variation inflow hydrographs, with respect to changing subdivisions from six to sixteen and the accuracy of the model has decreased when increasing the sub divisions. Furthermore, reliable results have been given in the model with AMC-II than AMC-III. In this study, baseflow estimation has been done using a recession method.

The two-parameter (2-P) and four-parameter (4-P) model has been developed for the Maha Oya basin by Perera & Rajapakse, 2018, to model the river flow. Model performance was evaluated by using the Pearson Correlation Coefficient and Mean Relative Error. The results revealed that the 4-P model performed well compared to the 2-P model. The runoff estimation has been done with the use of two different CN determination methods for Badalgama watershed in the Maha Oya basin (Adhikari, 2018). The SCS unit hydrograph method was used in this research, since it is more popular and reliable method to use in ungauged watersheds with similar hydrological characteristics. The concave method was used as a baseflow separation method, while the constant loss method was used for direct runoff estimation. Finally, this research concluded that, SCS-CN method could be used to obtain accurate runoff estimations. However, no studies have been conducted to determine the best drain prediction methods. This is an important prerequisite for the planning and management of water resources in unmeasured water catchment areas in the Maha Oya basin.

1.7 Problem Statement

After extensive literature research, it was identified that the unavailability of accurate streamflow measurements and adequate length of observed data series are the main constrains in water resources management, which could common in developing countries including Sri Lanka. To address the data scare situations, it is significantly important to derive calibrated and validated hydrological parameters and investigate the accuracy level of hydrological parameter transferability in daily timescale to perform accurate assessment of water resources in ungauged catchments by enabling sustainable water resources planning and management.

Based on the literature, the regionalization of model parameters from the measured catchment area to the unmeasured catchment area is one of the best systems for data anxiety situations. Further, the HEC-HMS model was identified as most preferable model to investigate the model parameter transferability in daily timescale within Maha Oya basin, since this model is freely available and very popular among hydrological communities, even in Sri Lanka. In addition to this, there is a high potential for planning and managing water resources in the Maha oya basin, as it is located topographically in the wet zone in Sri Lanka and there is uncertainty in the observed time series.

1.8 Objectives

1.8.1 Overall objective

To investigate the level of applicability of hydrological parameter transferability by using the HEC-HMS model for Badalgama and Giriulla watersheds in the Maha Oya basin for sustainable planning, development and management of water resources.

1.8.2 Specific objectives

1. Review the state of the art of the process-based hydrological model and the transferability of parameters.
2. Perform data collection, data checking and specifying the calibration and verification datasets.
3. Develop, calibrate and validate of continuous HEC-HMS model for Badalgama and Giriulla watersheds.
4. Examine the transferability of hydrological parameters of the HEC-HMS model from the main watershed (Badalgama) to the sub-watershed (Giriulla) and vice versa.
5. Evaluate the results with discussion and make suitable conclusions and recommendations on the applicability of the transferability of hydrological parameters with the developed HEC-HMS model.

1.9 Study Area

The Maha Oya basin has a catchment area of 1,562 km^2, making it the eleventh largest river basin in Sri Lanka. Seventy five percent (75%) of the basin area is in Wet Zone of the western region, while 25% of the basin lies in the intermediate zone in Sri Lanka. The main river is approximately 134 km long and it originates in the western part of hill country in Kandy and Kegalle districts, with elevations of 1,500 m AMSL, and flows to the sea at Kochchikade. The main river has approximately 21 tributaries, of which Rambukkan Oya, Talagolla Oya and Hingul Oya are the main tributaries. In some areas Maha Oya meanders, as is typical of high-energy rivers (from a steeper upper catchment) meeting a low energy environment (flat flood plain) in unconsolidated soils.

The climate of the Maha Oya basin features a typical humid tropical climate. The average annual rainfall in the basin is approximately 2,220 mm and the average annual temperature is 26 ^{0}C depending on the altitude. The Maha Oya basin's major parts lie in Kegalle, (35%), Kurunegala (31%), while small parts in Gampaha (18%), Kandy (10%), and Puttalam (6%) Districts. The stream flows measured at the Badalgama and Giriulla gauging stations, therefore Badalgama and Giriulla watersheds were used for this research. The study area Map is shown in Figure 1-1.

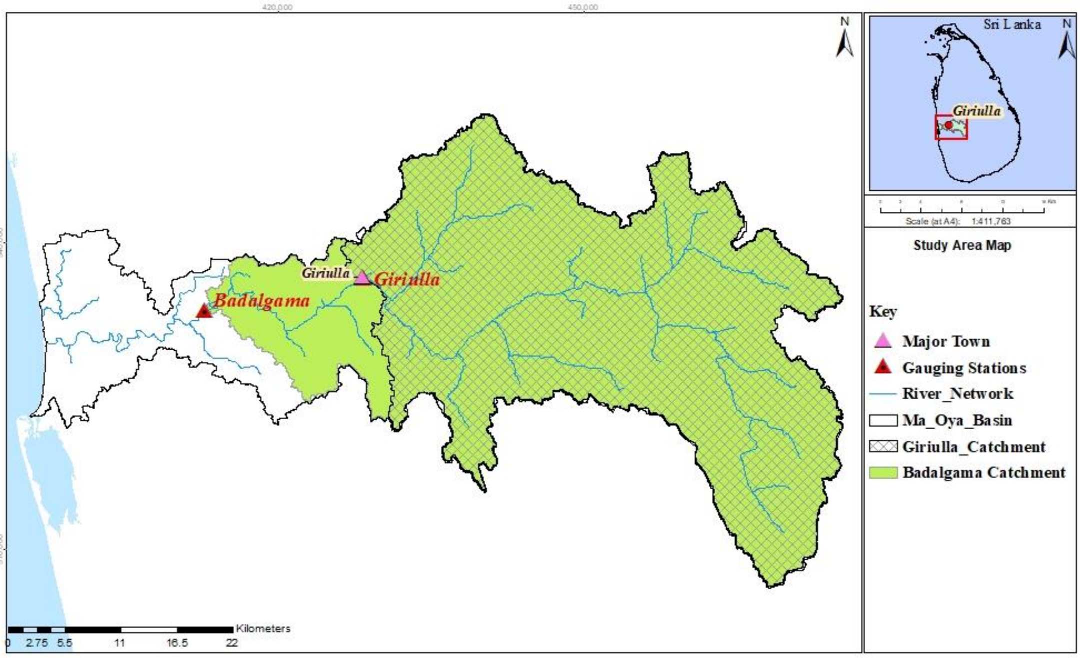


Figure 1-1: Study Area Map

2 LITERATURE REVIEW

2.1 General

Sri Lanka is a country, which based on the agricultural economy and more than 50% of power generated through hydropower plants. Hence, water resources management is being taken high priority. However, modern techniques in rainfall-runoff modeling have been fairly used in the field of water resources planning and management, but it was stated that various types of numerical models can be used to enhance the planning and managing water resources projects in Sri Lanka (Dharmasena, 1997).

The level of detail from conceptual models to complex spatially distributed or physics-based models is illustrated in various backgrounds are varied based on catchment conditions (Wagener & Wheater, 2006). Therefore selection of most appropriate model is very important, which represents the actual hydrologic conditions in a selected watershed.

2.2 Hydrological Models

Precipitation runoff models are the representation of real hydrological processes in a simplified way. The introduction of mathematical modeling was found to begin when M. Darcy (1856) published his analysis on hydraulic conductivity. Then it had been advanced based on the mathematical description of river hydraulics by Saint-Venant (1871) and significant improvement of Darcy's "Law" by Richard (1931). Further, hydrological model representation was improved with the introduction of the revolutionary in the description of runoff generation by Horton (1933) (Silberstein, 2006b). Accordingly, mathematical representation of groundwater flow, river routing, infiltration, and surface runoff generation have been modeled in hydrological models.

Hydrological models are therefore very versatile tools for the planning, development and management of water resources. However, there are some limitations mainly to both the model structures and the available data on parameter values (Mwakalila et al., 2001). There are several rainfall-runoff model classifications and the main classifications include physically based models, empirical model and conceptual models (Devia et al., 2015).

2.2.1 Empirical Models

These models use existing data, while considering the mathematical equations, which have been derived from the simultaneous input and output time series and it does not consider the physical process of the watershed, such as Unit hydrograph method (Devia et al., 2015). These models can be applied to poorly gauged or ungauged watersheds by regional analysis (Pechlivanidis et al., 2011). Artificial Neural Network (ANN) and fuzzy regression are some of the machine learning techniques used in this model. ANN uses the available runoff data and rainfall to understand the hydrological process (Pechlivanidis et al., 2011).

2.2.2 Conceptual Models

The components of the hydrological processes in a watershed-scale input-output relationship has been characterized by the conceptual models (Wheater, 2002, Pechlivanidis et al., 2011). This model consists of many schematic storages to represent the important hydrological features. The complexity of the model varies based on the number of reservoir (storages), which was introduced to the model to represent the percolation, infiltration, and rainfall are emptied by evaporation, drainage, runoff, etc. Devia et al (2015), stated that, semi-empirical comparisons have been used in this method and the assessment of model parameters was done not only based on the field data, but also based on the calibration. One of the disadvantages of this method is land-use change can not be estimated with good sureness. The first conceptual model was the Stanford watershed model, and it had been established in 1966 by Crawford and Linsley with the use of 16 to 20 parameters (Devia et al., 2015).

2.2.3 Physically-based Models

These are the models that represent the real hydrological processes in watersheds including, infiltration, evapotranspiration, overflow, saturated and unsaturated flows using leading equations (Pechlivanidis et al., 2011). In the physics-based models water movements are represented using finite differences equations and a large number of data including topography, topology of the river network, soil moisture content, and initial water depth. However, it has been found that there is some dependency on existing data, which leads to results with a poor formal confidence specification. (Wheater, 2002). SHE/ MIKE SHE model is an example (Abbott et al. 1986 a, b).

The features of these three models are summarized in Table 2-1.

Table 2-1: Characteristics of different models

Empirical model	Conceptual model	Physically-based model
Data based or black box	Parametric or Grey box model	Mechanistic or white-box model.
Use Mathematical equations	Based on modeling of storages along with the semi-empirical equations	Based on special distribution, evaluation of parameter describing physical characteristics
High predictive power and low explanatory level	Simple and can be easily executed in computer code.	Required data on initial state of model and morphology of catchment.
Cannot be used for other catchments	Need Large Hydro-meteorological data.	Valid for a wide range of situations, and it needs human expertise and computation capabilities, since its complexity.
ANN, Unit hydro graph	HBV, TOPMODEL	MIKESHE, SWAT

2.2.4 Other types of classifications

Further to the above classification, there are some other important classifications, including Deterministic and stochastic models, distributed and Lumped models, and Time-scale based models, Space-scaled based models, etc..

The lumped models consider the watershed as a unit, and state variables represent the average values across the watershed. Inputs, boundary conditions, spatial variability of processes and geometric properties of the system (catchment area) are not taken into account, while distributed models are based on geometry or spatial variability (Pechlivanidis et al., 2011; Singh, 1995). The lumped models required a lesser data requirement with compared to the distributed model (Mcintyre & Wheater, 2008).

The deterministic models were exceptionally determined by known relationships between the states and data, which led to a single result of the simulation with a single set of parameter values and input data. Random variables have been used in stochastic models to represent uncertainty of process, and it produces diverse outcomes from individual parameter values and input data when performed “externally seen” under identical conditions (Beven, 2001).

Further hydrological models can be categorized either event-based or continuous simulation models. Simulation of the continuous hydrological model would generally take into account precipitation time series with more than one thunderstorm event or longer durations that include dry and wet conditions, while the event-based model focuses on the response of each rainfall event in the basin, including amount of surface runoff, detention, timing of peak, and peak (Chu & Steinman, 2009). In addition, other categorizations of continuous models are distinguished; annual, monthly, daily and sub-daily patterns (Pechlivanidis et al, 2011).

2.3 Hydrological Modeling in Sri Lanka

Continuous and event hydrologic models were developed for Kelani River basin by using HEC-HMS model. To represent the infiltration loss in event-based modeling, Green and Ampt infiltration loss method was adopted. Moreover, in continuous modeling, five-layer soil moisture accounting (SMA) loss method was used. In this study to reproduce the direct runoff and baseflow, Clark unit hydrograph method and the recession base flow method has been utilized, respectively. According to the results it was shown that, the stream flows has been modeled by the HEC–HMS model with the high performance as Nash–Sutcliffe efficiencies (0.91) for event-based models, while same indicator for continuous modeling was 0.88 (De Silva et al., 2014).

Similarly, the HEC-HMS model was developed to simulate runoff in Deduru Oya Basin, Sri Lanka, which has been used recession as baseflow method, Clark unit hydrograph as transformation method, and SMA as loss method. The performance indicators represented that the ability of HEC-HMS to model the river flows in the catchment by Nash Sutcliffe efficiencies of 0.80. Finally it was stated that this model is accurate enough to model the seasonal variation in Streamflow (Sampath et al., 2015).

The HEC-HMS model was developed to Attanagalu Oya Basin, which is located in western part of Sri Lanka. The model has been calibrated by changing three different methods, such as a) the deficit constant loss method b) the Soil Conservation Service Curve Number (SCS-CN) loss method, c) the Snyder unit hydrograph method and the Clark unit hydrograph method to determine the most suitable simulation method. The current flows reproduced by each method were evaluated numerically using the coefficient of performance, the relative error and the residual method. Finally it was concluded that the most appropriate method is the Snyder unit hydrograph method to simulate streamflow than the Clark unit hydrograph method (Halwatura & Najim, 2013).

In 2016, hydrological model was developed for Kalu Ganga basin by using HEC-HMS model, which used the one layer deficit and constant loss method in HEC-HMS and it was used as precipitation loss model which accounts for soil moisture content in the continuous model. Moreover, simulation of direct runoff and baseflow have been done by adopting the SCS unit hydrograph and recession methods respectively. In this study manual calibration was performed using the MRAE as the objective function. Furthermore, another two statistical methods have been used as a percent error in volume and Nash-Sutcliff model efficiency (Kamran & Rajapakse, 2018).

2.4 Parameter Transferability

The accurate estimation of streamflow and peak discharge is very important to make decisions in planning, designing, and management of water resources. However, most of the watersheds are likely ungauged in worldwide, while some watersheds are poorly gauged. For example, in some watersheds, Hydro-meteorological data including streamflows are not recorded in sufficient accuracy level, or in some other watersheds, were previously gauged but discounted due to malfunction or failure of instrument or termination of measurement programme (Loukas & Vasiliades, 2014).

To overcome these challenges, rainfall-runoff models are commonly used to estimate or extrapolate the streamflow in ungauged watersheds (Wagener & Wheater, 2006), hydrologists have to develop models by using modern techniques to predict the streamflows. According to the Loukas and Vasiliades (2013), it can be done by developing a hydrologic model to gauged watershed and transfer the parameters to the ungauged watersheds considering its physiographic characteristics. The other method proposed by them is to establish the regionalized relationship to transfer the parameters, where watersheds exist with similar hydrological characteristics.

Similarly, the temporal and spatial portability of calibrated model parameters was analyzed in Nepal using the BTOPMC model to reproduce different drainage components including peak flows, base flows and discharge volumes in different physiographic areas. According to the results, finally it was concluded that the model was responded satisfactorily in reproducing different runoff components, while capturing annual and seasonal variation in runoff (Shrestha et al., 2007).

Further, temporal transferability of the SLURP model parameter was tested for the Black sea region in Turkey (Apaydin et al., 2006) and it was revealed that a decrease in model performance indicators were detected when calibrated parameters applied for the periods before and after the calibration. Further, it was investigated that, this was occurred due to land cover change over the period.

Gitau and Chaubey (2010), the SWAT model has been utilized to examine the viability of developing a regionalized parameter set to use in poorly gauged or ungauged catchments. In this study, global averaging and regression-based methods are used as regionalization methods. Finally, results have been proven that, the SWAT model with regionalized parameters could be used for reproducing the streamflow with satisfactory accuracy in ungauged watersheds.

Piman and Babel (2013), has been carried out a study to estimate runoff in an ungauged catchment in a region of northern Thailand, which has been utilized a weather radar technology and modeling approach to estimate rainfall and to simulate streamflow respectively. In this research quasi distributed rainfall-runoff model HEC-HMS was used to reproduce the runoff in gauged and ungauged watersheds. Further, transposition and regionalization techniques were used to calculate the model parameters in the assumed unmeasured watershed. According to the study results, it revealed that this method provides a promising alternative for enhanced hydrological forecasts in ungauged catchments.

During the literature search, it was found that Razavi, Coulibaly, and Asce (2012a), was illustrated the precise classification based on the extrapolation methods used to transfer the hydrological model parameters, which is illustrated in Table 2-2.

Table 2-2: classification of Hydrological model parameter transferring methods

No	Category	Studies
1	Arithmetic mean method	Merz & Blöschl, 2004 ; Oudin, Andréassian, Perrin, Michel, & Le Moine, 2008
2	Spatial proximity (spatial distance) approach	Merz & Blöschl, 2004; Oudin et al., 2008; Parajka, Merz, & Blöschl, 2005; Li, Zhang, Chiew, & Xu, 2009
3	Physical similarity approach	Oudin et al., 2008; Samaniego, Bárdossy, & Kumar, 2010; Samuel et al., 2011
4	Scaling relationships	Croke, Merritt, & Jakeman, 2004; Schreider, Jakeman, Gallant, & Merritt, 2002
5	Regression-based methods (linear and nonlinear)	Merz & Blöschl, 2004; Parajka et al., 2005; Oudin et al., 2008; Cheng, Ko, Yuan, Ge, & Zhang, 2006; Mohamoud, 2008
6	Hydrological similarity approach	Masih, Uhlenbrook, Maskey, & Ahmad, 2010

2.5 Model Selection

During the literature survey, it was observed that there are a vast number of rainfall-runoff models are used in hydrological studies depending on different criteria. To identify the most appropriate model, to use in this study was selected by applying evaluation criteria as specified below (Table 2-3).

Table 2-3: Model selection criteria

No	Criteria	High	Medium	Low
1	Model Application	Applied in Sri Lanka	Applied in Asian region	Applied in other regions
2	Parameter transferability applications	All around the world	Part of the world	Only for specific countries
3	Parameter transferability applications in Sri Lanka	More than 5 applications	Less than 5 applications	No applications
4	Time of simulation	Continuous and event base	Continuous base	Event base
5	Geometry or spatial variation	Lumped and distributed model	Lumped model	Distributed model
6	Model accessibility	Freely available model	Freely available for education purpose	Fully commercial
7	Physical process representation	Physics-based model	Conceptual model	Empirical model
8	Temporal resolution	sub-daily, daily	Monthly	Annually
9	Data requirement	Model runs with limited data availability	Model runs with moderate limited data availability	Model runs with more data availability
10	Availability of manuals and quick guides	freely available user guides and manuals	Commercially available user guides and manuals	None availability of manuals and guides

The evaluation criteria were formulated based on the purpose of sustainable water resources management and the facts that have been identified through a comprehensive literature survey. Identified models have been prioritized, by allocating marking scheme.

Following the literature review, seven models were selected for aforementioned evaluation, for selecting the most appropriate model. The Table 2-4 illustrate the prioritization performed with the literature.

Table 2-4: Model Selection prioritization

Criteria	**J2000**	**SWAT**	**TOPMODEL / BTOPMC**	**MIKE 11/ NAM**	**TANK**	**HEC-HMS**	**SLURP**
Criteria 1	M (2)	H (2)	H (3)	H (3)	H (3)	**H (3)**	M (2)
Criteria 2	L (1)	L (1)	L (1)	L (2)	L (1)	**L (1)**	L (1)
Criteria 3	L (1)	L (1)	L (1)	L (1)	M (2)	**L (1)**	L (1)
Criteria 4	H (3)	H (3)	H (3)	H (3)	M (2)	**H (3)**	H (3)
Criteria 5	L (1)	H (3)	L (1)	H (3)	M (2)	**H (3)**	L (1)
Criteria 6	H (3)	H (3)	M (2)	L (1)	H (3)	**H (3)**	L (1)
Criteria 7	H (3)	H (3)	H (3)	H (3)	M (2)	**H (3)**	M (2)
Criteria 8	H (3)	H (3)	H (3)	H (3)	H (3)	**H (3)**	H (3)
Criteria 9	L (1)	M (2)	L (1)	H (3)	H (3)	**H (3)**	L (1)
Criteria 10	H (3)	H (3)	L (1)	H (3)	L (1)	**H (3)**	H (3)
Total	**21**	**24**	**19**	**25**	**22**	**26**	**18**

Accordingly, the HEC-HMS model has been prioritized as the most appropriate model to carry out this study, since it obtained the highest marks for criteria 6 (Model accessibility) with respect to the second option, which is MIKE11/NAM.

2.6 HEC HMS Model Structure

HEC-HMS is a physical model based on precipitation and runoff, which was developed by the US Army Corps of Engineers Hydrologic Engineering Center (HEC) to reproduce hydrological processes in watersheds. This model can be used to a number of geographic areas, from larger to smaller, urban or natural water catchments. The system includes losses, open-channel routing, runoff transformation, rainfall-runoff simulation, analysis of meteorological data and parameter estimation (Verma, Jha, & Mahana, 2010). It was stated that the program used a separate model to represent each component of the drainage process, including the calculation of drainage volume, the direct drainage / baseflow / channel flow and a separate model to account for cumulative losses. Finally, runoff volume was calculated by subtracting losses like infiltration, storage, interception, evaporation, etc... from the precipitation (Khadka & Bhaukajee, 2018).

2.6.1 Canopy Method

This model component can represent the existence of vegetation cover on the real ground. Selecting the Canopy method is optional but is required to use in continuous simulation applications (Scharffenberg, Bartles, Brauer, Fleming, 2018). Further, it was stated that, all the precipitation would be presumed as direct rainfall on the ground surface and any interception or evapotranspiration would not be computed, if any canopy method was not selected and it will be subjected to interception by the surface and infiltrate into the soil. Three types of Canopy methods can be appropriately selected in HEC HMS modeling, such as Simple Canopy, Dynamic Canopy, and Gridded Simple Canopy.

To represent the plant canopy, the simple canopy method was used, while the gridded simple canopy method is a simple interpretation of the soil surface in a grid cell basis. The Dynamic canopy method includes an interception storage capacity and a harvest coefficient that changes over time (Sok & Oeurng, 2016; Scharffenberg, Bartles, Brauer, Fleming, 2018).

The two methods were adopted to extract the water in the soil, such as soil moisture accounting loss rate or deficit constant method and simple method. The tension reduction method extracts water at the potential evapotranspiration rate from the gravity zone, but the speed decreases when the tension zone is extracted (Bill Scharffenberg, Mike Bartles, Tom Brauer, Matt Fleming, 2018).

2.6.2 Surface Method

To exemplify surface depression storages in the ground, the surface method has been adopted in the model. When rate of the rainfall increased beyond the rate of infiltration and the surface storage is filled, surface runoff will be originated. Generally surface method selection done only for continuous model applications (Bill Scharffenberg, Mike Bartles, Tom Brauer, Matt Fleming, 2018). During the literature search it was found that, Bennett (1998) has illustrated the surface storage values based on the gradient of the watersheds and land use types as in Table 2-5.

Table 2-5: Surface Depression Storage

Description	Slope %	Surface Storage (mm)
Paved impervious areas	NA	3.2 – 6.4
Steep, smooth slopes,	≥ 30	1
Moderate to gentle slopes	5 - 30	12.7 – 6.4
Flat, furrowed land	0 - 5	50.8

2.6.3 Selecting a Loss Model

The basin elements conceptually represent the infiltration, surface runoff and subsurface processes and runoff, while real infiltration estimations are conducted by utilizing a loss method. There are twelve loss methods are available, some of them are used to reproduce events, while some of them used for continuous simulation. In this context, all the rainfall will be considered as excess, while not estimating the infiltration. Further, it was subjected to surface storage and runoff, if any of the loss method was not selected among provided twelve methods. The summary of the available loss model is given in the Table 2-6.

Table 2-6: Summary of Loss models

Loss Model	Description
Deficit and Constant Loss	In this method, a single soil layer is considered to account for continuous changes in moisture content. Further, it should be used with the canopy method, since it will extract

Loss Model	Description
	water from the soil in response to potential evapotranspiration computed.
Exponential Loss	Should not be used without calibration. It represent incremental infiltration as a logarithmically decreasing function of accumulated infiltration. It is not appropriate for the continuous simulations.
Green and Ampt Loss	It is a simplification of the comprehensive Richard's equation for unsteady flow in soil. This method assumes the soil is initially at uniform moisture content and infiltration takes place with so-called piston displacement.
Gridded deficit constant loss	This is essentially implemented the deficit constant method on grid cell by grid cell basis. It accounts for precipitation and evapotranspiration from the meteorological model for each grid cell. The Initial Deficit Grid, Maximum deficit grid, Constant Rate grid and impervious grid must be selected from the list of choices, while the Initial deficit grid ratio, maximum deficit grid ratio, constant rate grid ratio and impervious grid ratio must be entered.
Gridded Green and Ampt Loss	This method implements the Green and Ampt method on a grid cell by grid cell basis. It accounts for precipitation and evapotranspiration from the meteorological model for each grid cell. Initial water content grid, wetting front suction grid, Hydraulic conductivity grid and impervious grid must be selected from the list of choices.
Grided SCS Curve Number Loss	This Method implements the Soil Conservation Service (SCS) curve number method on a grid cell by grid cell basis. Each grid cell receives separate precipitation from the meteorological model. In this method, the curve number grid must be selected from the list of choices, while default initial abstraction ratio (0.2), and default potential retention scale factor (1) may optionally be changed.

Loss Model	Description
Gridded Soil Moisture Accounting	This method essentially implements the soil moisture accounting method on a grid cell by grid cell basis. Each grid cell receives separate precipitation and potential evapotranspiration from the meteorological model.
Initial and constant loss	This is a very simple method, but still suitable for watersheds that lack detailed soil information. It is also suitable for flow-frequency studies
SCS Curve Number Loss	This method implements the curve number methodology for incremental losses (NRCS, 2007). Originally, it was intended to calculate total infiltration during the storm. It can optionally enter the initial abstraction and curve number and impervious area must be entered.
Smith Parlange Loss	It approximates the Richard's equation for infiltration into the soil by assuming the wetting front can be represented with an exponential scaling of the saturated conductivity.
Soil Moisture Accounting Loss	In this method three layers used to represent the dynamics of water movement in the soil. It should be used in conjunction with a canopy method and surface method. There will be no soil water extraction unless a canopy method is selected. The surface layer holds precipitation and allows it to infiltrate after the rain has stopped.

Source: (Bill Scharffenberg, Mike Bartles, Tom Brauer, Matt Fleming, 2018)

2.6.4 Selecting a Transform method

A transform method is an approach for computing direct runoff at the watershed outlet from the excess rainfall falling over it (Khadka & Bhaukajee, 2018). The transform method consisted within the basins was utilized to estimate real surface runoff, and there are total eight diverse transform methods are available in HEC-HMS, which include a kinematic wave implementation, various unit hydrograph methods, and linear quasi distributed method. The required transform method can be chosen from the available list.

The most popular way of transformation is SCS unit hydrograph, since it could be used for many different environments and has been proven that similar response in surface runoff generated from rainfall in hydrological modeling (Chu & Steinman, 2009). Moreover, Ponce and Hawkins (1996), stated the benefits of this transformation method is, its straightforwardness, its predictableness, its steadiness, its dependence on only one parameter, and its sensitivity to major runoff producing watershed properties such as surface condition, land use, soil type and antecedent condition.

2.6.5 Selecting a Baseflow Method

Baseflow comprises of interflow and flow in groundwater aquifer (Khadka & Bhaukajee, 2018). The HEC-HMS specifies six different baseflow methods, including constant monthly baseflow, non-linear Boussinesq flow, Bounded recession baseflow, Recession baseflow, and linear reservoir baseflow. Some methods are mainly used to reproduce the events, while other methods are for continuous simulation (Scharffenberg, Bartles, Brauer, Fleming, 2018).

2.6.6 Routing model

There are nine diverse routing methods are provided in the model, including Normal Depth, Lag and K, Modified plus, Muskingum-Cunge, Lag, Muskingum, kinematic wave, and straddle stagger. The actual computations are executed by the routing method, which contained within the stream. Each method consists of the diverse levels of details and it is required to use appropriately for a particular system (Scharffenberg, Bartles, Brauer, Fleming, 2018).

2.7 Objective function

The purpose of the objective function is to numerically evaluate the goodness-of-fit between reproduced streamflow vs recorded streamflow at hydrometric station. To manage water resources, studying and evaluating different flow regimes are significant, especially in irrigation, water supply, and hydropower (Engeland and Hisdal, 2009; Lang Delus, 2011). Hence, the selection of appropriate objective functions is paramount important, as it will be oriented towards the decision making on engineering applications (Diskin & Simon, 1977).

The most popular objective functions were developed based on the least-square error method and maximum likelihood methods (Garcia et al., 2017). However, there are different objective functions are used by the hydrological communities, depending on the purpose of the hydrological modeling, such as event modeling or continuous modeling. Accordingly some objective functions are focus on different flow regimes and a time step of model simulation, hence not able to use as a universal function to evaluate the level of model performance (Beven, 2012). In 1999, Legates and McCabe, emphasize that, it is required to include at least one objective function such as Nash and Sutcliffe Efficiency Coefficient (NSC), and one absolute error measure, e.g. root mean square error (RMSE) to perform complete performance evaluation. NSC is more penetrating for the high flows. Hence it tends to mislead on other flow conditions (Esse et al. 2013 and Song et al. 2019).

Moreover it was observed that, objective functions have been categorized as scale-independent and scale-dependent measures. The scale-dependent objective functions are suitable for data with the same scale, which are mean absolute error (MAE), mean square error (MSE), and root mean square error (RMSE) (Hwang et al., 2012; Hyndman & Koehler, 2006; S. Kim & Kim, 2016).

Based on the literature, it was further revealed that some hydrological models, itself has the capability to optimise the model using a different objective function. For example, two different approaches such as stochastic and deterministic were consist within HEC-HMS model optimization. Various objective functions have been provided to measure the goodness of fit between modeled and measured flow in different ways. To optimize the results, there are 14 different objective functions available under the minimization goal, while eight different objective functions available under maximization goal (Scharffenberg, Bartles, Brauer, Fleming, 2018). The most popular objective functions are illustrated in the Table 2-7 below.

Table 2-7: Objective function commonly in practice

No	Objective Function	Equation	Range of values	Reference
1	Nash Sutcliffe efficiency coefficient (NSE)	$NSE = 1 - \frac{\sum_{i=1}^{N}(Q_c - Q_O)^2}{\sum_{i=1}^{N}(Q_O - \bar{Q}_O)^2}$	∞ to 1.0	Nash & Sutcliffe (1970); Servat & Dezetter (1991); (Muleta, 2009)
2	Mean Ratio Absolute Error (MRAE)	$MRAE = \frac{1}{N}\sum_{i=1}^{N}\frac{\lvert Q_C - Q_O\rvert}{Q_O}$	0.0 to ∞	Dissanayake (2017); Kamran & Rajapakse (2018); Wijesekera (1993, 2000)
3	Root Mean Square Error (RMSE)	$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(Q_C - Q_o)^2}$	0.0 to ∞	(Hwang et al., 2012); Song et al. (2019); (Muleta, 2009)
4	Ratio of Standard Deviation of Observations to RMS (RSR)	$RSR = \frac{\sqrt{\sum_{i=1}^{N}(Q_C - Q_o)^2}}{\sqrt{\sum_{i=1}^{N}(Q_O - Q_{mean})^2}}$	0.0 to ∞	Moriasi et al., 2007; Atkinson et al., 2010; (Muleta, 2009)
5	Coefficient of Determination (R2)	$R^2 = \left\{\frac{\left(\sum_i^N (Q_{oi} - Q_{omean})\,(Q_{ci} - Q_{c\,mean})\right)}{\left[\sum_i^N (Q_o - Q_{omean})\right]^2 \left[\sum_i^N (Q_c - Q_{cmean})\right]^{0.5}}\right\}^2$	0 to 1.0	Bai et al., 2015; Gracia et al., 2017; Patil & Stieglitz, 2015
6	Volumetric Efficiency	$VE = 1 - \frac{\sum_{i=1}^{N}\lvert S_i - O_i\rvert}{\sum_{i=1}^{N} O_i}$	∞ to 1.0	Criss and Winston (2008); (Muleta, 2009)

2.8 Model Warm-up

To achieve the dynamic equilibrium of the hydrological models, warm-up period is required to introduce to the model, which facilitate the model to run an adequate number of years before start actual simulation period (Daggupati, et al., 2015). K. B. Kim and Han (2016), was stated that the application of initial conditions from the catchments to hydrological models were not studied adequately.

Further, Grassmann (2014) highlighted that the warm-up period is not necessary, where the models have good starting conditions. However, when simulating complex systems, it is difficult to identify such a good starting state (Grassmann, 2014). Hoad et al., (2008), pointed out that various methods could be used to warm the hydrological models, in particular; run the model for the warming phase until realistic conditions are reached. Define the initial condition for the realistic value, define the partial condition and then run the warm-up period and delete the warm-up data. According to some researches, the warm-up period shall be reduced when simulating a model for longer periods (Grassmann, 2014).

2.9 Model Calibration and Validation

Once the schematization and parametrization of the hydrological model have been completed, the calibration and validation of the model must be carried out before using this model or its parameters for water resources development activities. Though initial model parameters derived based on catchment characteristics, the set of best fit parameters could not be measured accurately for the specific catchment. Therefore, it is a usual practice to estimate the set of parameters that cannot be derived directly with field data, by facilitating the model to provide the best fit between measured and modeled flows. According to the Refsgaard and Storm (1996), there are three different approaches can be used; a) manual parameter adjustment, trial and error; b) Automatic, numerical parameter optimization and c) combination of a & b.

However, there are some advantages and disadvantages are associated with manual and automatic methods. The manual calibration method is most commonly in practice as well as most researches preferred this method, since it can be used for more complicated models as well (Refsgaard & Storm, 1996). But this method is more time consuming when there is a higher number of parameters has to be calibrated, expertise knowledge, skills and experience in hydrological modeling are required (Sorooshian & Gupta, 1983; Kumarasamy & Belmont, 2018; Madsen, 2000).

In the context of an automatic calibration method, numerical algorithms are used, which identify the best values based on the chosen objective function (Kamali et al., 2012). This method able to search through, a large number of combinations within a comparatively shorter time period (Refsgaard & Storm, 1996). The main advantages of the automatic method over the manual method are, time effectiveness (Henriksen et al., 2003) and the work carried out by the computer, hence optimized values are not dependent on personal judgments. On the other hand, the main disadvantages are optimization will probably result in the local optimum, without reaching to global optimum, when the model contains the few parameters and algorithms assumes that, all the parameters are independent.

The combination of manual and automatic methods is also very useful in terms of optimization, though it does not popular in practice. In this method either automatic or manual method could be performed initially and then it would be possible to calibrate the parameters, for identifying the best fit (Refsgaard & Storm, 1996).

The calibrated model, has to be tested with different temporal datasets, from those used for calibration, before using it for the subsequent use (Stephenson & Freeze, 1974; Patil & Stieglitz, 2015).

2.10 Data requirement and quality assessment

2.10.1 Data and data durations

As stated by Wijesekera and Perera (2012), water resources and management are highly dependent on hydro-meteorological data quality. Therefore the availability of good quality longer time series with well special distribution is favorable in hydrological modeling in order to obtain proper hydrological responses in the catchment (Ariyasena, 2019). In addition to hydro-meteorological data, soil data and land use data have been taken greater importance in hydrological model performance, especially in distributed models (Devia et al., 2015).

Orellana et al. (2008), was highlighted that, 8 years of hourly data (rainfall and flow data) and monthly data (evapotranspiration) had been used to simulate the hydrological model in upper Lee watershed in the United Kingdom. In here, separate four years were considered for calibration (1991-1998) and validation (1998-2002). Similarly Li et al. (2010), also highlighted that the availability of 8 years of data is adequate for daily hydrological models.

In addition, Jayadeera (2016) developed a hydrological model for the Kalu Ganga basin using the HEC-HMS model, which proves that separate four-year data periods are sufficient to calibrate and validate the hydrological models. The study was conducted by Kamran and Rajapakse (2018), to evaluate the impact of Antecedent moisture conditions and watershed subdivisions in the Maha Oya basin by using the same model. In that context, also different four year periods were allocated for model calibration (2005 – 2008) and validation (2010 -2013). Based on aforementioned researches, it was identified that, lengthy data series were increased the model performance.

2.10.2 Data Quality Assessment

In some countries, different organizations have the data collection authorities (Wijesekera & Perera, 2012b), which will create difficulties in hydrological modeling, in terms of data collection, data formats and maintaining a good databases. However following the data collection, pre-processing has to be carried out before perform quality assessment. The quality assessment and validation has to be undertaken on the available hydro-meteorological data in preparation for its use in subsequent hydrological analysis, rainfall-runoff modeling.

Wijesekera and Perera (2012) highlighted that, homogeneity and consistency of collected data series have to be checked before use it in the practical applications. However, he further emphasized that, when selecting lengthy time series, there is a high probability of these data neither stationary, consistent nor homogeneous. Therefore adequate data checking must be carried out to ensure the data accuracy (WMO, 2018).

The hydrological communities take different approaches to perform data checking, including, statistical methods, graphical methods (Silva, Ranjith Premalal De, Dayawansa, 2007). According to the case study carried out by the Wijesekera and Perera, (2012b), they have been performed different tests including, extremes testing, visual inspection of data, Double mass analysis, Homogeneity testing (serial-correlation, pre-whitening), normality testing, the stability of variance (F-test), Standard Normal Homogeneity (SNHT), Spearman’s rank correlation, , method of cumulative residual, Stability of mean (T-test), to assure the data qualities.

2.10.3 Fill missing data

Existence of missing data in the input data series is another major constrain in the hydrological studies. However, several conventional and some modern practices are available to overcome this issue, such as statistical methods and different interpolation methods (Hasana, Crokea, 2013; Brunetti, Maugeri, Nanni, 2010). Literature survey revealed that, most frequently used methods for filling gaps in the meteorological input data series are the Thiessen method, the inverse distance method (IDW), arithmetic mean methods, etc… (Kodippili, 2019; Hartkamp, De Beurs, Stein, White, 1999).

Furthermore, according to the study carried out by Silva (2007), various calculation methods for different hydrological regions of Sri Lanka were recommended. Consequently, IDW is suitable for all three climatic zones, arithmetic mean method is suitable for the wet zone areas in the highlands, normal ratio method is for intermediate zones in the lowlands and highlands suitable, and aerial precipitation ratio method is suitable for wet zone areas in the mid country.

2.10.4 Data Limitations and Associated Uncertainties

It is important to understand the underlying ambiguity that is associated with the input data to the hydrological model and the observed data used for performance testing and calibration (Domeneghetti et al., 2012). Due to this reason, watershed models face large model uncertainties related to the model schematisation (such as simplifications in the conceptual model), input data (such as quality of temperature and rainfall data) and selected parameters (such as processes that the user is not aware of and has not modeled explicitly). Khadka and Bhaukajee (2018), stated that model uncertainties could be occurred due to various reasons including quality of meteorological data collected, data gaps, and quality of topographical data.

Moreover, to derive continuous discharge time series, stage data (water level) were converted to discharge data with the use of derived rating curves. However, with the use of this method, sometimes several uncertainties might be introduced to the derived time series including, availability of insufficient rating fitting, or extrapolation procedures, inadequate cross-section data availability, changes in river geometry with time, etc… (Hulsman et al., 2017). However, the errors associated with rating curve issues cannot be neglected, as it is directly affected by the simulated streamflow measurements (Pelletier, 1988; Sikorska et al., 2013)

One of the issue in model calibration is that of uncertainty in the prediction, which uncertainties can be divided into three groups as a) uncertainty of Conceptual Models, b) uncertainty of inputs, c) uncertainty of parameters. The uncertainties in conceptual model could occur in the following circumstances, including model uncertainties due to simplification in the model, and process occurs in the watershed, but not included in the model, model uncertainties due to process that are included in the model, but those are not known well. Input uncertainty occurs due to errors in input data, including precipitation rainfall, temperature and more importantly, an extension of the point data in large areas. The parameter uncertainty is usually caused by the inherent ambiguity of parameters in inverse modeling (Atkinson et al., 2010).

2.11 Flow Classification

In water resources management activities, evaluation of model performance in different flow regimes are very important. To address a wide range of water-related problems in the field of hydrology, the prediction of extreme events such as low flows and high flows are significantly important (Tallaksen et al., 1997; Laaha & Blöschl, 2007; Thielen et al., 2009). However it is a very difficult task, to represent all different phases of flow regimes, from low environmental flows to high flood faces, with the same model parameters used in the rainfall-runoff models (Madsen, 2000). Huang and Loucks (2000), further elaborate the importance of streamflow classification as high, medium and low using probability-based thresholds for water resources management under uncertainty.

During the literature survey, it was revealed that, the United Kingdom, has adopted the low flow estimation procedure from the early days in Europe. In early days low flow estimates were done concerning the catchment characteristics based on the Low flow study report (Institute of Hydrology, 1980). Further, the regional regression approach is used in Switzerland (Aschwanden & Kan, 1999a). Laaha and Blöschl (2007) emphasized that Q95 is the flow rate that is exceeded in 95% of the cases and is considered to be a low flow rate in the catchment area. In addition to that, five to ten percent exceedances were considered as high flows, while ninety five percent exceedance was considered as low flows in the study carried out by the (Risley et al. 2008). Based on the research conducted by the Wijesekera (2018), it was concluded that, traditional FDC curve plots do not provide discriminate flow thresholds. There are some limitations exist, in terms of usage of flow duration curve, due to inability to fully reflect the quality of simulation, since it does not indicate accurate flow timing (van Werkhoven et al., 2009). Further, it was emphasized that, FDC indicates the distribution of flow throughout the entire period.

3 METHODOLOGY

The methodology used in this research is explained by showing the flowchart in Figure 3-1. Dominant problems and research gaps were identified during the literature search. As a result, study objectives have been established. Moreover, throughout the literature review, current state-of-the-art on development of finer resolution rainfall-runoff models, including its data requirement, data processing methods, and appropriate way of model evaluation, calibration and verification were identified. The selection of the study area was also made based on the research gaps identified during the documentary search. Accordingly, Maha Oya basin was chosen as area of interest to perform this study and data collection and checking was initiated accordingly.

Then, precipitation, and evaporation, data were obtained from the Meteorological Department of Sri Lanka, and streamflow data and land use data have been collected from the Department of Irrigation and the Survey Department (SD) respectively. Data checking was performed in various methods identified under literature review, including visual checking of observed streamflow over the precipitation of each gauges as well as Thiessen average rainfall, annual water balance checking, normality and consistency checking, etc... Based on literature Thiessen averaging methods were selected as the most appropriate method for catchment rainfall averaging.

Once data checking was completed, HEC-HMS model schematization and parameterization have been undertaken by using input data. Then model simulation, calibration and validation were performed and in this stage multiple trials have been done changing initial model parameters to identify the optimized set of parameters. The identified set of parameters were again tested with different, temporally different data set in terms of validation. If the validation results were not good enough similar procedure has been repeated multiple times. Similarly, model parameters were identified for both catchments in the Maha Oya basin. According to the objective of this study, an identified set of parameters were interchanged between both catchments to investigate the applicability of transferability of model parameters, in temporally, spatially and spatiotemporally. Further model performance evaluation has also been carried based on set objective function and visual evaluation of model results.

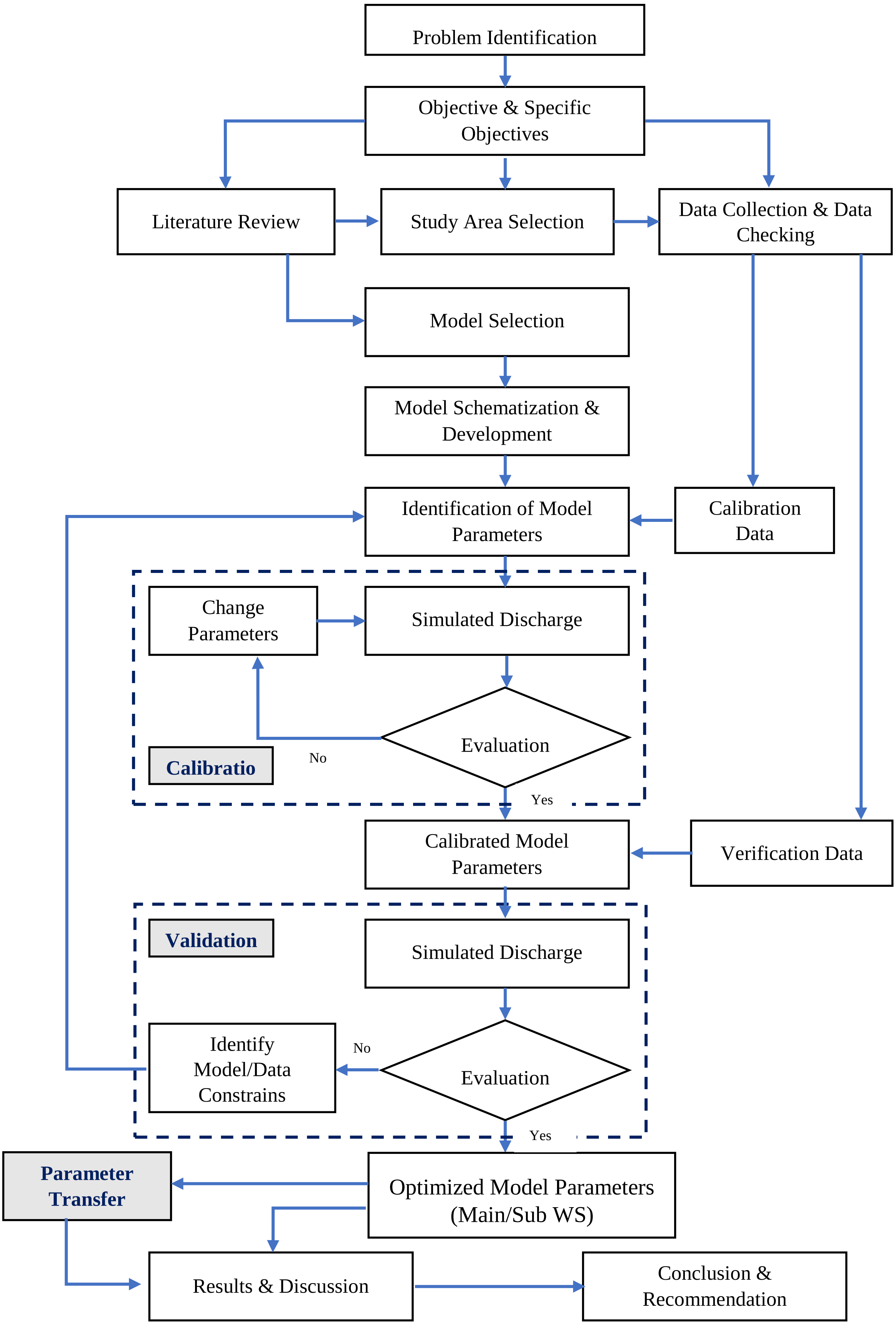


Figure 3-1: Methodology Flow Chart

4 DATA AND DATA VALIDATION

4.1 Introduction

Two sub-catchments in the Maha Oya basin were used to investigate the applicability of parameter transferability by using HEC-HMS model. Accordingly, once in twenty-four hour data was gathered for the time duration of eighteen and fourteen years from the beginning of 2000/2001 to 2018/2019 and 2005/2006 to 2018/2019 water year for the Giriulla and Badalgama watersheds respectively. This chapter describes the process of data collection, processing and validation to use in HEC-HMS model.

The hydro-meteorological stations were identified taking into account the temporal and spatial distribution of the rainfall stations and data were obtained for the above-mentioned reference period, including river flow, precipitation, evaporation, etc.. Within Sri Lanka, it is notable that, several organizations are responsible for the collection of different types of hydro-meteorological data. Table 4-1, summaries the details of data collection including responsible authorities.

Table 4-1: Summary of data collection and responsible Authorities

Data Type	Data Resolution	Data type	Source
Rainfall	Daily	Time Series & Vector layer	Department of Meteorology Department of Irrigation
Stream Flow	Daily	Vector Layer	Department of Irrigation
Evaporation	Daily	Time Series & Vector layer	Department of Meteorology
Topographic Maps	1:50,000	Raster	Survey Department
Land Use	1:10,000	Vector layer	Survey Department
Contour Data	1:10,000	Vector layer	Survey Department

In the initial phase of data acquisition, all of the recorded data was preprocessed in order to convert the raw data into time series. Then, a data check was performed, including a visual data check, for the hydro-meteorological data collected, such as precipitation, flow and evaporation, to identify inconsistencies, outliers and missing data etc..

In addition, the double mass curves and annual water balance were used to identify data inconsistencies. The Thiessen polygon method was chosen as the most suitable method for averaging catchment area precipitation (Ven Te Chow, Maidment, 1988) to fill the precipitation data, while the long-term average was used to fill the evaporation data.

4.2 Hydro-Meteorological data

The summary of selected hydro-meteorological stations are given in the Table 4-2.

Table 4-2: Hydrometric Station Summary

Station Name	Location (SLD 99)		Data Type	Duration
Aranayaka_Mini Hydro	455188.74	533323.46	Rainfall	2009 - 2019
Eraminigolla	455188.74	533323.46		
Polgahawela	448244.66	536959.68		
Ambepussa	438167.56	526964.8		
Andigama_Farm	427575.08	540520.8		
Walpita	420196.87	529473.15		
Makandura	410149.84	534273.95	Pan Evaporation	2009 - 2019

4.2.1 Missing data

Prior to use data in the application, a consistency check was carried out. Accordingly, all the data gaps were identified, once data collection has been completed and data gaps have been summarized in the Table 4-3. A WMO guideline states that not more than 10% of a record should have interpolated Data.

Table 4-3: Summary of data missing Periods

Station	Type	Missing Data
Ambepussa	Rainfall	-
Andigama_Farm		5.3 %
Eraminigolla		12.3 %
Aranayake Mini Hydro Pro		1.8 %
Polgahawela		10.5 %
Walpita		3.6 %
Makandura	Evaporation	5.7 %

4.3 Data Gap filling

Throughout the literature search, it was found that various techniques for filling data gaps can be used, including IDW, Kriging, Thiessen-Polygon method, etc... During this study, the Thiessen Polygon method was adopted for precipitation data gap filling.

4.3.1 Giriulla watershed

The five (05) rainfall stations, Aranayaka_Mini Hydro, Eraminigolla, Polgahawela, Ambepussa, and Andigama Farm were considered for the Giriulla watershed while Giriulla Gauging station considered as streamflow station. Makandura pan Evaporation station was considered as evaporation station in this study. The Thiessen polygon for Giriulla catchment was shown in Figure 4-1, while station density and Thiessen weights illustrated in Table 4-4.

4.3.2 Badalgama Watershed

The five (05) rainfall stations, Aranayaka_Mini Hydro, Eraminigolla, Ambepussa, Andigama Farm and Walpita were considered for Badalgama watershed, while Badalgama gauging station and Makandura station were taken as discharge measuring station and Pan Evaporation station respectively. Figure 4-2, shows the Thiessen Polygon for the Badalgama catchment and

Table 4-5 summaries the station density and Thiessen weights.

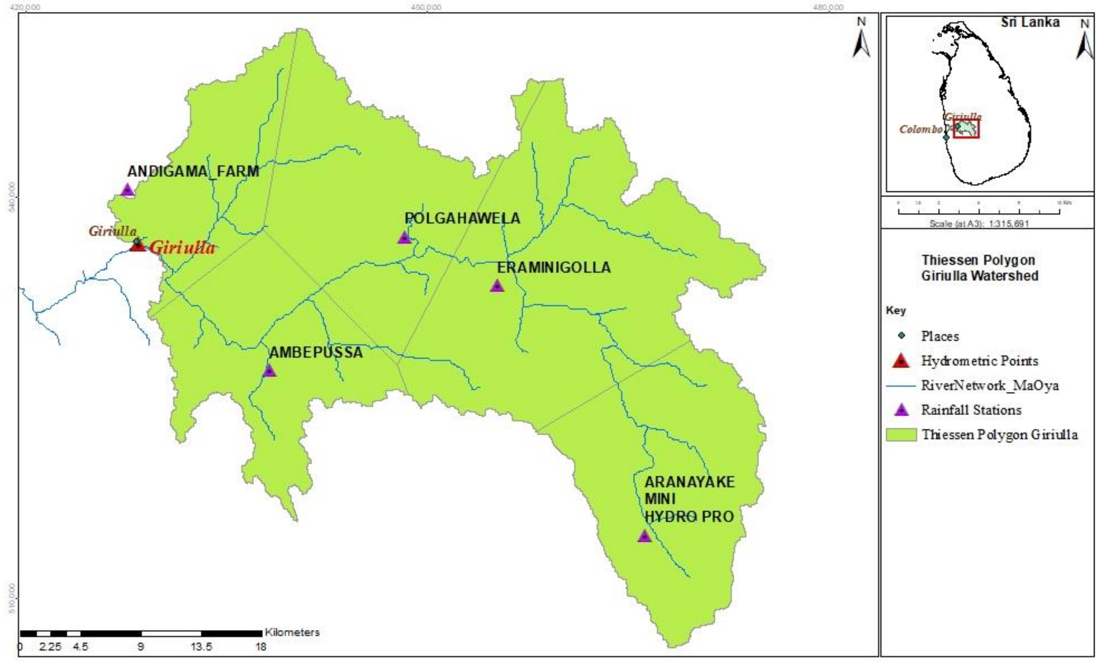


Figure 4-1: Thiessen Polygon Giriulla Watershed

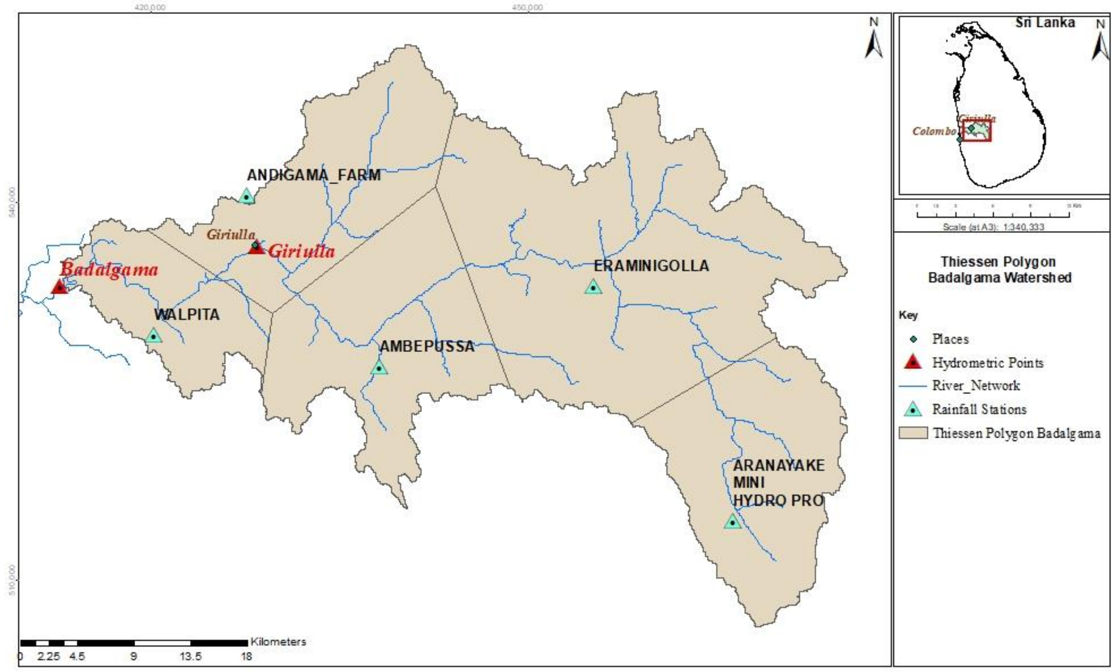


Figure 4-2: Thiessen Polygon Badalgama Watershed

Table 4-4: Station Density and Thiessen weights of Giriulla watershed

Station	Station Density (km^2/station)	Thiessen Area (km^2/station)	Thiessen Weight	WMO Standards (km^2/station
Ambepussa	224.10	183.03	0.16	575
Andigama_Farm		131.71	0.12	
Eraminigolla		361.26	0.32	
Aranayake Mini Hydro		223.28	0.20	
Polgahawela		221.07	0.20	

Table 4-5: Station Density and Thiessen weights of Badalgama watershed

Station	Station Density (km^2/station)	Thiessen Area (km^2/station)	Thiessen Weight	WMO Standards (km^2/station)
Ambepussa	258	239.26	0.19	575
Andigama_Farm		216.35	0.17	
Eraminigolla		490.36	0.38	
Aranayake Mini Hydro		223.29	0.17	
Walpita		120.52	0.09	

4.4 Data checking

Engineering studies and designs of water resources development and management highly reliable upon the hydrological data. Therefore, a data checking is essential before the same data is used in the application. In this study, to determine the inconsistencies and outliers, graphical data checks, visual checks, and annual water balance checks were carried out. Additionally, the double mass curve was also used to check the consistency of the data by comparing data for a single station with respect to several other stations in the region.

4.4.1 Annual Water Balance

This is a one of the imperative method of data checking, which compare the streamflow, rainfall, and evaporation, run-off coefficient of both Giriulla and Badalgama watersheds. The reason for choosing the water year, as it represents a complete cycle of the water year. The continuity equation could be used in any water balance, which is given below,

$$(Precipitation + GW_{in}) - (ET + GW_{out} + SF) = \frac{\Delta s}{\Delta t}$$

Where; *GW* represents the groundwater component while *ET* and *SF* represent the Evaporation and Streamflow respectively. The *GW* components are negligible compared to the other components, hence it was assumed that *GW* variation is in a very minimal level.

The annual water balance for the period of 2000/2001 to 2018/2019 for Giriulla and 2005/2006 to 2018/2019 Badalgama Watersheds are illustrated in Table 4-6 and Table 4-8, while graphical representation is shown in Figure 4-3 and Figure 4-4 correspondingly. Further, in Table 4-7 and Table 4-9, it shows the missing observed streamflow measurements at Giriulla from 2000/2001 to 2018/2019 and Badalgama from 2005/2006 to 2018/2019.

Accordingly variation of annual runoff coefficient is 0.16 to 0.87, while showing lowest runoff coefficients in 2013/2014, and higher runoff coefficients in 2010/2011 and 2006/2007 water years at Giriulla. During the last 19 years and average runoff coefficient is 0.40. According to Table 4-7, its availability of streamflow data is less after the 2011/2012 to 2015/2016 eriod, which might be one of the reasons caused to low runoff coefficients. The highest annual rainfall and streamflow occurred in 2014/2015 and 2010/2011 respectively.

Table 4-6: Annual Water Balance Giriulla Watershed

No	**Water Year**	**Rainfall (mm/yr)**	**Observed Streamflow (mm/yr)**	**Observed Pan Evaporation (mm/yr)**	**Water Balance (mm/yr)**	**Runoff Coefficient**
1	2000/2001	2,340.8	902.1	1,026.5	1,438.6	0.39
2	2001/2002	2,651.3	1,109.4	1,026.5	1,541.9	0.42
3	2002/2003	2,365.7	1,301.8	1,026.5	1,063.9	0.55
4	2003/2004	2,551.6	871.7	1,026.5	1,679.9	0.34
5	2004/2005	2,407.9	1,243.3	1,026.5	1,164.6	0.52
6	2005/2006	2,455.8	1,321.5	1,024.6	1,134.2	0.54
7	2006/2007	1,461.2	1,153.5	1,023.9	307.6	0.79
8	2007/2008	2,779.4	1,388.5	918.9	1,390.9	0.50
9	2008/2009	2,023.7	786.7	1,065.5	1,236.9	0.39
10	2009/2010	2,682.0	1,326.2	1,099.7	1,355.7	0.49
11	2010/2011	2,456.0	2,145.6	1,029.9	310.4	0.87

No	Water Year	Rainfall (mm/yr)	Observed Streamflow (mm/yr)	Observed Pan Evaporation (mm/yr)	Water Balance (mm/yr)	Runoff Coefficient
12	2011/2012	1,369.3	253.7	1,121.5	1,115.6	0.19
13	2012/2013	2,925.4	1,100.3	1,057.8	1,825.0	0.38
14	2013/2014	1,955.4	319.1	1,122.6	1,636.2	0.16
15	2014/2015	2,929.5	917.8	1,025.6	2,011.7	0.31
16	2015/2016	2,879.3	951.7	1,089.3	1,927.6	0.33
17	2016/2017	1,830.9	100.6	994.6	1,730.3	0.05
18	2017/2018	2,471.0	564.7	885.7	1,906.2	0.23
19	2018/2019	2,332.1	395.7	1,060.0	1,936.4	0.17
	Average	**2,361.5**	**955.5**	**1,034.3**	**1,406.0**	**0.40**

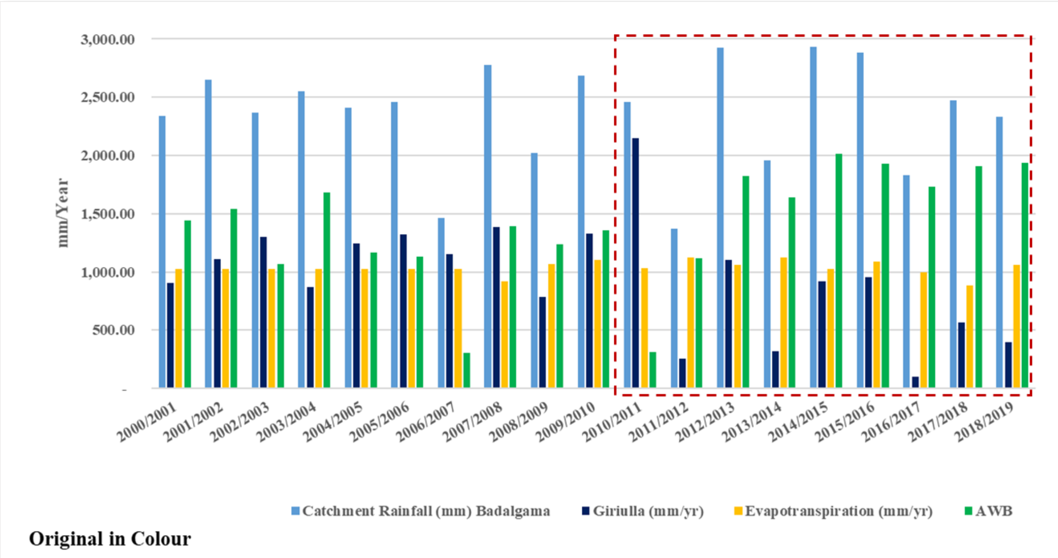


Figure 4-3: Comparison of Annual rainfall, Stream Flow, Evaporation and runoff coefficient Giriulla watershed

Table 4-7: Missing percentages of observed streamflow measurements at Giriulla Gauging Station

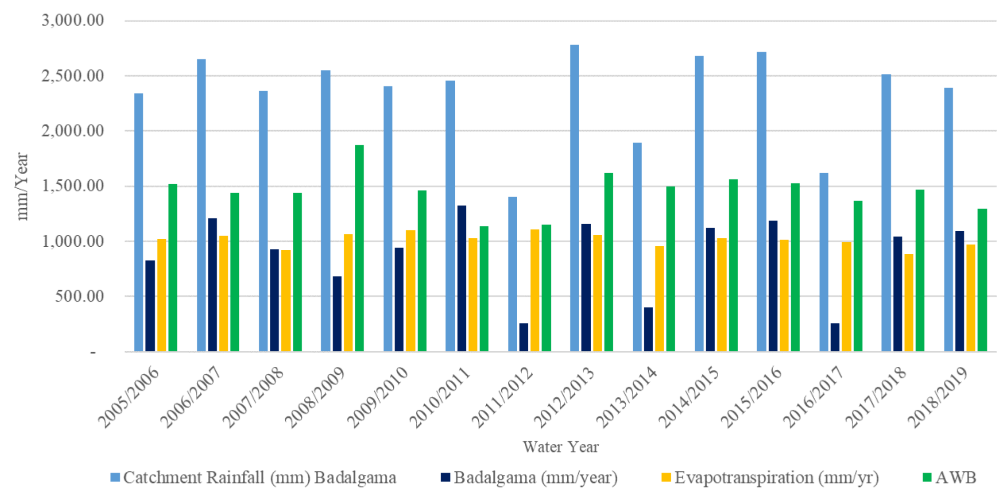
Water Year	**No of Missing Data**	**Missing Data**
2000/2001	11	3%
2001/2002	0	0%
2002/2003	0	0%
2003/2004	0	0%
2004/2005	42	12%
2005/2006	0	0%
2006/2007	6	2%
2007/2008	0	0%
2008/2009	0	0%
2009/2010	0	0%
2010/2011	0	0%
2011/2012	221	61%
2012/2013	35	10%
2013/2014	169	46%
2014/2015	102	28%
2015/2016	178	49%
2016/2017	0	0%
2017/2018	0	0%
2018/2019	0	0%

Based on the annual water balance in Badalgama watershed, run of coefficient varies from 0.16 to 0.54, while maintaining minimum values in 2016/2017, 2011/2012, and 2013/2014 water years. Runoff coefficients of the rest of the years show good agreement. The missing data percentage in Badalgama Gauging station (Table 4-9) is minimal compared to Giriulla Gauging station. The maximum annual rainfall and observed streamflow were recorded in 2015/2016 as 2,789 mm/yr and 2010/2011 as 1,322 mm/yr respectively.

Besides, it was noted that observed streamflow measurements at Giriulla Gauging station are much higher compared to Badalgama Gauging station, though Giriulla Gauging station was located at upstream of Badalgama Gauging station. Hence this study is being carried out with data uncertain situation. In APPENDIX C, comparison of streamflow measurements at Giriulla vs Badalgama over catchment average rainfall at Badalgama was illustrated, to understand the flow measurement uncertainties.

Table 4-8: Annual Water Balance Badalgama Watershed

No	Water Year	Annual Rainfall (mm) (Thiessen)	Observed Annual Streamflow Badalgama (mm)	Annual Water Balance (AWB) (mm)	Observed Pan Evaporation EP (mm)	Runoff coefficient
1	2005/2006	2,340.78	824.04	1,516.73	1,280.79	0.35
2	2006/2007	2,651.27	1,210.02	1,441.25	1,311.59	0.46
3	2007/2008	2,365.69	924.44	1,441.25	1,148.69	0.39
4	2008/2009	2,551.61	679.70	1,871.91	1,331.93	0.27
5	2009/2010	2,407.94	943.48	1,464.46	1,374.66	0.39
6	2010/2011	2,455.76	1,322.20	1,133.56	1,287.44	0.54
7	2011/2012	1,461.18	253.78	1,207.40	1,401.92	0.17
8	2012/2013	2,779.36	1,159.61	1,619.76	1,322.28	0.42
9	2013/2014	2,023.65	400.51	1,623.14	1,403.25	0.20
10	2014/2015	2,681.97	1,120.40	1,561.57	1,282.01	0.42
11	2015/2016	2,788.81	1,184.00	1,604.81	1,361.66	0.42
12	2016/2017	1,618.45	254.46	1,363.99	1,243.30	0.16
13	2017/2018	2,514.48	1,045.96	1,468.52	1,107.17	0.42
14	2018/2019	2,658.67	1,229.47	1,429.20	1,325.04	0.46
	Average	**2,378.5**	**896.6**	**1,482.0**	**1,298.7**	**0.36**



Original in Colour

Figure 4-4: Comparison of Annual rainfall, Stream Flow, Evaporation and runoff coefficient in Badalama watershed

Table 4-9: Missing percentages of observed streamflow measurements at Badalgama Gauging Station

Start Date	End Date	No of Missing Data	Missing Data
10/1/2005	9/30/2006	0	0%
10/1/2006	9/30/2007	0	0%
10/1/2007	9/30/2008	0	0%
10/1/2008	9/30/2009	0	0%
10/1/2009	9/30/2010	0	0%
10/1/2010	9/30/2011	0	0%
10/1/2011	9/30/2012	5	1%
10/1/2012	9/30/2013	0	0%
10/1/2013	9/30/2014	53	15%
10/1/2014	9/30/2015	0	0%
10/1/2015	9/30/2016	22	6%
10/1/2016	9/30/2017	0	0%
10/1/2017	9/30/2018	0	0%
10/1/2018	9/30/2019	0	0%

4.4.2 Annual rainfall and variation in streamflow

Variation of annual river flow concerning annual precipitation was shown in Figure 4-5, which also graphically represent the observed streamflow uncertainties. When scrutinized Figure 4-5, it clearly shows that observed annual streamflows are comparatively low in year 2012/2013, 2014/2015, and 2015/2016, even though annual rainfall records shows the highest values.

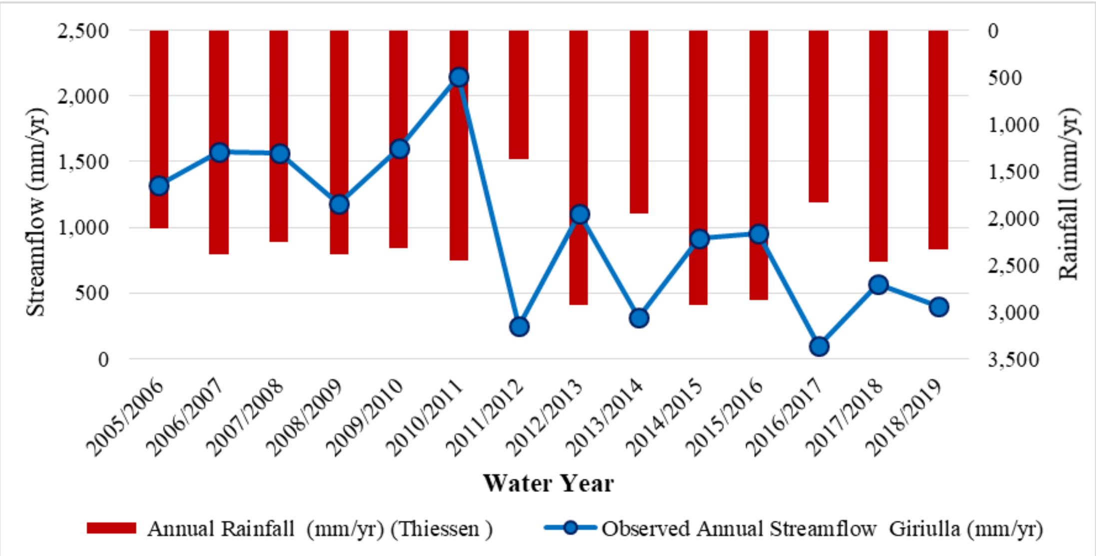


Figure 4-5: Variation of Annual Rainfall and Streamflow at Giriulla

The Figure 4-6 illustrate the annual streamflow variation over annual rainfall at Badalgama catchment. However, the annual flow for 2008/2009 shows the relatively low flow which was a deviation from the annual flow compared to other years with similar precipitation. As shown in figure below, 2012/2013, 2015/2016 could be considered as wettest years throughout the selected period, while 2011/2012 and 2016/2017 were the dryest years.

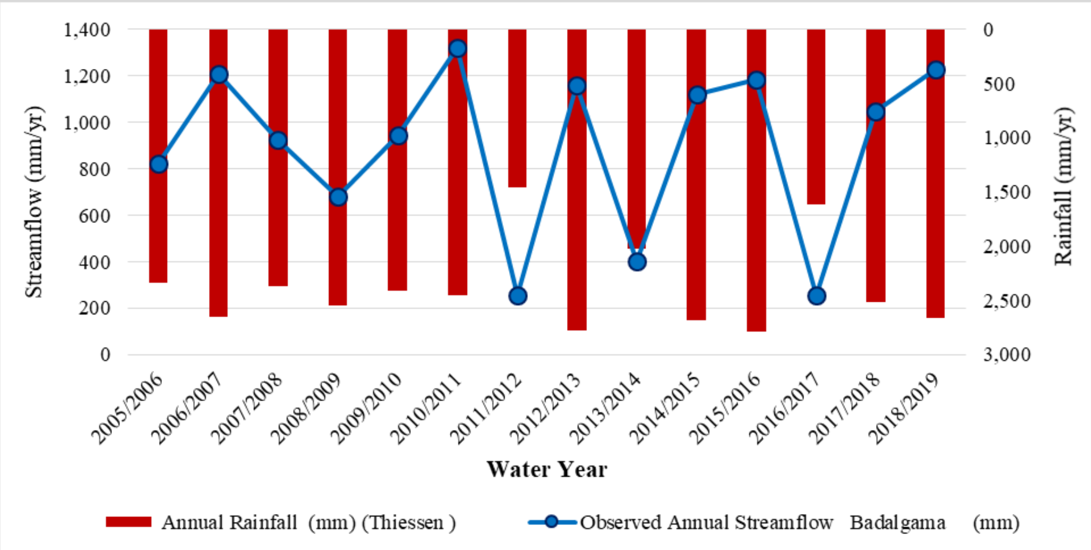
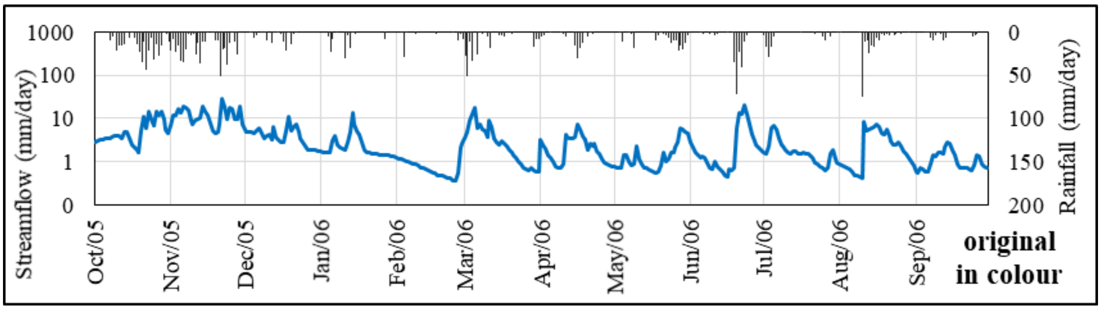


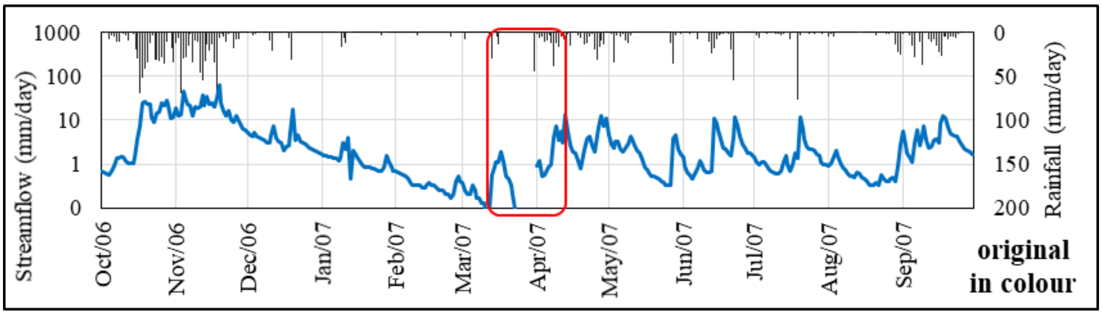
Figure 4-6: Variation of Annual Rainfall and Streamflow at Badalgama

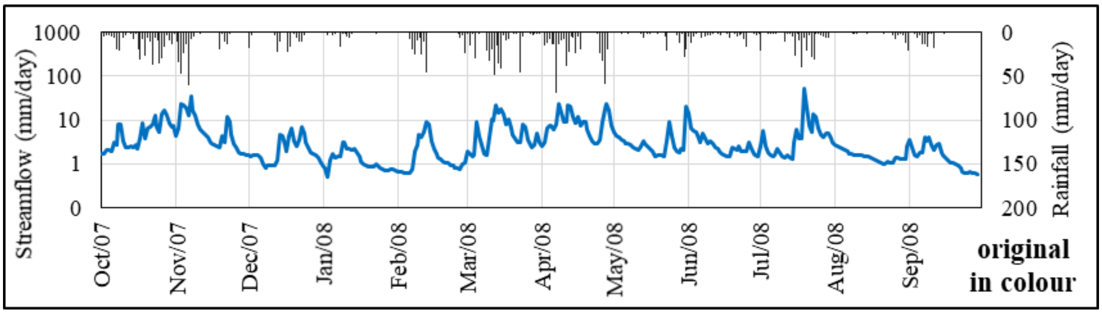
4.4.3 Visual Data Checking after gap-filling of missing data

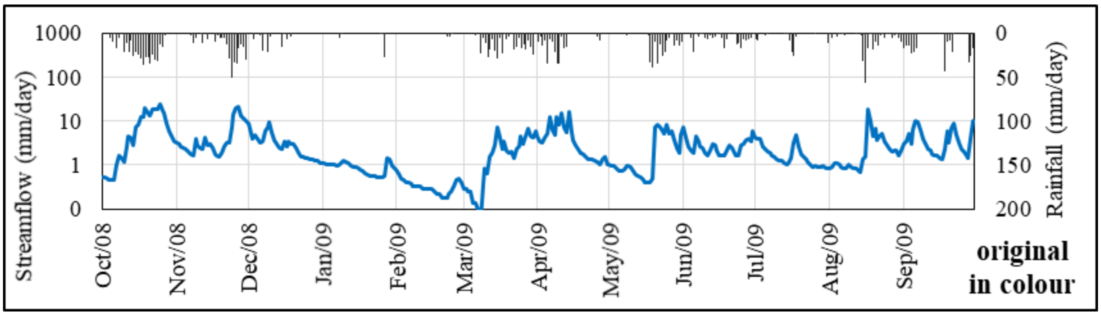
Visual data checking has been performed following the gap-filling of the missing data. Accordingly catchment rainfall responses and individual daily rainfall were plotted with observed daily streamflow and a visual comparison was made to identify data inconsistencies. The Figure 4-7 and Figure 4-8 show the daily streamflow responses over the Thissen average catchment rainfall for the period of 2009/2010 to 2018/2019 water year in both Giriulla and Badalgama Watersheds. The identified inconsistencies are marked in the figure with red boxes.

In APPENDIX A, streamflow response over each rainfall station are shown and identified inconsistencies are marked with red boxes for further understanding.


Streamflow (mm/day)
1000
100
10
1
0
Rainfall (mm/day)
0
50
100
150
200
Oct/05
Nov/05
Dec/05
Jan/06
Feb/06
Mar/06
Apr/06
May/06
Jun/06
Jul/06
Aug/06
Sep/06
original
in colour


Streamflow (mm/day)
1000
100
10
1
0
Rainfall (mm/day)
0
50
100
150
200
Oct/06
Nov/06
Dec/06
Jan/07
Feb/07
Mar/07
Apr/07
May/07
Jun/07
Jul/07
Aug/07
Sep/07
original
in colour


Streamflow (mm/day)
1000
100
10
1
0
Rainfall (mm/day)
0
50
100
150
200
Oct/07
Nov/07
Dec/07
Jan/08
Feb/08
Mar/08
Apr/08
May/08
Jun/08
Jul/08
Aug/08
Sep/08
original
in colour


Streamflow (mm/day)
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1
0
Rainfall (mm/day)
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50
100
150
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Oct/08
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Jan/09
Feb/09
Mar/09
Apr/09
May/09
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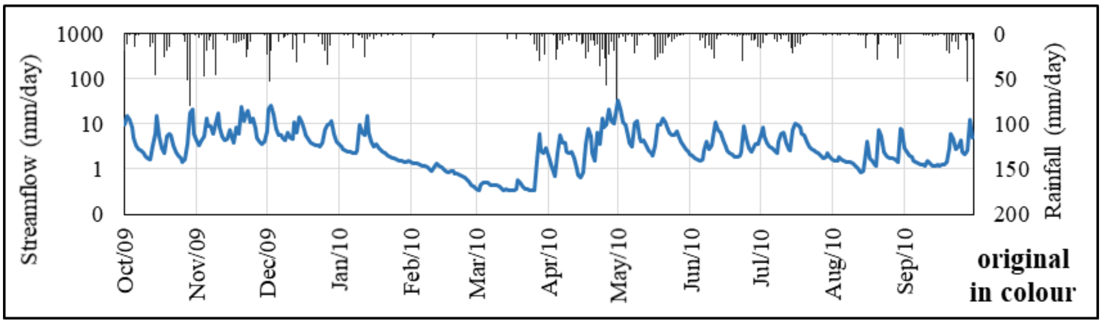
Aug/09
Sep/09
original
in colour


Streamflow (mm/day)
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10
1
0
Rainfall (mm/day)
0
50
100
150
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Oct/09
Nov/09
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Feb/10
Mar/10
Apr/10
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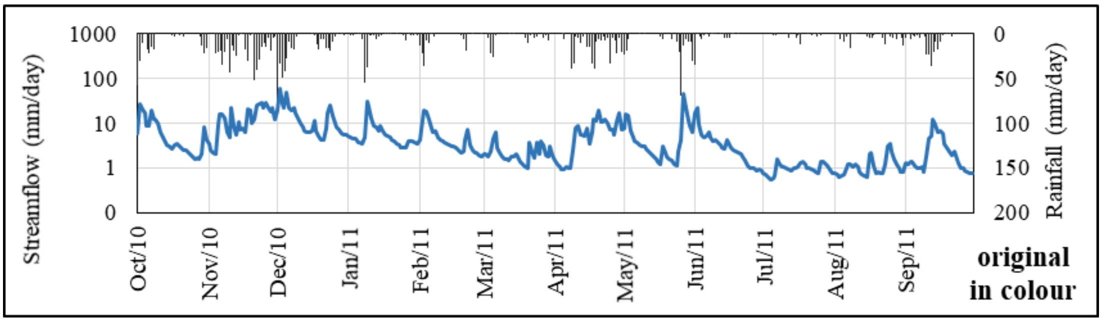
Jul/10
Aug/10
Sep/10
original
in colour


Streamflow (mm/day)
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0
Rainfall (mm/day)
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100
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200
Oct/10
Nov/10
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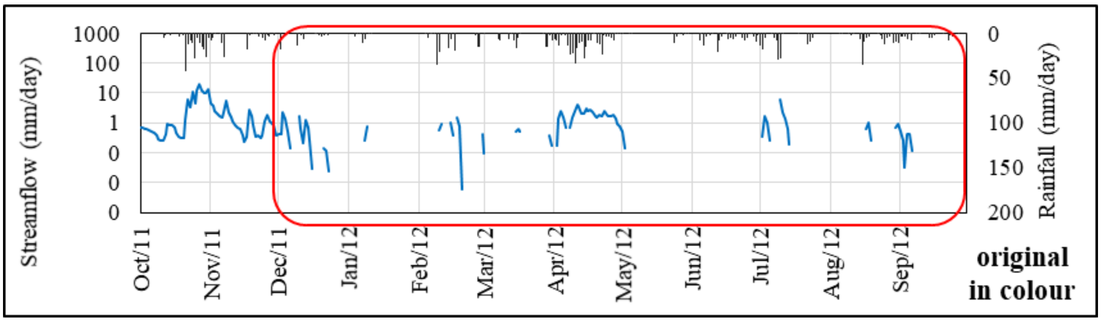
Sep/11
original in colour


Streamflow (mm/day)
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100
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1
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0
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Rainfall (mm/day)
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50
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Oct/11
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Aug/12
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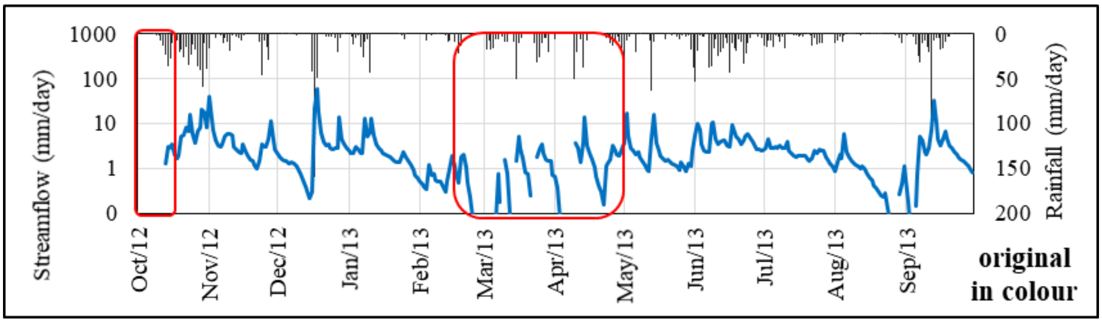
original in colour


Streamflow (mm/day)
1000
100
10
1
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Rainfall (mm/day)
0
50
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150
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Oct/12
Nov/12
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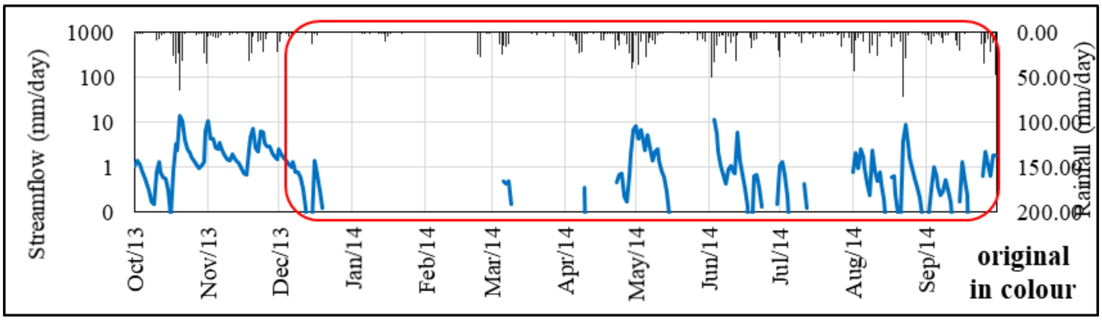
Aug/13
Sep/13
original in colour


Streamflow (mm/day)
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100
10
1
0
Rainfall (mm/day)
0.00
50.00
100.00
150.00
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Aug/14
Sep/14
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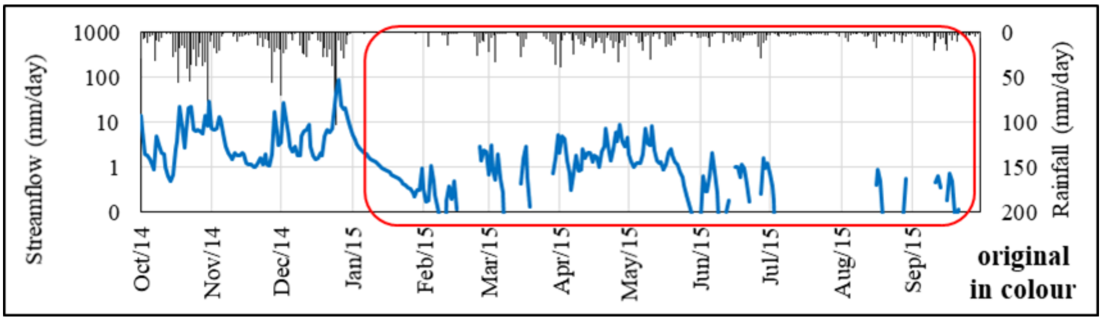
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100
10
1
0
Rainfall (mm/day)
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50
100
150
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Oct/14
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Aug/15
Sep/15
original in colour

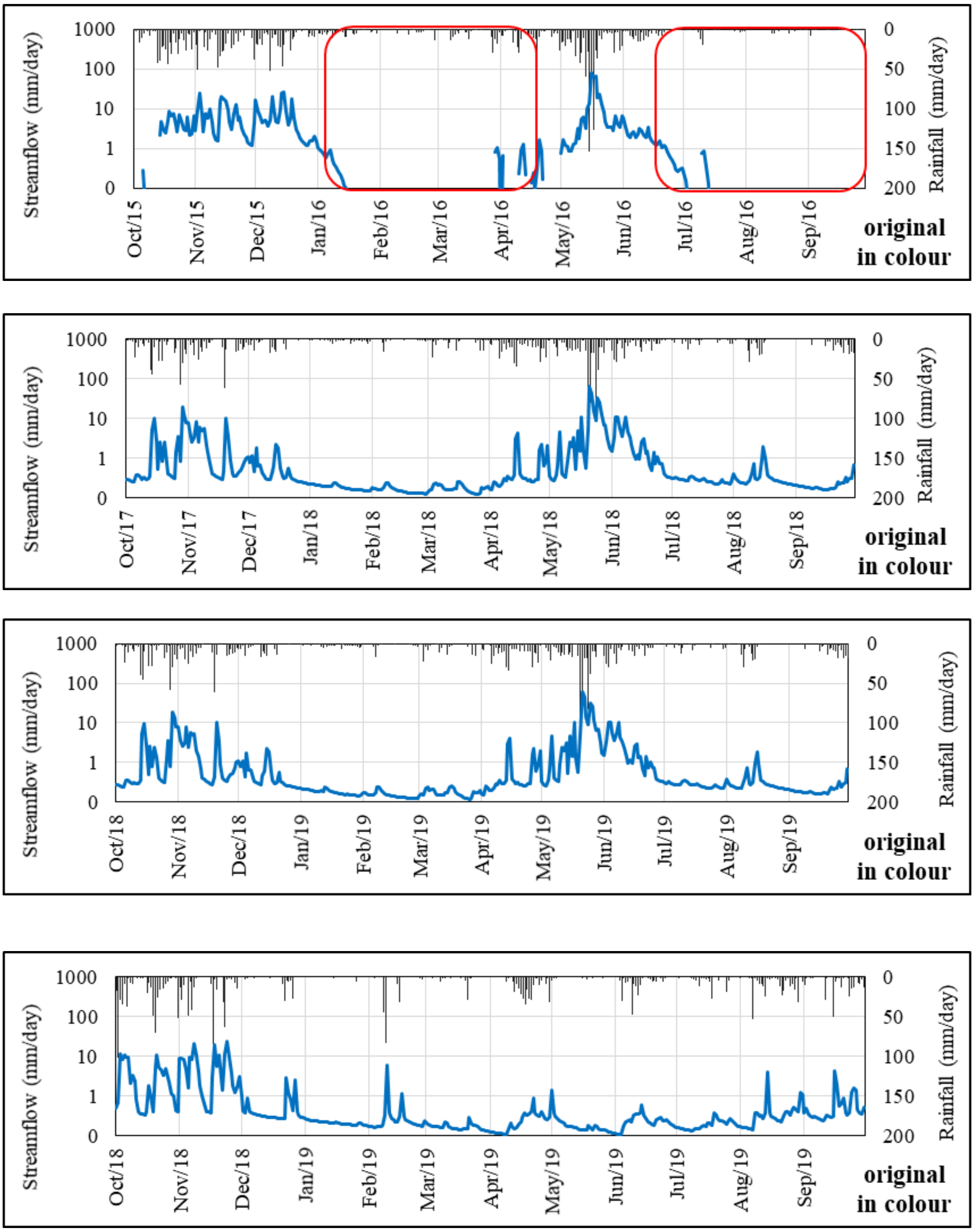
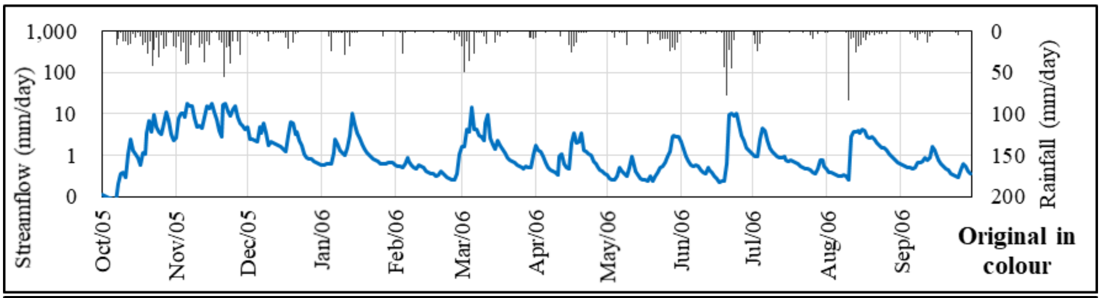


Figure 4-7: Thiessen Rainfall and stream flow responses at Giriulla watershed


Streamflow (mm/day)
1,000
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Rainfall (mm/day)
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Oct/05
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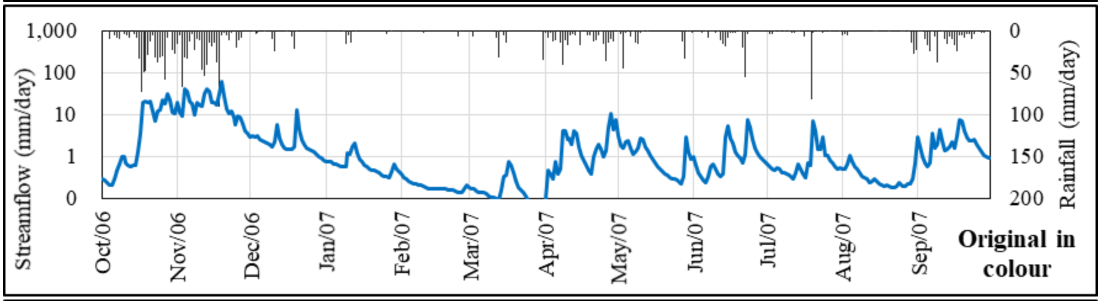
Aug/06
Sep/06
Original in colour


Streamflow (mm/day)
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Rainfall (mm/day)
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Oct/06
Nov/06
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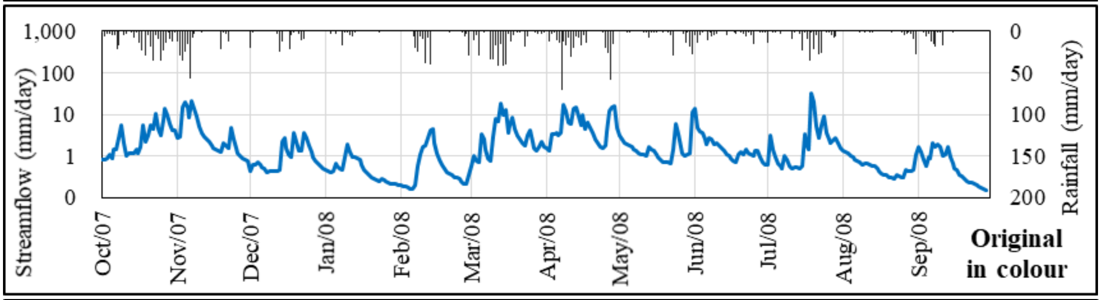
Aug/07
Sep/07
Original in colour


Streamflow (mm/day)
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Rainfall (mm/day)
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Oct/07
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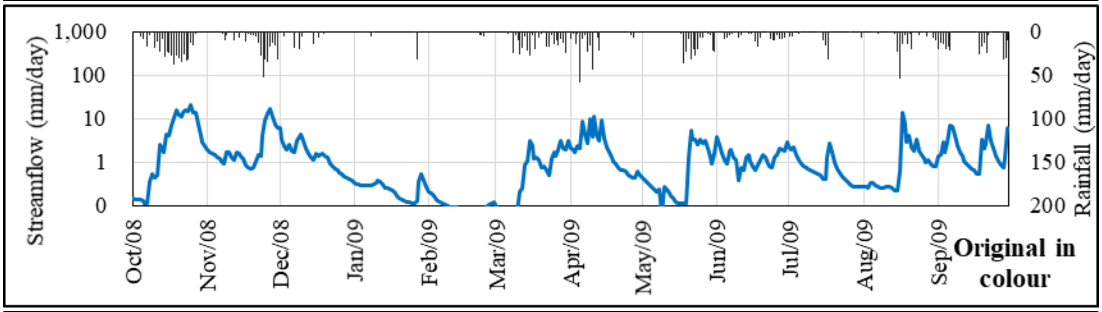
Sep/08
Original in colour


Streamflow (mm/day)
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Rainfall (mm/day)
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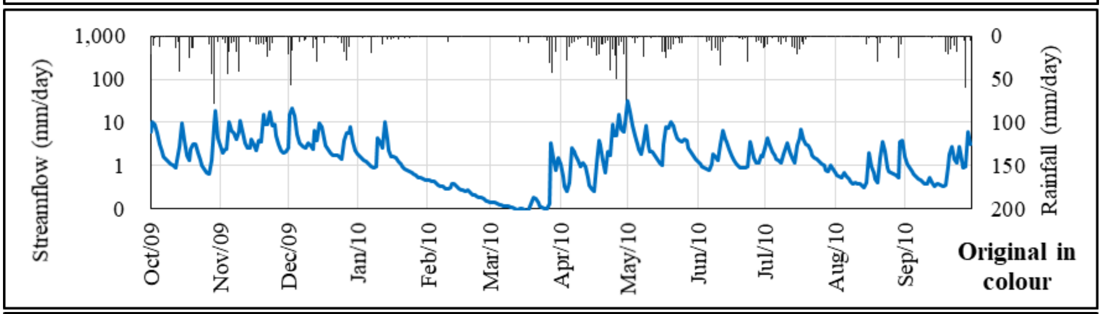
Aug/09
Sep/09
Original in colour


Streamflow (mm/day)
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Rainfall (mm/day)
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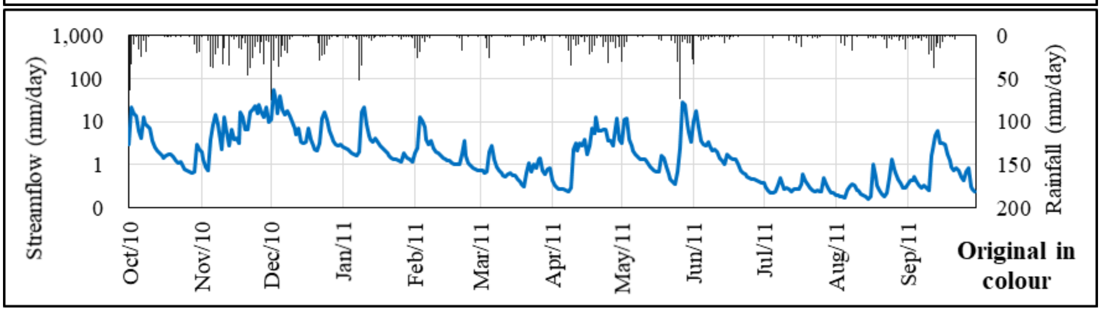
Aug/10
Sep/10
Original in colour


Streamflow (mm/day)
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Rainfall (mm/day)
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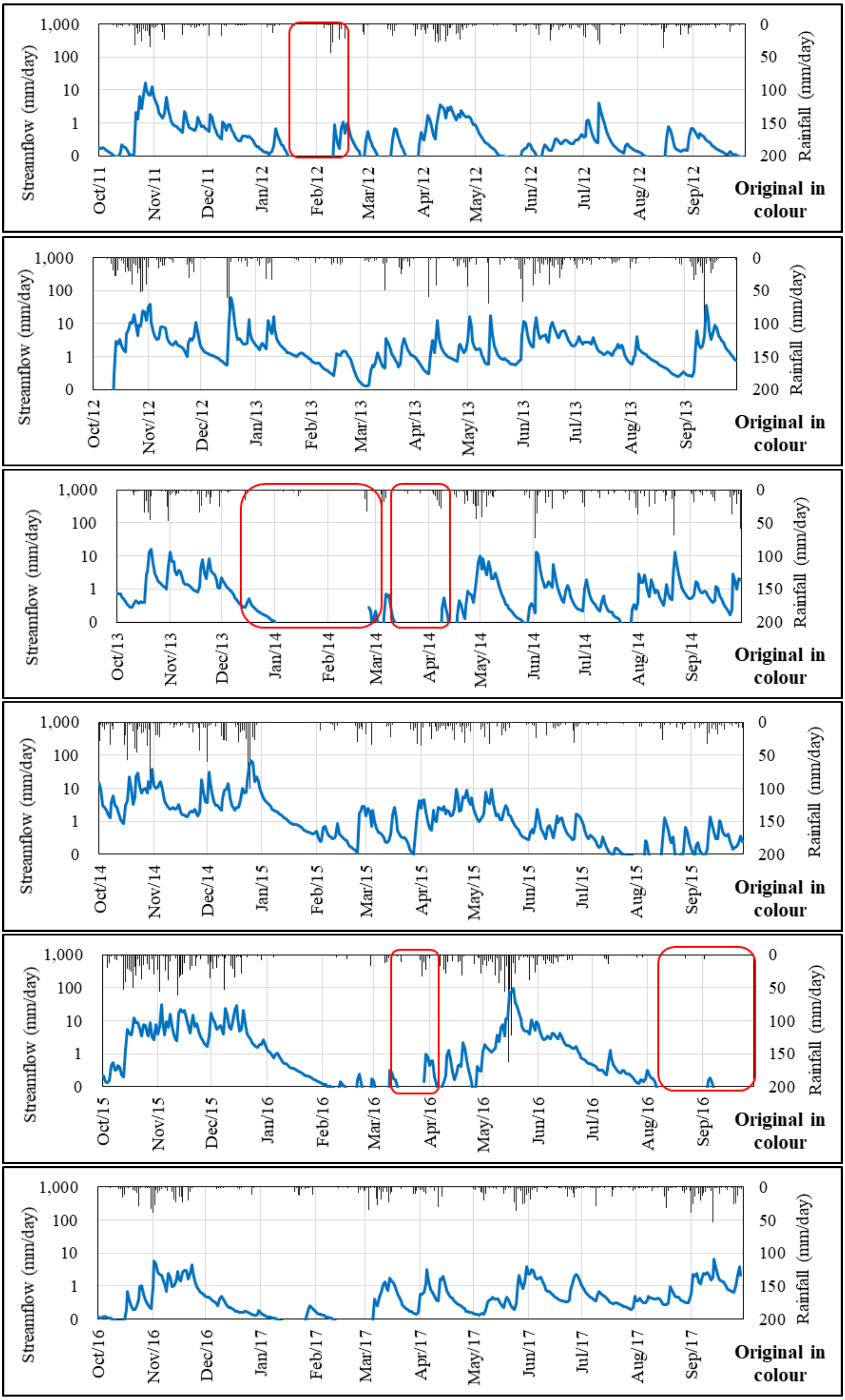
Jan/11
Feb/11
Mar/11
Apr/11
May/11
Jun/11
Jul/11
Aug/11
Sep/11
Original in colour



Streamflow (mm/day)
1,000
100
10
1
0
Rainfall (mm/day)
0
50
100
150
200
Oct/11
Nov/11
Dec/11
Jan/12
Feb/12
Mar/12
Apr/12
May/12
Jun/12
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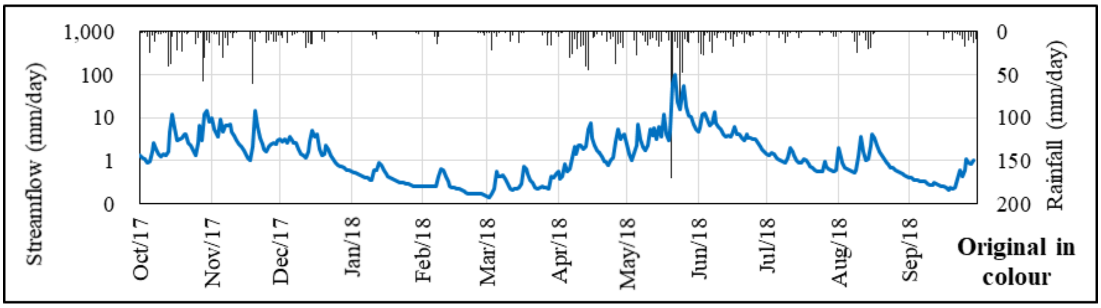


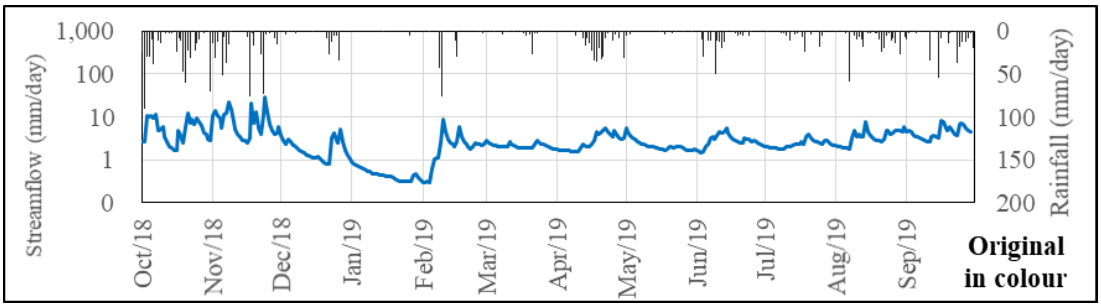


Figure 4-8: Rainfall and stream flow responses in Badalgama Watershed

4.4.4 Monthly and Annual rainfall

There was a good match between, monthly rainfall variation in selected stations, including Ambepussa, Andigama, Eraminigolla, Aranayake, Walpita and catchment Average monthly rainfall, which is given in Table 4-10, while graphically shown in the Figure 4-9.

Table 4-10: Monthly Average Rainfall at selected stations

Month	**Ambepussa**	**Angigama_ Farm**	**Eraminigolla**	**Aranayake**	**Walpita**
October	409.23	378.09	341.06	360.22	21.92
November	273.11	264.41	312.82	307.18	71.33
December	143.92	182.08	171.10	188.39	46.21
January	31.18	36.32	51.17	67.69	3.46
February	80.07	59.90	76.15	75.76	61.13
March	142.03	134.78	174.06	149.79	139.64
April	267.72	250.91	274.90	229.79	234.51
May	241.34	221.63	208.82	231.59	295.19
June	191.85	155.56	138.35	209.24	223.54
July	86.57	56.49	91.25	148.92	85.14
August	130.54	100.41	09.03	156.79	137.34
September	185.99	156.11	64.77	146.46	224.13
Annual Total	**2,183.55**	**1,996.69**	**2,113.49**	**2,271.83**	**2,283.55**

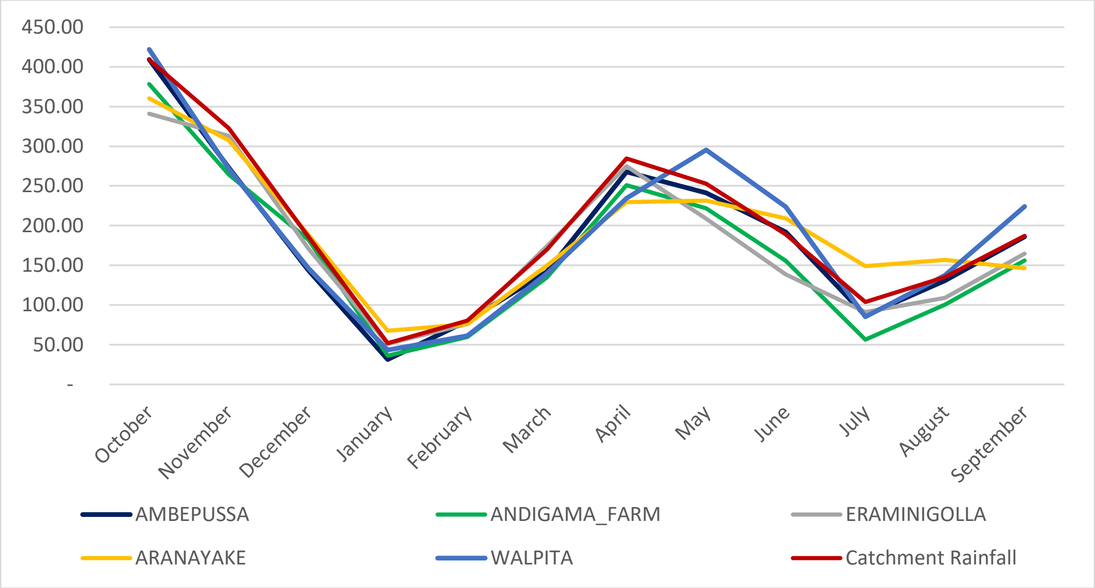


Figure 4-9: Variation of monthly rainfall at Badalgama watershed

The figure clearly shows that, it follows two monsoon periods, such as southwest and northeast monsoon. Table 4-11 was shown the annual rainfall of selected stations, while graphical representation was given in Figure 4-10.

Table 4-11: Annual rainfall at selected rainfall stations

Water Year	Ambepussa	Andigama _Farm	Eraminigo lla	Aranayak e	Walpita	Polgahaw ela
2005/2006	2,198	2,164	2,003	2,123	2,379	2,203
2006/2007	2,751	2,577	2,252	2,240	2,320	2,352
2007/2008	1,969	2,326	2,196	1,880	2,453	2,921
2008/2009	2,354	2,213	2,259	2,447	2,383	2,518
2009/2010	1,722	1,899	2,378	2,571	2,094	2,691
2010/2011	2,265	2,231	2,125	2,484	2,074	2,870
2011/2012	1,113	1,371	1,148	1,631	1,812	1,672
2012/2013	2,448	2,404	2,160	3,401	2,698	4,264
2013/2014	2,245	1,467	1,691	2,064	1,838	2,285
2014/2015	2,943	2,059	2,362	2,385	2,454	4,900
2015/2016	2,679	2,029	2,529	2,869	2,490	3,929
2016/2017	1,401	1,396	1,539	1,263	1,815	3,452
2017/2018	2,259	1,840	2,522	2,204	2,263	3,345
2018/2019	2,296	2,182	2,470	2,286	3,035	2,353

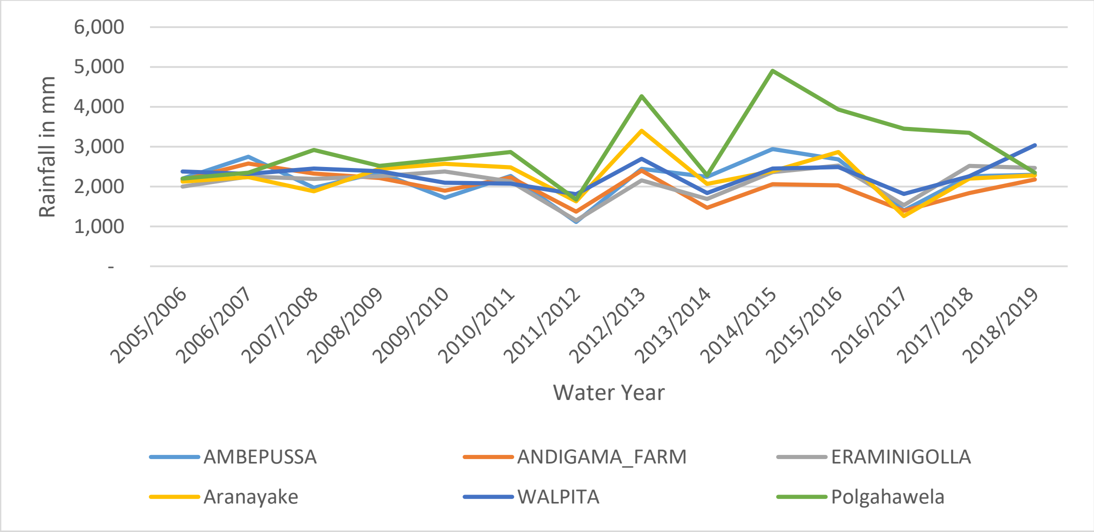


Figure 4-10: Annual rainfall variation in selected rainfall stations

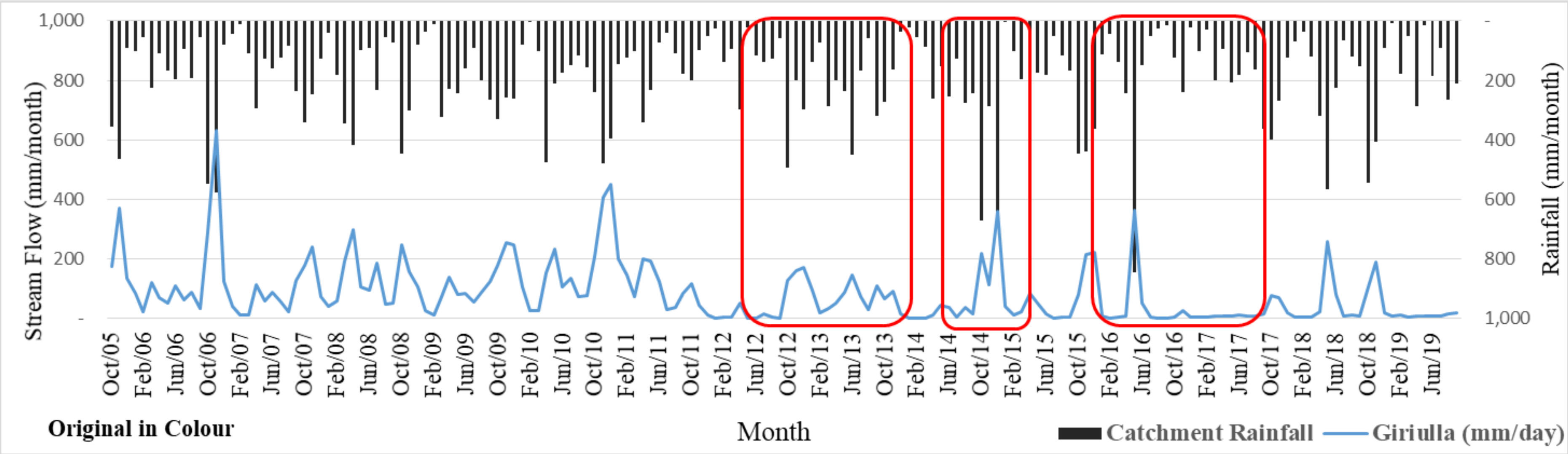
Annual rainfall in all the selected stations follow a similar pattern throughout the 2005/2006 water year to 2018/2019 water years, except Polgahawela station. From 2005/2006 to 2011/2012, Polgahawela station also follows a similar pattern and it shows a slightly increased annual rainfall pattern in the rest of the years.

4.4.5 Monthly streamflow variation over Thiessen Rainfall

The monthly streamflow response over the Thiessen rainfall shows an acceptable level of agreement and the graphical variation is illustrated for both Giriulla and Badalgama watersheds in Figure 4-11. The non-responsive rainfall events are outlined in red color. These discrepancies might be occurred due to the non-responsiveness of selected rain gauges or erroneous streamflow measurements or unavailability of observed streamflow measurements.

4.4.6 Double Mass Curve

It is common to check relative consistency with double mass analysis graphs. Accordingly hydrological data at a certain measuring location is generated by the same mechanism that generated data similar to other stations (Dahmen & Hall, 1990). Based on the literature, to determine relative consistency, the observations from a subject station are compared with the mean of observations from a number of closer stations (Survsy, 1960). The Figure 4-12 shows the double mass curve for each of the precipitation stations over the duration of 2009/2008 to 2018/2019.



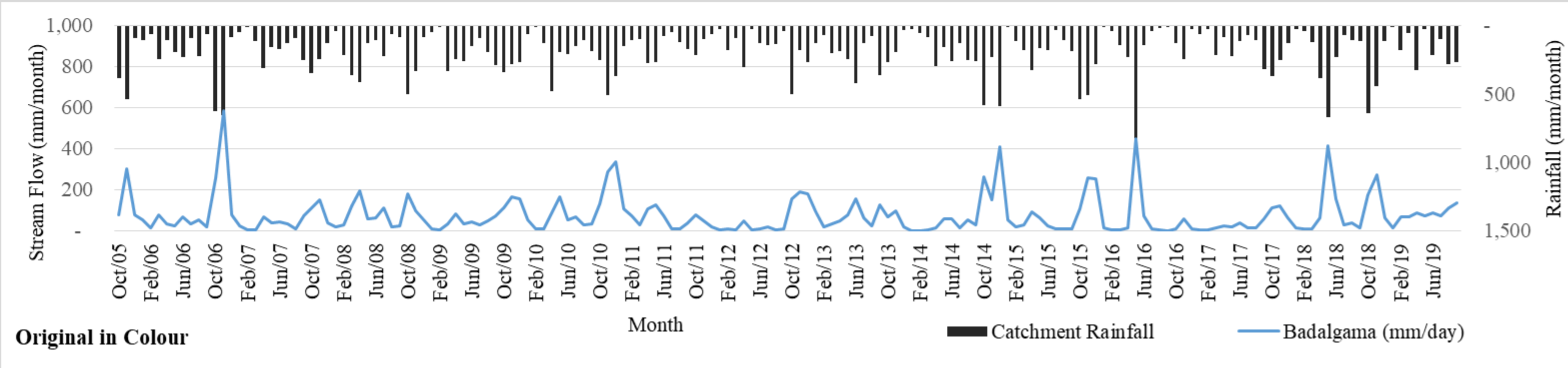


Figure 4-11: Monthly Stream flow and Thiessen rainfall in Giriulla (Top) and Badalgama (Bottom) watersheds

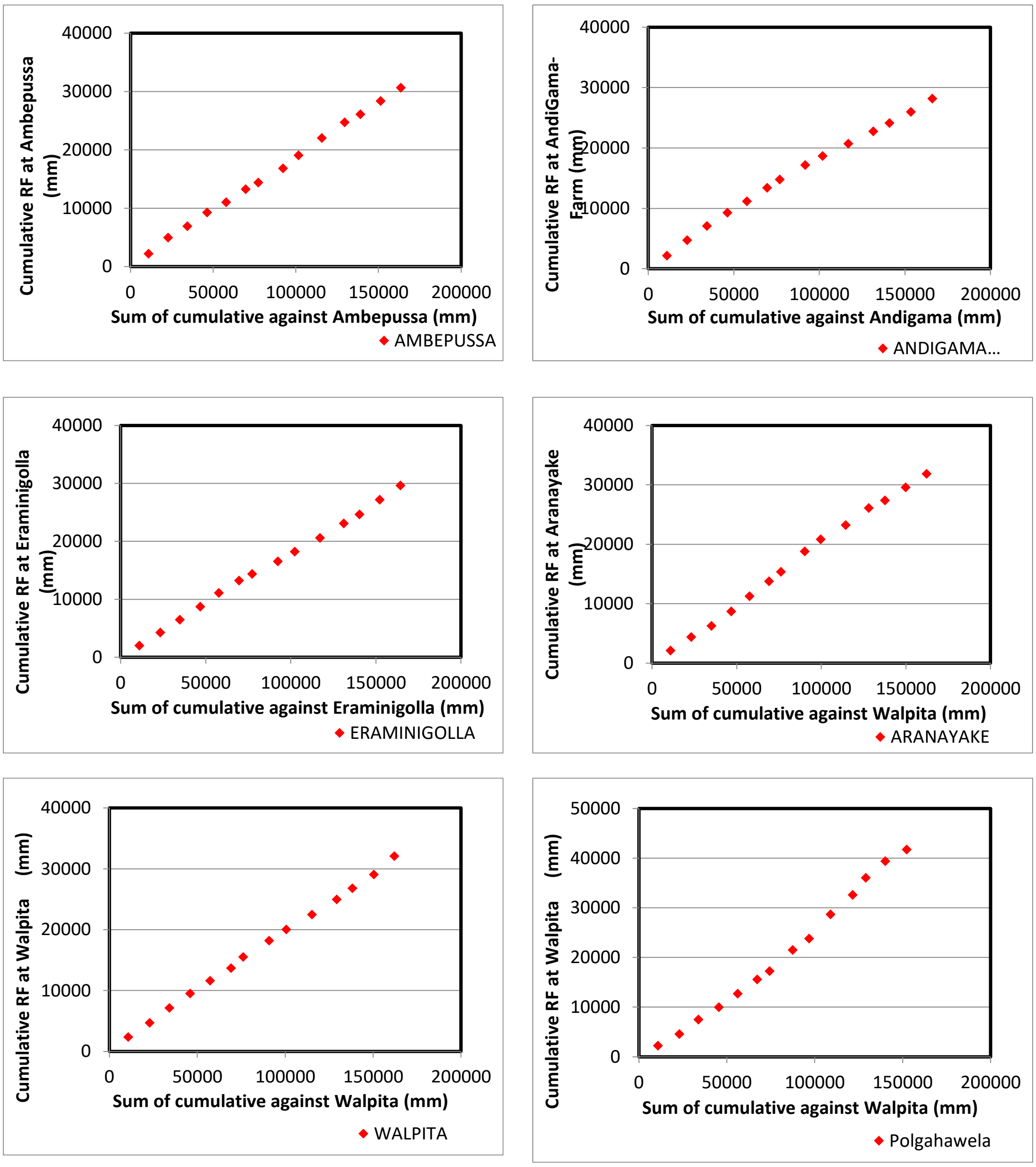


Figure 4-12: Double mass curve at selected rainfall stations

According to the double mass curves given in Figure 4-12, the slope of each graph remains constant, while minor variation in Polgahawela station. However, according to the double mass plots, it is evident that, consistency of rainfall data in selected stations are at an acceptable level.

5 RESULTS AND ANALYSIS

5.1 Catchment Selection

Based on the streamflow and precipitation data availability, Giriulla and Badalgama catchments were selected to investigate the applicability of parameter transferability in the Maha Oya Basin. These catchments were selected based on hydrological heterogeneity and the data availability. Further, it was noted that, lack of the water resources management activities have been implemented in the Maha Oya basin, though it lies within the wet zone.

5.2 Model Selection

The comprehensive literature survey reveals that, there are diverse types of models available for hydrological modeling and the HEC-HMS model was selected to reproduce the runoff responses in the selected catchments, as it has been prioritized (Table 2-4) as a best model based on the identified criteria. Moreover, HEC-HMS is a very popular hydrological model among hydrologists, since it is a free software and it has been used for Sri Lanka as well.

5.3 Development of HEC-HMS Model

Two HEC-HMS models have been built for both watersheds (Giriulla and Badalgama) as lump models, to investigate the parameter transferability in the Maha Oya basin. It was developed to represent the physical properties of the watershed, which was represented through five components as mentioned below.

5.3.1 Basin Model Development

5.3.1.1 Canopy Method

In order to represent the presence of plants in the landscape, the canopy method must be selected, which is an essential prerequisite for continuous simulation. Otherwise, interception or evapotranspiration will not be estimated by the model, and all precipitation is considered as direct precipitation. Accordingly, a simple canopy method was chosen in this study, since it is a simple representation of a plant canopy. The crop coefficient, water uptake, initial and maximum storage of canopy, method has to be introduced to the model (Ouédraogo et al., 2018).

Many studies have been conducted adopting initial canopy storage as 0%, which assumes that initial simulation was started after no rainfall period (Ahbari et al., 2018; Mcenroe & Ph, 2010). Further, many studies were conducted to identify the precipitation losses due to interception, which depends on the meteorological and vegetation factors (Curtis, 2017). The study carried out for Kandyan Forest garden in Sri Lanka by Hall et al., (1996), concluded that maximum canopy storage varied between 3.4 – 6.24 mm. The study carried out in Greensboro Watershed indicated that maximum canopy storage varied from 2 – 10mm (Yen et al., 2015).

Accordingly, 0% was adopted as initial storage, while 3.4 mm was assigned as maximum storage for both watershed as initial parameter values.

5.3.1.2 Surface Method

The ground surface, which collect water in depression areas were represented by Simple surface method and it was used in the continuous model simulation, based on the literature. Initial parameters were selected considering the Gradient of the catchment and land use type as mentioned in Table 2-5 in Section 2.6.2. Consequently, a 12.7 mm surface storage (depression) was used in both Giriulla and Badalgama water catchment areas.

5.3.1.3 Loss Method

It was introduced to the model to perform real infiltration estimation, by selecting Deficit and constant loss method in this research, which accounts for only one soil layer to represent moisture content variations. This method also requires the use of the canopy combination that extracts water from the soil in response to possible evapotranspiration. Considering the soil condition of the watershed, initial deficit and maximum deficits were specified. Further impervious area was defend in the model considering the prevailing land use layer.

It is required to calculate the initial parameters to represent the hydrological processes of the selected watersheds. Accordingly, maximum storage was estimated by using SCS equation. The weighted average CN was estimated by considering the land use types and the hydrological soil groups in the basin. The Land-use map of the Giriulla and Badalgama were shown in Figure 5-1 and Figure 5-2, while weighted average CN are demonstrated in Table 5-1 and Table 5-2 correspondingly.

Accordingly maximum potential retention S was calculated by using Equation 1, given in Chow et al. (2010).

$$S = \frac{25400}{CN} - 254 \quad \text{……………………………….Equation 1}$$

Then initial abstraction, $I_a = 0.2\,S$ …………………..…… Equation 2

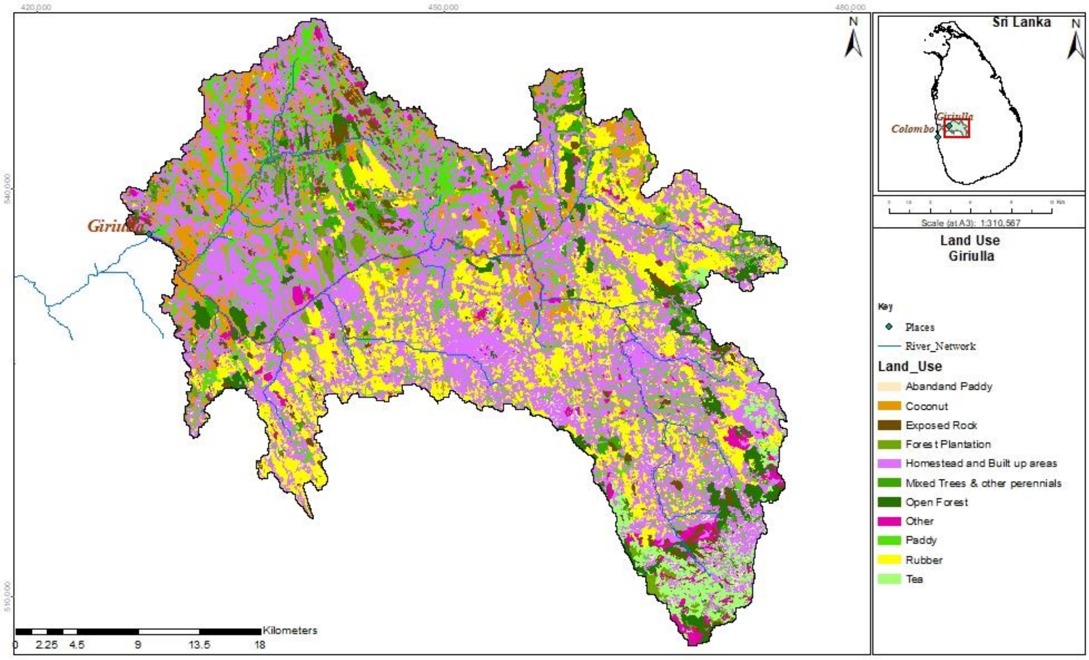


Figure 5-1: Land use map of Giriulla watershed

Source: Survey Department 2002

Table 5-1: Weighted Average CN of Giriulla Watershed

Row Labels	**Area %**	**CN**	**Weighted CN**
Homesteads/Home gardens	41.4%	83	34.4
Rubber	18.3%	77	14.1
Paddy	11.9%	88	10.5
Coconut	7.8%	77	6.0
Mixed tree and other perennials	4.0%	86	3.5
Open forest	3.6%	60	2.1
Tea	2.9%	67	1.9
Rocks	2.2%	91	2.0
Scrub Land	2.1%	60	1.2
Abandoned Paddy	1.4%	81	1.1
Forest plantation	1.3%	60	0.8
Other	3.1%	65	2.0
Weighted Average CN			**79.7**

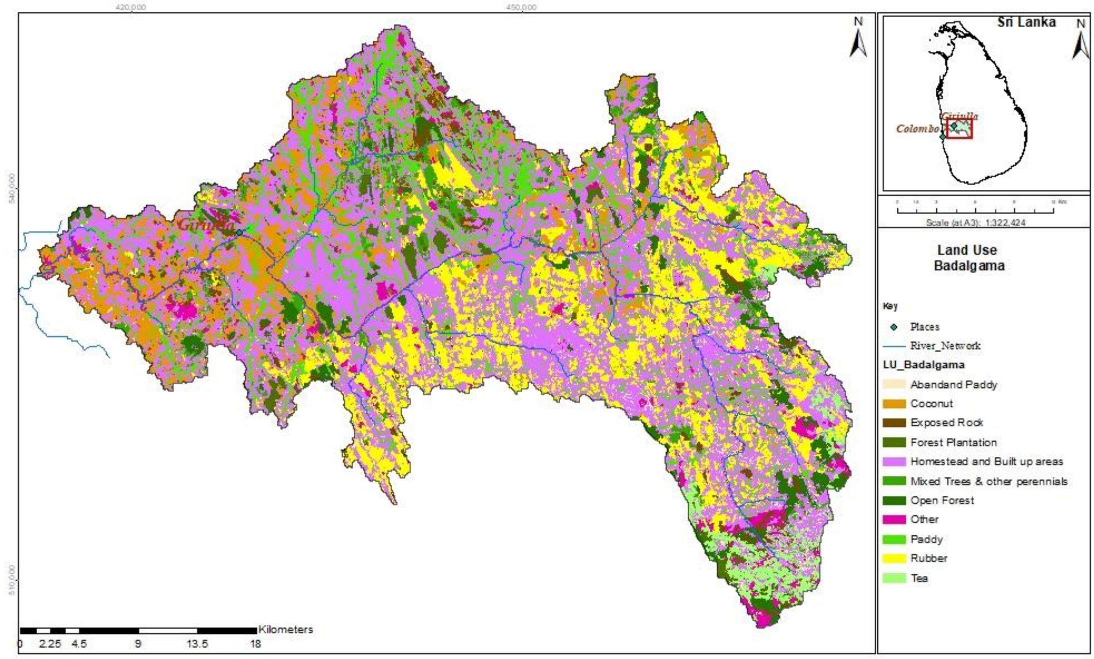


Figure 5-2: Land use map of Badalgama Watershed
Source: Survey Department 2002

Table 5-2: Weighted Average CN of Badalgama Watershed

Row Labels	Area %	CN	Weighted CN
Homesteads/Home gardens	41.0%	83	34.0
Rubber	16.1%	77	12.4
Paddy	11.7%	88	10.3
Coconut	10.7%	77	8.2
Mixed tree and other perennials	4.0%	86	3.5
Open forest	3.4%	60	2.0
Tea	2.5%	67	1.7
Area with exposed rocks	2.2%	91	2.0
Scrub Land	2.1%	60	1.2
Abandoned Paddy	1.3%	81	1.1
Forest plantation	1.3%	60	0.8
Other	3.8%	65	2.5
Weighted CN			**79.6**

Accordingly, initial parameters were derived, which is illustrated in Table 5-3.

5.3.1.4 Transform method

To estimate the actual surface runoff with in the sub basins, transform method has been used. SCS Unit Hydrograph Transformation method was chosen to model the Giriulla and Badalgama watersheds out of available eight methods. By changing the graph type, it could be adjusted the runoff percentage happening before the peak flow, since it rely on the gradient, and flow length of the basin and rest of the watershed properties. It has been identified that flat watersheds have lower peak rate factor, while sloppy watersheds have higher peak rate factor. Further Initial lag time was estimated by using Kirpitch formula.

$$T_{lag} = 0.6\ t_c \quad \text{……………………………….Equation 3}$$

Where t_c is the time of concentration, which can be derived using Kirpitch equation

$$t_c = 0.01947\ L^{0.77} S^{-0.385} \quad \text{……………….Equation 4}$$

Where L is entire length of the stream and S represent the Slope of the watershed.

Accordingly, derived set of initial parameters were illustrated in Table 5-3.

5.3.1.5 Baseflow Method

There are six different baseflow methods have been introduced in the HEC-HMS model, and few methods are recommended for event simulations, while other methods are for continuous simulations. Out of those six methods, the Recession baseflow method has been selected to model the Giriulla and Badalgama watersheds, as this method is recommended for continuous simulations and parameter requirement is minimal.

The equation used in the exponential recession model is presented below.

$$Q_t = Q_0 k^t \quad \text{……………………………….. Equation 5}$$

Where Q_t is the base flow at any time t; k = an exponential decay constant defined as the ratio of the base flow at time t to the base flow one day earlier; Q_0 = initial baseflow (at time zero); (Chow et al., 1988)

Initial baseflow has been specified based on the initial discharge method, since observed flow data was available for both selected watersheds. The ratio of baseflow at the present time, to single day before was taken as recession constant. Moreover, threshold type was selected as Ratio to peak, which was specified considering the flow ratio to the peak of several historical events.

5.3.2 Meteorological Model

One of the other impotent component in the project is a Meteorological model, which prepare meteorological boundary settings for the sub-basins. Thiessen polygon method was chosen as a precipitation method to model the watershed.

5.3.3 Control specifications

The model simulation is managed by the control specification and it is a main component in the project.

5.4 Schematic Diagram of HEC-HMS model

The HEC-HMS model schematic of this study, incorporating selected methods are given in the Figure 5-3.

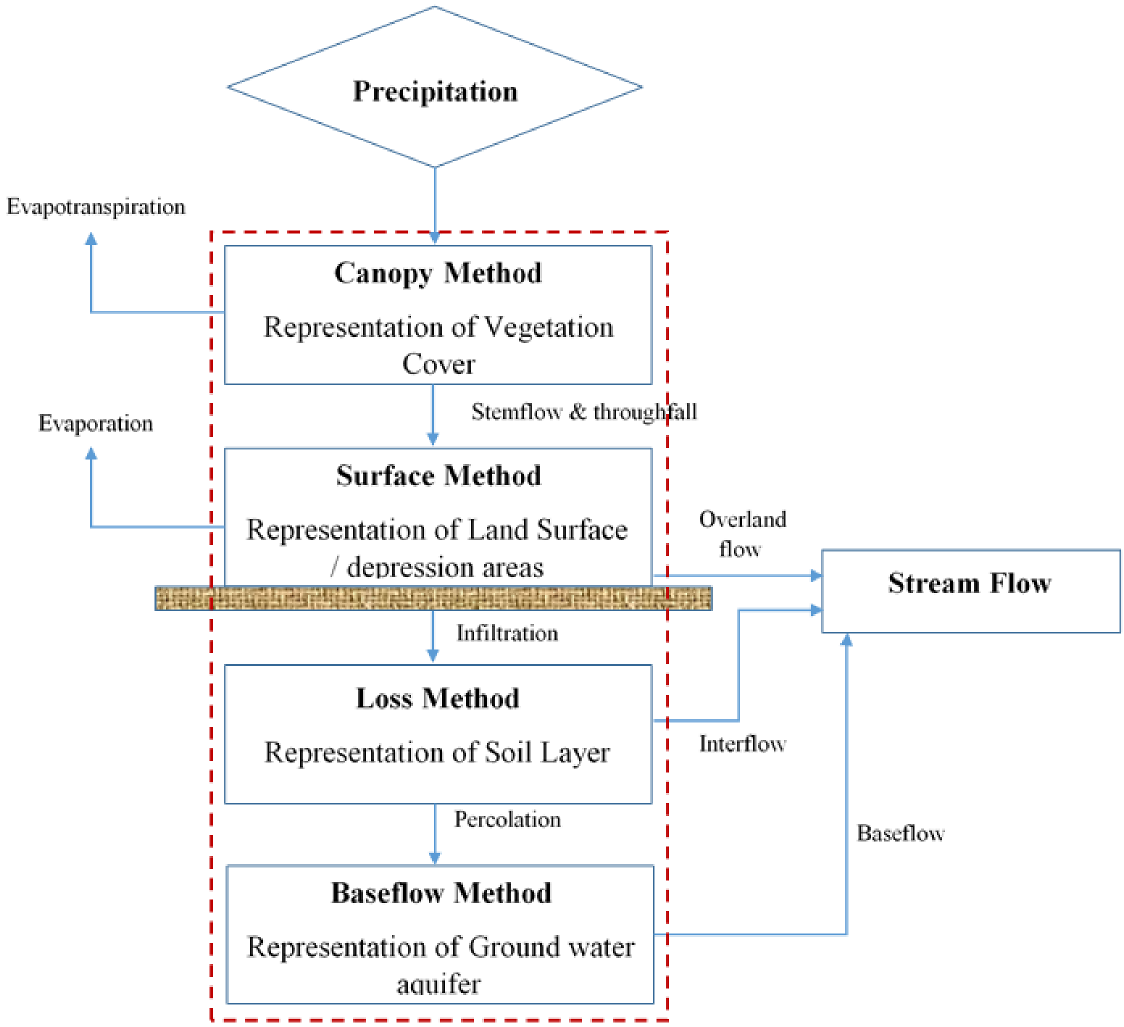


Figure 5-3: Schematic Diagram of HEC-HMS model used in the Study

5.5 Initial model parameters

The derived initial model parameters are tabulated in Table 5-3.

Table 5-3: Derived Initial Parameters of selected watersheds

Model	Parameter	Giriulla	Badalgama
Canopy - Simple Canopy	Initial Storage (%)	0	0
	Max Storage (mm)	3.4	3.4
	Crop Coefficient	1	1
Surface - Simple Surface	Initial Storage (%)	0	0
	Max Storage (mm)	12.7	12.7
Loss - Deficit and Constant	Initial Deficit (mm)	12.94	13
	Maximum Deficit (mm)	64.7	65
	Constant Rate (mm/hr)	1.27	1.27
	Impervious (%)	35	42
Transform - SCS Unit Hydrograph	Lag Time (Min)	652	815
Baseflow - Recession	Initial Discharge (m3/s)	15	14
	Recession Constant	0.94	0.9
	Ratio	0.15	0.15
(Bennett, 1998); (Bill Scharffenberg, Mike Bartles, Tom Brauer, Matt Fleming, 2018); (Ouédraogo et al., 2018); (Ahbari et al., 2018); (Arlen D. Feldman, 2000); etc..			

5.6 Model Simulation

Once control specifications introduced to the model, simulation could be performed. Accordingly, separate calibration periods and validation periods were selected for both models and by selecting the basin model, precipitation model, and the defined period initial simulation run was performed.

5.7 Model Warm-up

As stated in Section 2.8, it is required to warm up the model before starting the simulation, to eradicate the error propagation caused owing to the initial settings of the model based on the complexity of the model. Further, during the literature review, it was noted that the period of warm-up would support the model to minimize the effect of initial conditions on objective function as well. Therefore, it was decided to use consecutive four years in a cyclic order by facilitating the model to be properly warmed up, since there was no specific number of years specified and it highly depends on catchment characteristics.

5.8 Parameter optimization

In HEC-HMS model, three different optimization approached could be adopted, such as manual optimization, the semi-automatic optimizations, and automatic optimization. In the automatic optimization, the model was allowed to identify the best-optimized parameters, while semi-automatic optimization defined the initial parameters and let the model to find the set of optimized parameters based on catchment characteristics.

Both approaches, automatic and semi-automatic optimization were tested in this study, in order to identify the best method. Accordingly, it was confirmed that the semi-automatic method would be the most promising approach to perform parameter optimization. However, once optimized the parameters from semi-automatic approached, it was further analysed with the automatic approach, in order to check the availability of a further optimized set of parameters.

5.9 Classification of Flow Regime

Comprehensive literature review revealed that, there is no defined flow classification available in the field of water resources management. Hence, under this study it was estimated the low and high flow thresholds considering entire flow regimes. In this assessment, the disparity of the slope in FDC, which was identified based on changes in the order of magnitude of streamflow. Figure 5-4 and Figure 5-5 show the graphical representation of the low and high flow threshold identification.

According to the analysis executed, low and high flow boundaries for Giriulla are approximately 11% and 83% respectively. Similarly, at Badalgama high flow threshold is approximately 8% and the low flow threshold is approximately 93%. Hence, these threshold values were used in this study to performance evaluation of the different flow regimes.

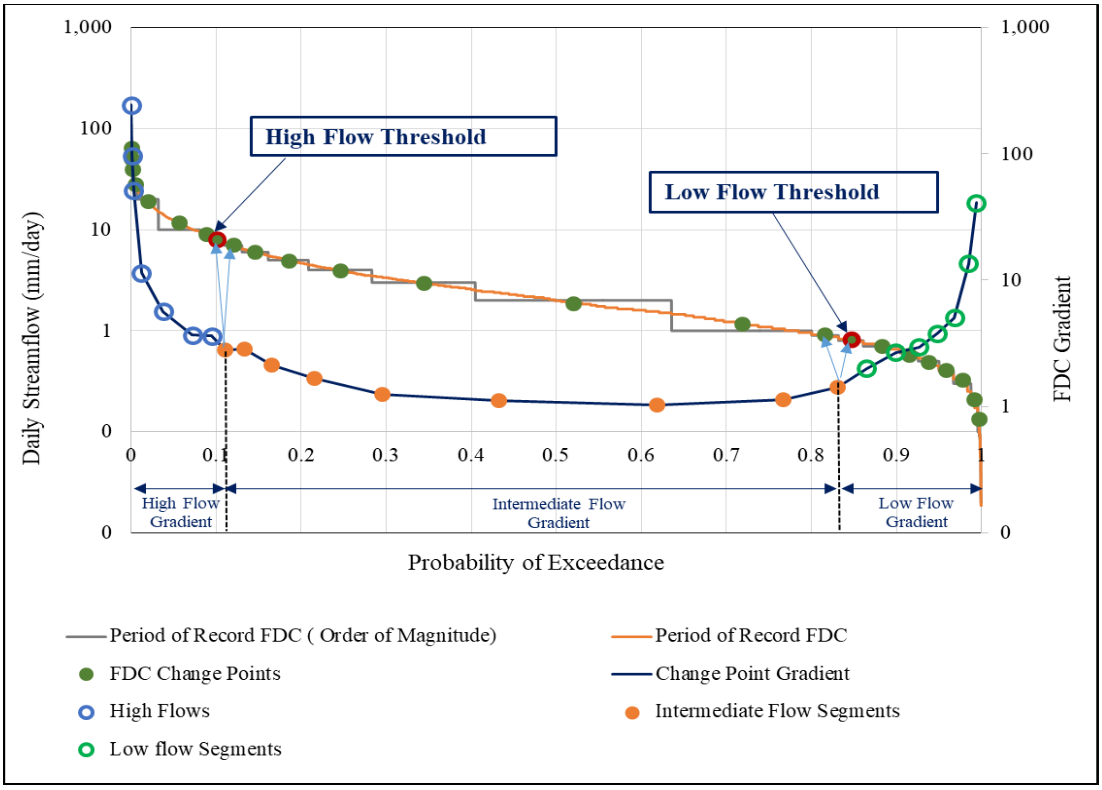


Figure 5-4: High, Intermediate and Low flow classification at Giriulla

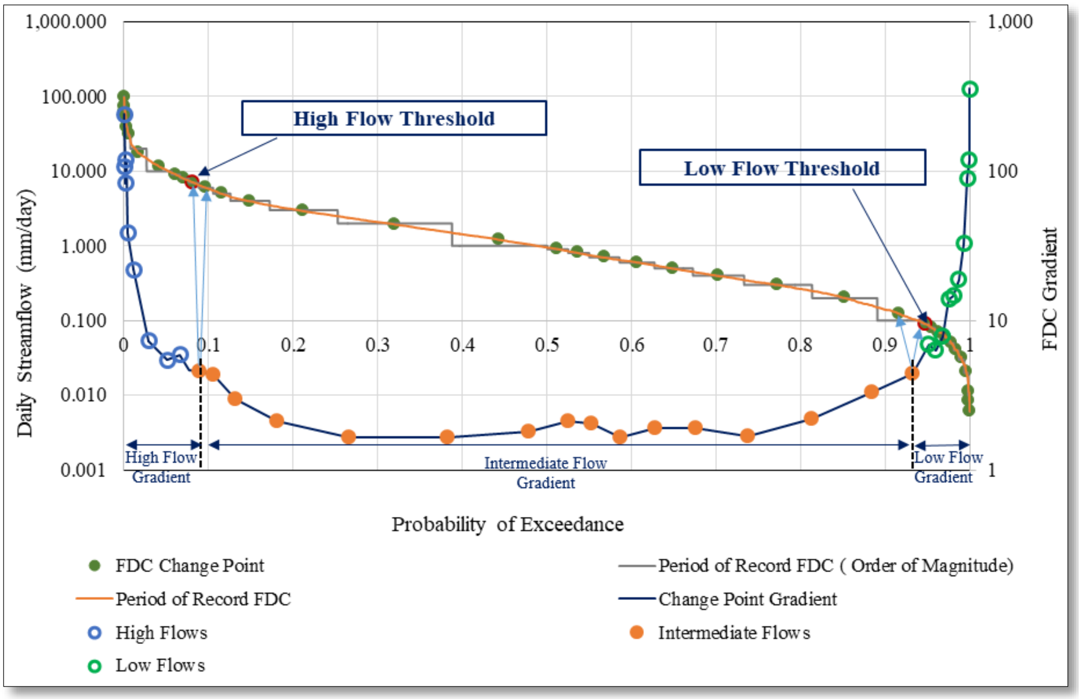


Figure 5-5: High, Intermediate and Low flow classification at Badalgama

5.10 Calibration of HEC-HMS model

Two catchments in the Maha Oya basin were selected to investigate the parameter transferability within the same hydrological region, in terms of achieving research objectives. The analysis was based on the developed daily rainfall-runoff model in HEC-HMS (4.3) platform. One reference period was selected for both catchments for calibration, while two different periods were chosen for the validation, based on the availability of daily data, including rainfall and streamflow. Accordingly, 2005/2006 to 2009/2010 period was selected as the calibration period for both catchments.

To calibrate the model, five years were selected for both watersheds as mentioned above. Semi-automatic calibration procedure has been utilized to optimize the MRAE, by changing model parameters, while observing visual matching of simulated and measured flow hydrographs. The number of calibration trials has been carried out to obtain good performance in objective function and performance was evaluated graphically and numerically with the use of performance indicators including, total hydrograph (in semi-log), annual water balance, low, medium and high flows in FDC.

5.10.1 Model calibration for Giriulla watershed

5.10.1.1 Statistical measures of goodness of fit

The illustration of model performance indicators for the entire periods and three different flow segments such as low, medium and high flows as given in Table 5-4.

Table 5-4: Statistical performance of the model for Calibration – Giriulla

Gauging Station	RMSE (mm/day)	MRAE	Flow Duration Curve					
			High		Medium		Low	
			RMSE (mm/day)	MRAE	RMSE (mm/day)	MRAE	RMSE (mm/day)	MRAE
Giriulla (Sorted)	2.24	0.24	6.71	0.32	0.62	0.13	0.06	0.66
Giriulla (Unsorted)	3.14	0.58	3.37	0.38	3.29	0.64	4.07	0.37

5.10.1.2 Comparison of observed and simulated streamflow hydrographs

The comparison of measured flow hydrograph and modeled flow hydrograph is illustrated in Figure 5-6, which facilitates visual checking of observed flow hydrograph vs modeled flow hydrograph at Giriulla gauging station.

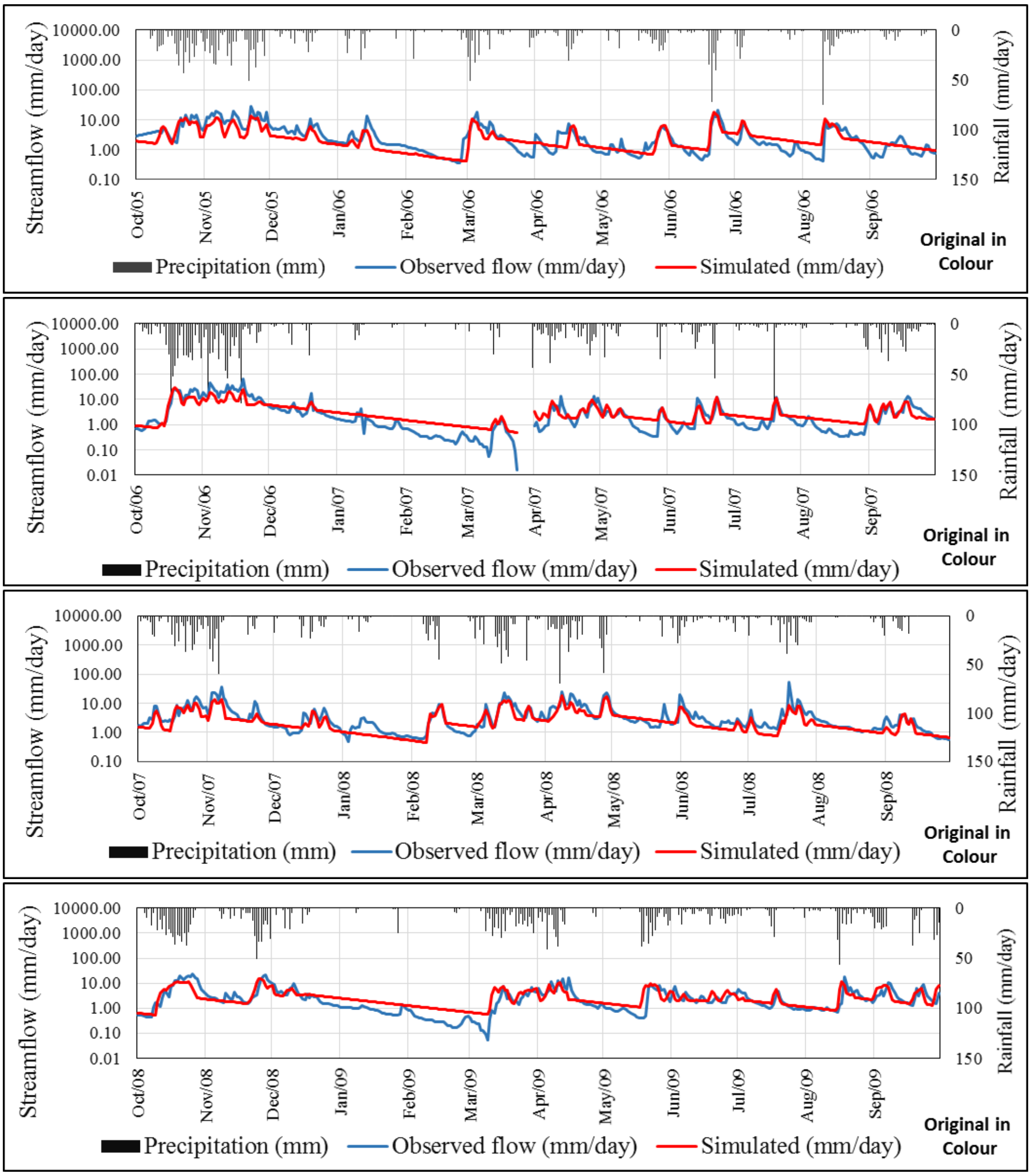


Figure 5-6: Observed and Simulated flow hydrograph in Giriulla - calibration

5.10.1.3 Annual and Seasonal water balance Error

The annual water balance, is illustrated in Table 5-5 and Figure 5-7. Seasonal water balance errors are graphically illustrated in Figure 5-8 and Figure 5-9 for Maha and Yala seasons respectively.

Table 5-5: Annual Water Balance for Giriulla - Calibration

Water Year	RF (mm)	Observed SF (mm)	Sim. SF (mm)	Pan Evpo. (mm)	AWB for Obs. Data	AWB for sim.	AWB Error
2005/06	2117.2	1321.5	1028.4	1,280.7	795.7	1088.9	-22%
2006/07	2344.4	1572.1	1297.4	1,311.5	772.3	1047.0	-17%
2007/08	2256.8	1567.1	1075.5	1,148.6	689.7	1181.4	-31%
2008/09	2349.0	1184.0	1117.2	1,331.9	1165.0	1231.8	-6%
2009/10	2318.3	1606.0	1309.2	1,374.6	712.3	1009.1	-18%
Average	**2277.2**	**1450.1**	**1165.5**	**1,289.4**	**827.0**	**1111.6**	**-19%**

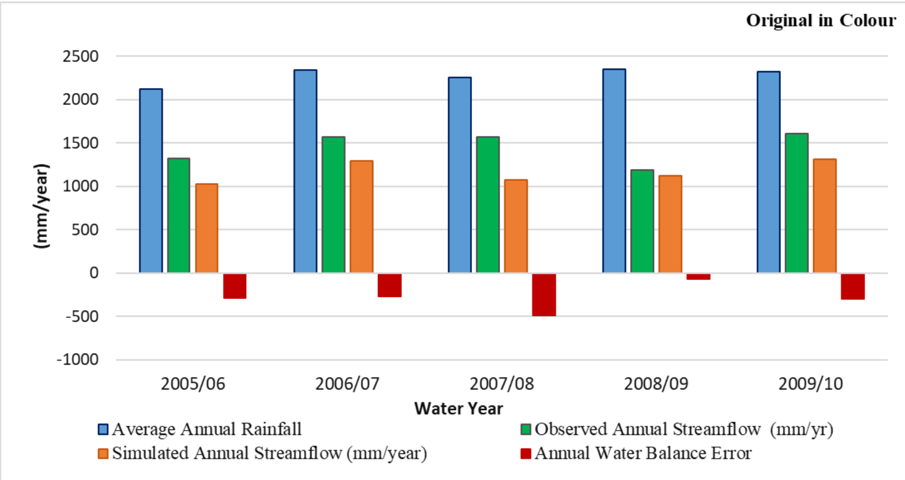


Figure 5-7: Annual Water Balance in Giriulla - calibration

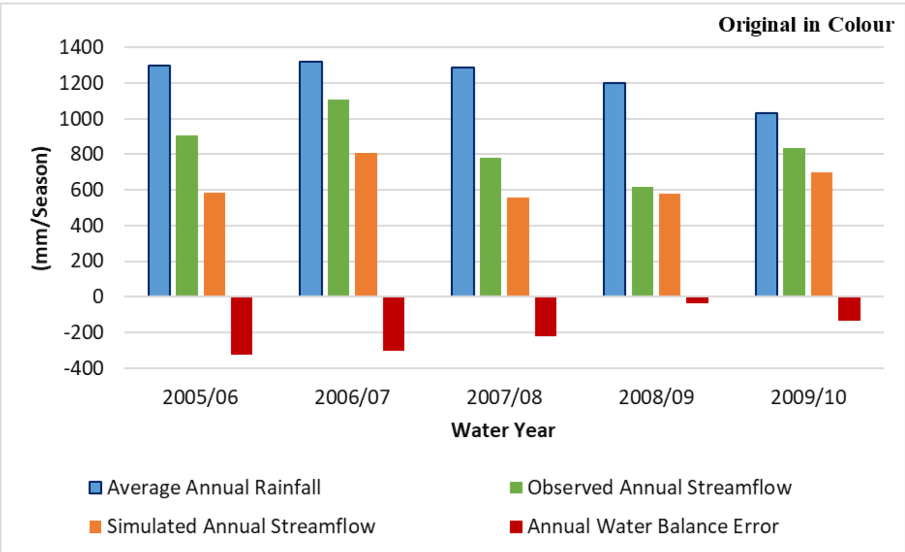


Figure 5-8: Seasonal (Maha) water balance in Giriulla - calibration

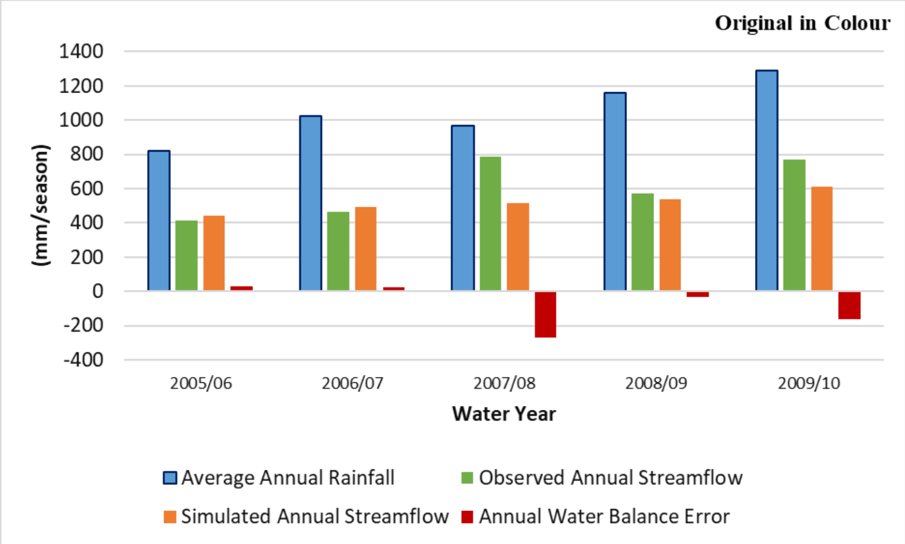


Figure 5-9: Seasonal (Yala) water balance in Giriulla - calibration

5.10.1.4 Comparison of Flow Duration Curve

The relationship between the frequency and the magnitude of streamflow were explained by the flow duration curve. It is very important in the field of planning and management of water resources and has been used to solve the Water resources management. Further flow duration curve illustrates the behavior of various flow segments, including low, medium and high flows. Accordingly, it would be much useful to do the water resources planning and management successfully. The Figure 5-10 shows the sorted FDC, while Figure 5-11 shows the unsorted FDC for Giriulla watershed.

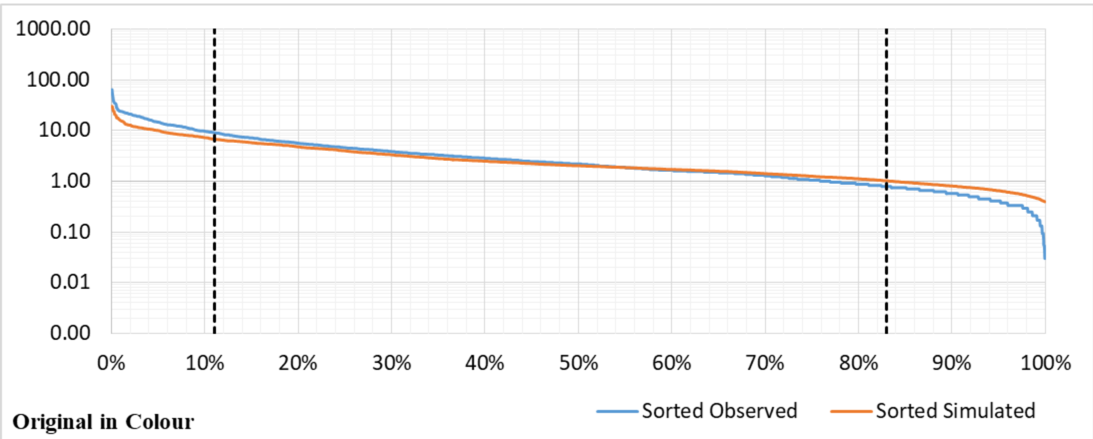


Figure 5-10: Flow duration curve (sorted) in Giriulla - Calibration

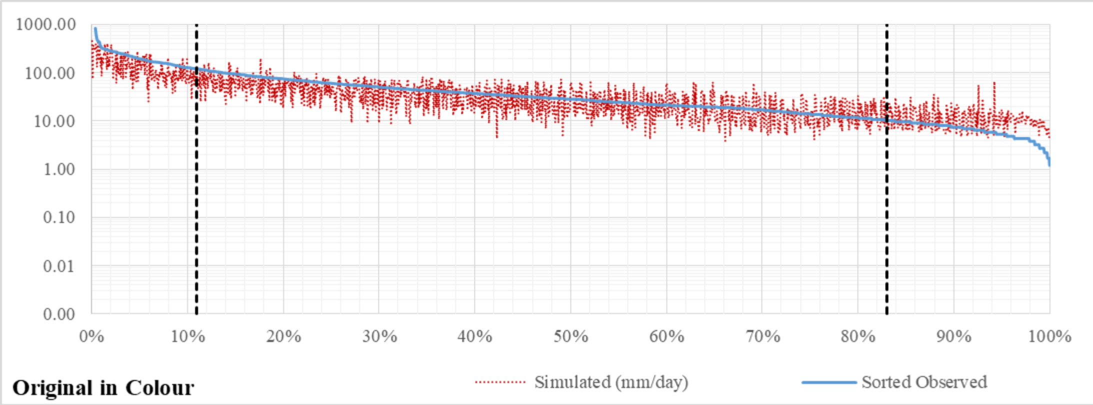


Figure 5-11: Flow duration curve (unsorted) for Giriulla - Calibration

5.10.2 Model calibration for Badalgama Watershed

5.10.2.1 Statistical measures of goodness of fit

As stated in Section 5.10.1.1, calibration of Badalgama watershed is performed and Table 5-6 shows the goodness of fit measures.

Table 5-6: Measure of goodness of fit of the model for Badalgama – Calibration

Gauging Station	RMSE (mm/day)	MRAE	Flow Duration Curve					
			High		Medium		Low	
			RMSE (mm/day)	MRAE	RMSE (mm/day)	MRAE	RMSE (mm/day)	MRAE
Badalgama (Sorted)	0.96	0.25	3.30	0.12	0.36	0.23	0.003	0.52
Badalgama (Unsorted)	3.07	0.86	3.10	0.74	3.16	0.89	2.63	0.68

5.10.2.2 Comparison of observed and simulated streamflow hydrograph

The Figure 5-12 illustrate the comparison of measured and modeled flow hydrographs in a semi-log plot, to observe the visual matching.

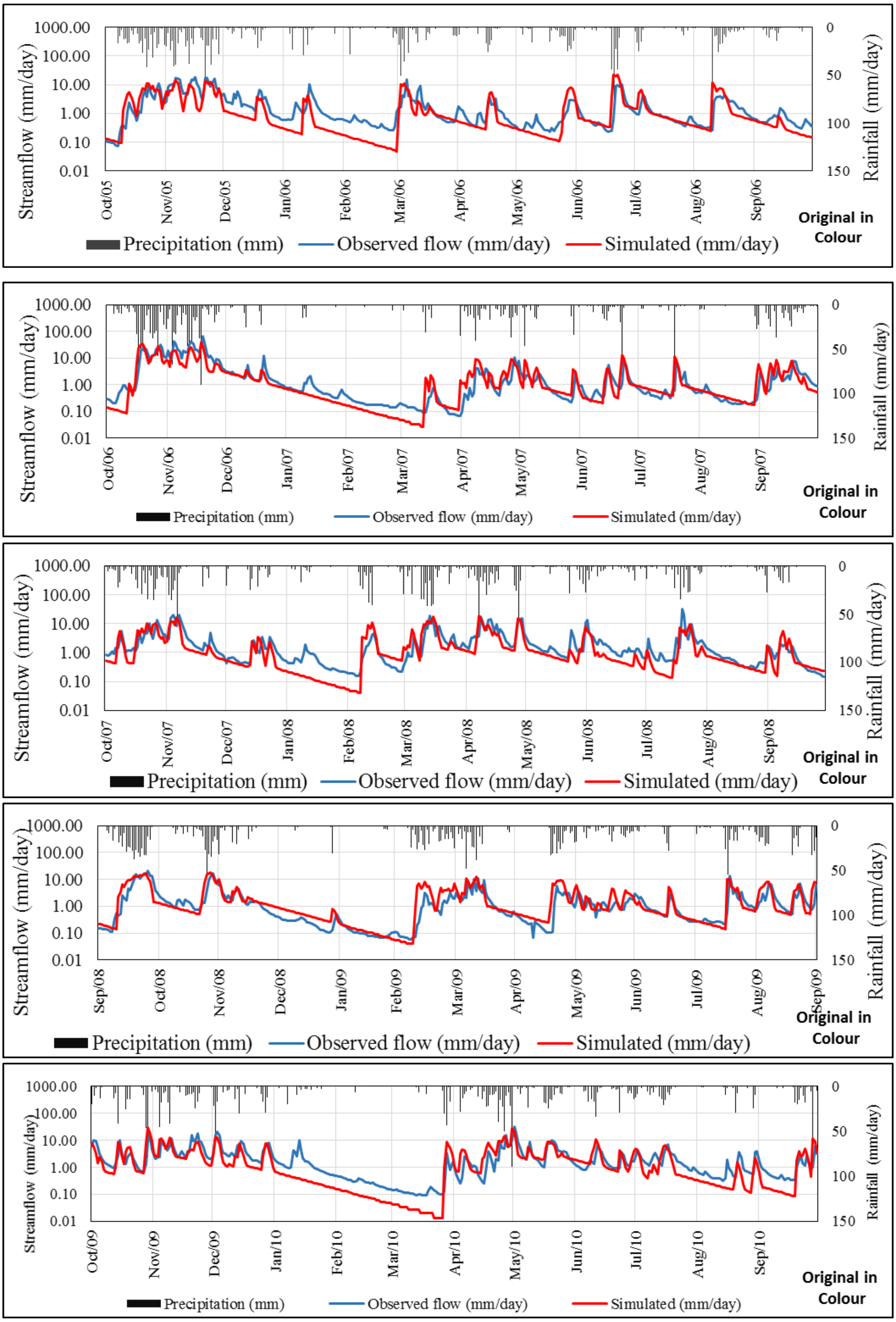


Figure 5-12: Observed and Simulated flow hydrograph in Badalgama - calibration

5.10.2.3 Annual and seasonal water balance error

Table 5-7 and Figure 5-13 illustrate the annual water balance error, while Figure 5-14 and Figure 5-15 shows Maha and Yala season water balance respectively.

Table 5-7: Annual Water Balance for calibration at Badalgama

Water Year	RF (mm)	Observed SF (mm)	Sim. SF (mm)	Pan Evpo. (mm)	AWB for Observed Data	AWB for sim.	AWB Error
2005/06	2121.7	823.4	744.2	1,280.7	1298.3	1377.5	-10%
2006/07	2406.4	1209.1	1014.6	1,311.5	1197.3	1391.8	-16%
2007/08	2144.1	923.7	754.5	1,148.6	1220.4	1389.6	-18%
2008/09	2361.4	679.2	873.7	1,331.9	1682.2	1487.7	29%
2009/10	2188.6	942.8	873.1	1,374.6	1245.8	1315.5	-7%
Average	**2244.4**	**915.6**	**852.0**	**1,289.4**	**1328.8**	**1392.4**	**-7%**

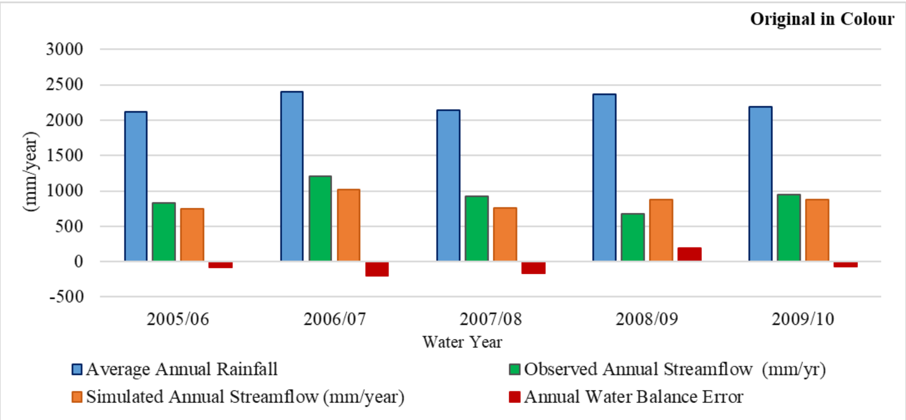


Figure 5-13: Annual water balance in Badalgama – calibration

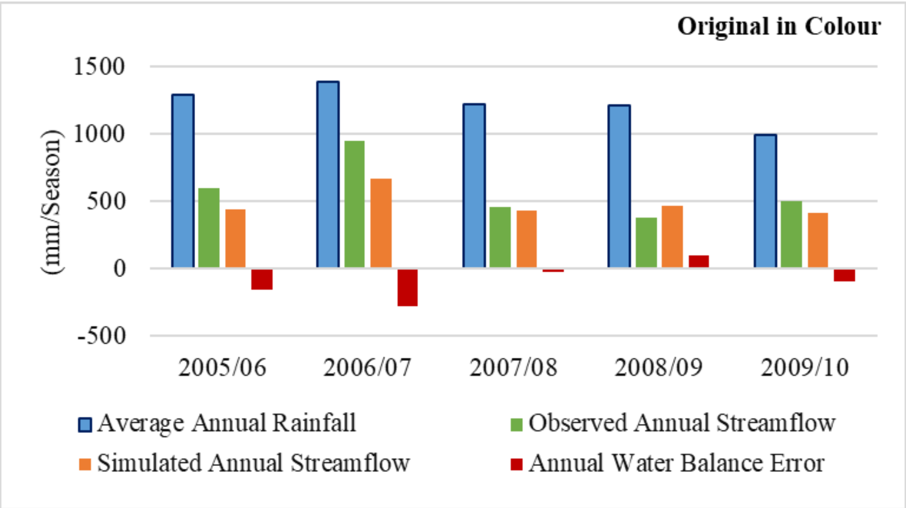


Figure 5-14: Seasonal (Maha) water balance in Badalgama – Calibration

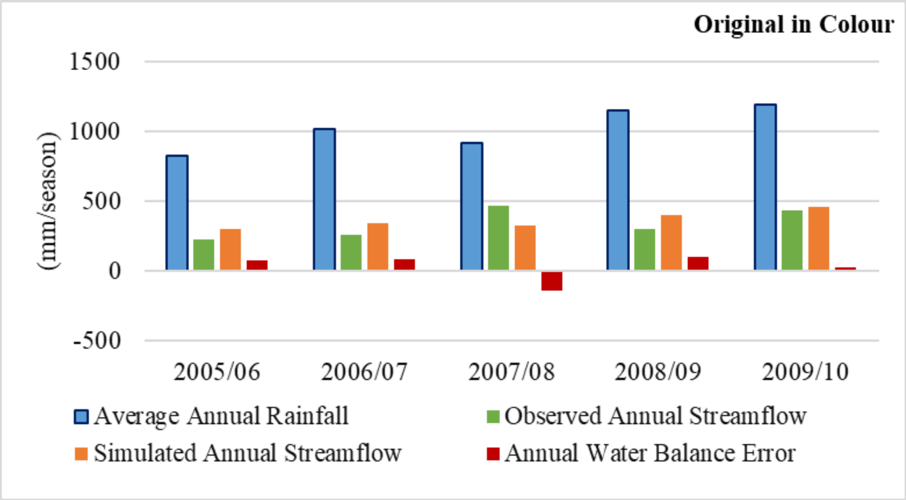


Figure 5-15: Seasonal (Yala) water balance in Badalgama – Calibration

5.10.2.4 Comparison of Flow Duration Curve

The Figure 5-16 and Figure 5-17 illustrate the sorted and unsorted flow duration curve for Badalgama watershed.

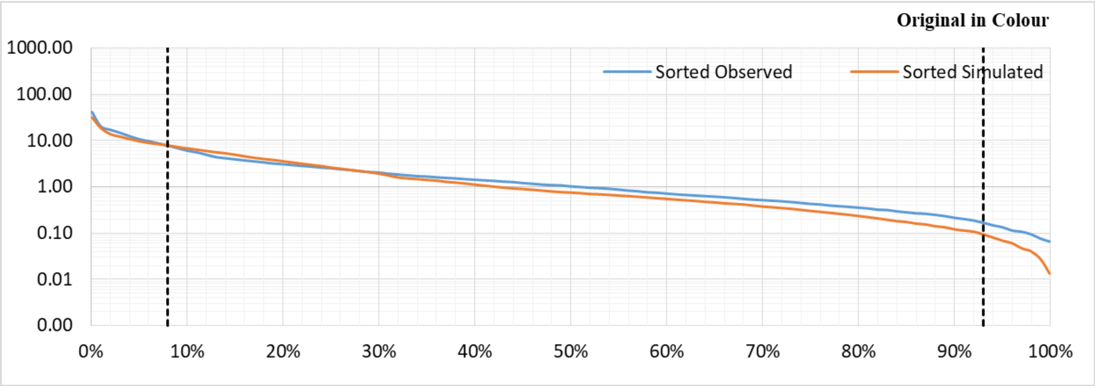


Figure 5-16: Sorted flow duration curve for Badalgama Sub-watershed – calibration

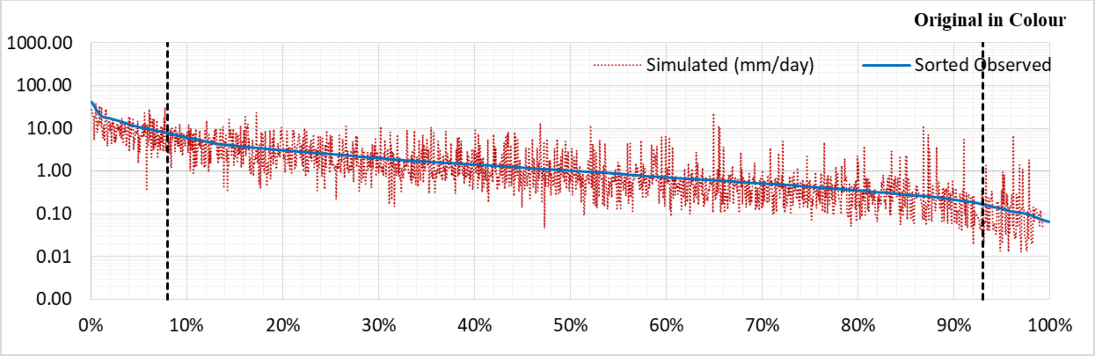


Figure 5-17: Unsorted flow duration curve for Badalgama Watershed – calibration

5.11 Validation of HEC-HMS Model

As mentioned above, two different periods have been selected for verification, as 2014/2015 to 2018/2019 for Badalgama and 2000/2001 to 2004/2005 for Griulla watershed, due to poor observed data availability at Giriulla watershed during recent period.

5.11.1 Model validation for Giriulla watershed

5.11.1.1 Statistical measures of goodness of fit

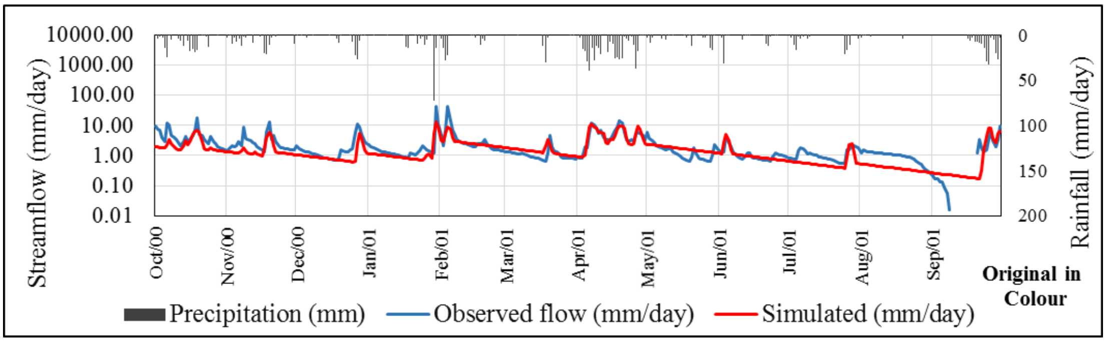
The model performance indicators are shown in Table 5-8 for Giriulla watershed for the above-mentioned verification period.

Table 5-8: Measures of goodness of fit of the model for Giriulla – validation

Gauging Station	RMSE (mm/day)	MRAE	Flow Duration Curve					
			High		Medium		Low	
			RMSE (mm/day)	MRAE	RMSE (mm/day)	MRAE	RMSE (mm/day)	MRAE
Giriulla (Sorted)	1.45	0.18	4.37	0.22	0.36	0.15	0.17	0.30
Giriulla (Unsorted)	2.34	0.38	4.21	0.36	2.31	0.39	2.77	0.33

5.11.1.2 Comparison of Observed and Estimated Streamflow Hydrograph

Figure 5-18 illustrate the behavior of observed hydrograph vs simulated hydrograph.



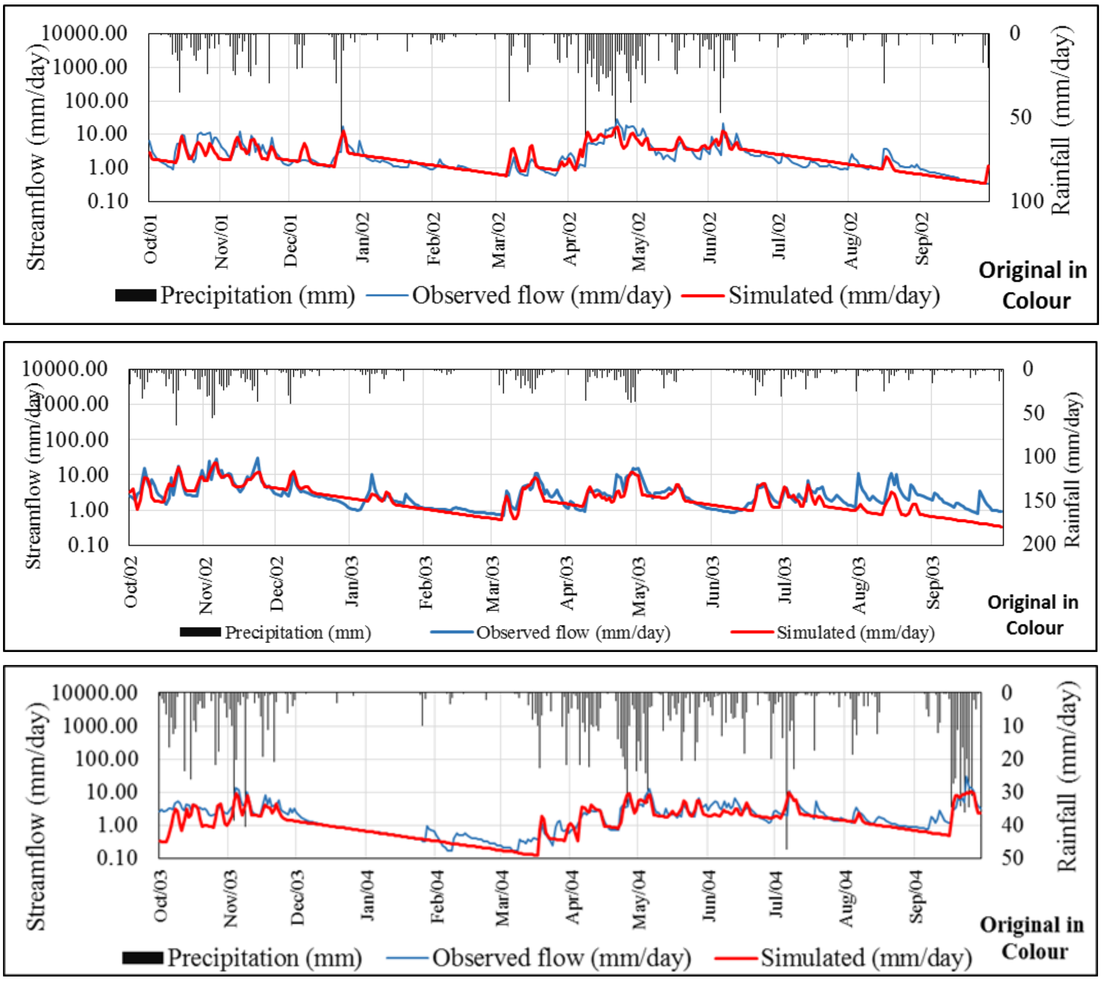


Figure 5-18: Observed vs simulated Streamflow hydrograph for Giriulla – Validation

5.11.1.3 Annual and seasonal water balance

Table 5-9 and Figure 5-19 shows the annual water balance error, while Figure 5-20 and Figure 5-21 shows the seasonal water balance for Giriulla watershed.

Table 5-9: Annual Water Balance for Giriulla - Validation

Water Year	RF (mm)	Observed SF (mm)	Sim. SF (mm)	Pan Evpo. (mm)	AWB for Observe	AWB for Cal.	AWB Error
2000/01	1487.1	902.1	656.9	1,280.7	584.9	830.2	-27%
2001/02	1928.5	1118.0	978.8	1,311.5	810.5	949.7	-12%
2002/03	2138.8	1304.4	1035.5	1,148.6	834.5	1103.4	-21%
2003/04	1698.6	869.1	696.3	1,331.9	829.5	1002.3	-20%
Average	**1813.2**	**1048.4**	**841.8**	**1268.2**	**764.8**	**971.4**	**-20%**

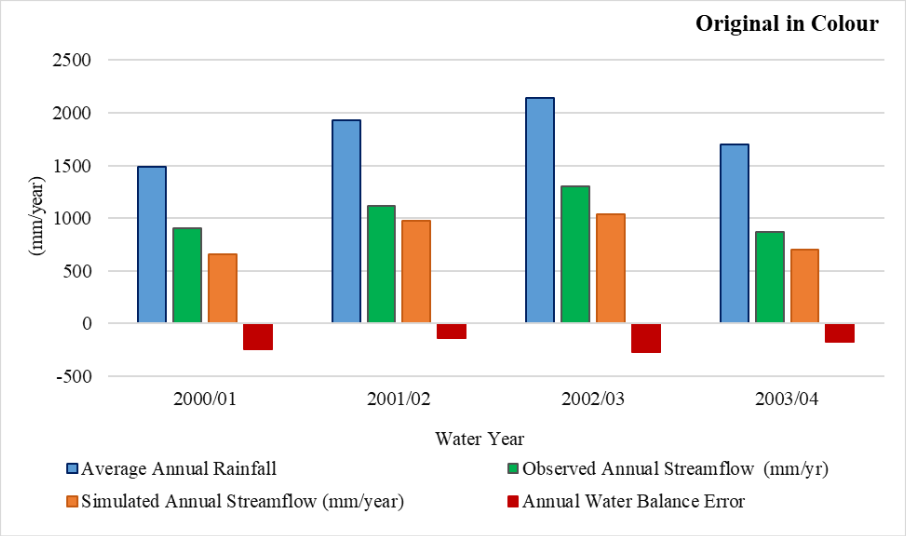


Figure 5-19: Annual water balance for Giriulla – validation

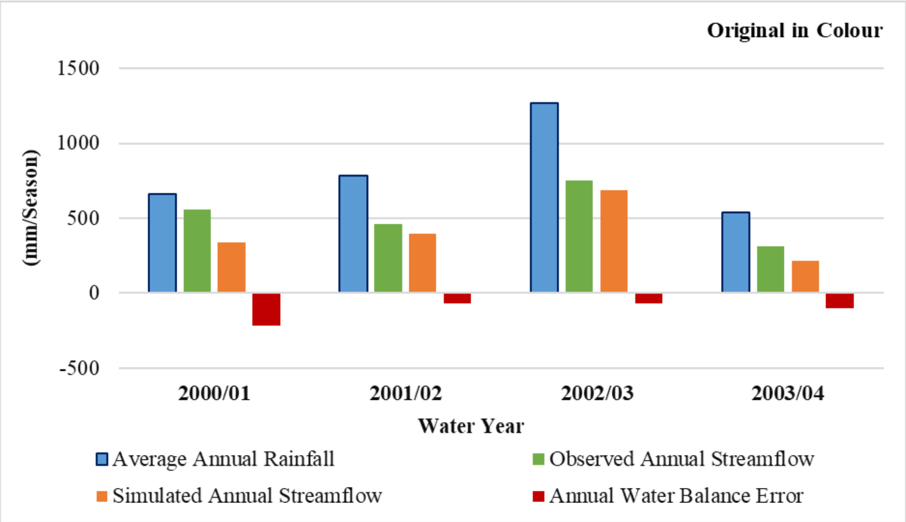


Figure 5-20: Seasonal (Maha) water balance in Giriulla – validation

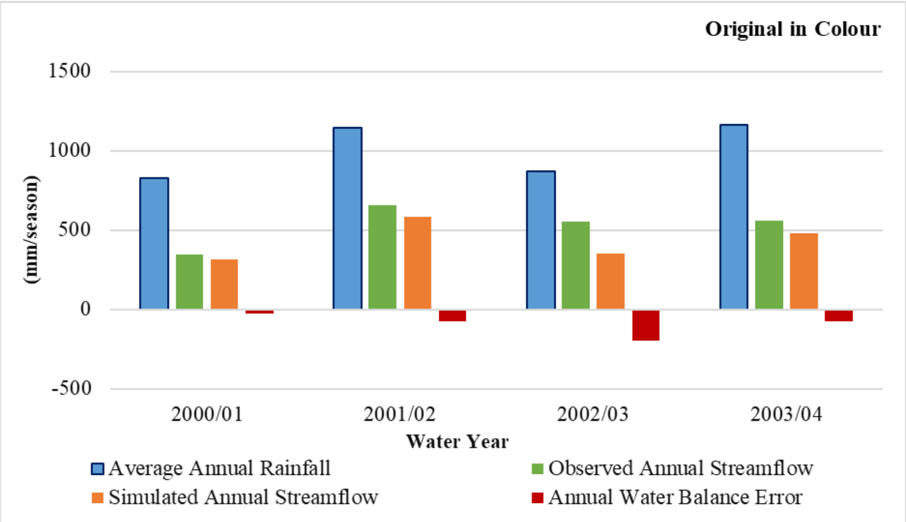


Figure 5-21: Seasonal (Yala) water balance in Giriulla – validation

5.11.1.4 Comparison of Flow Duration Curve

The sorted and unsorted Flow duration curves are shown in Figure 5-22 and Figure 5-23.

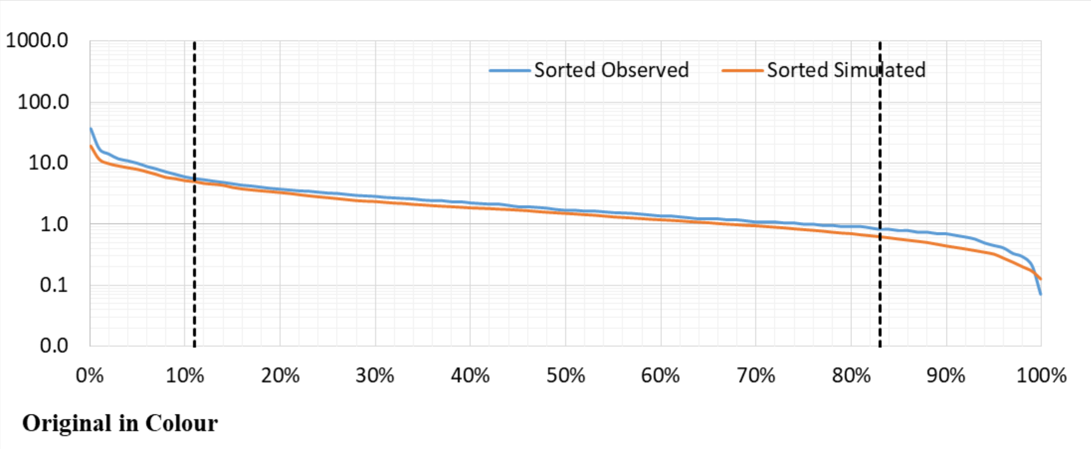


Figure 5-22: Sorted flow duration curve for Giriulla – validation

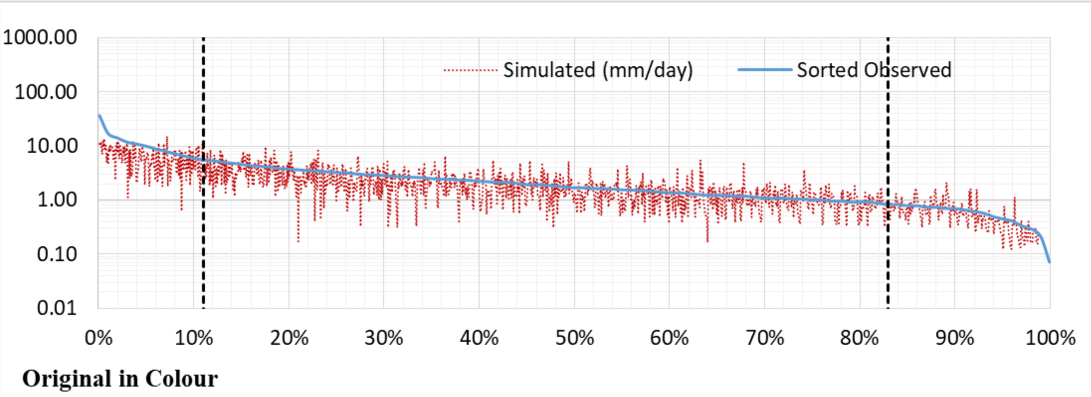


Figure 5-23: Unsorted flow duration curve for Giriulla – validation

5.11.2 Model Validation at Badalgama watershed

5.11.2.1 Statistical Measure of Goodness of Fit

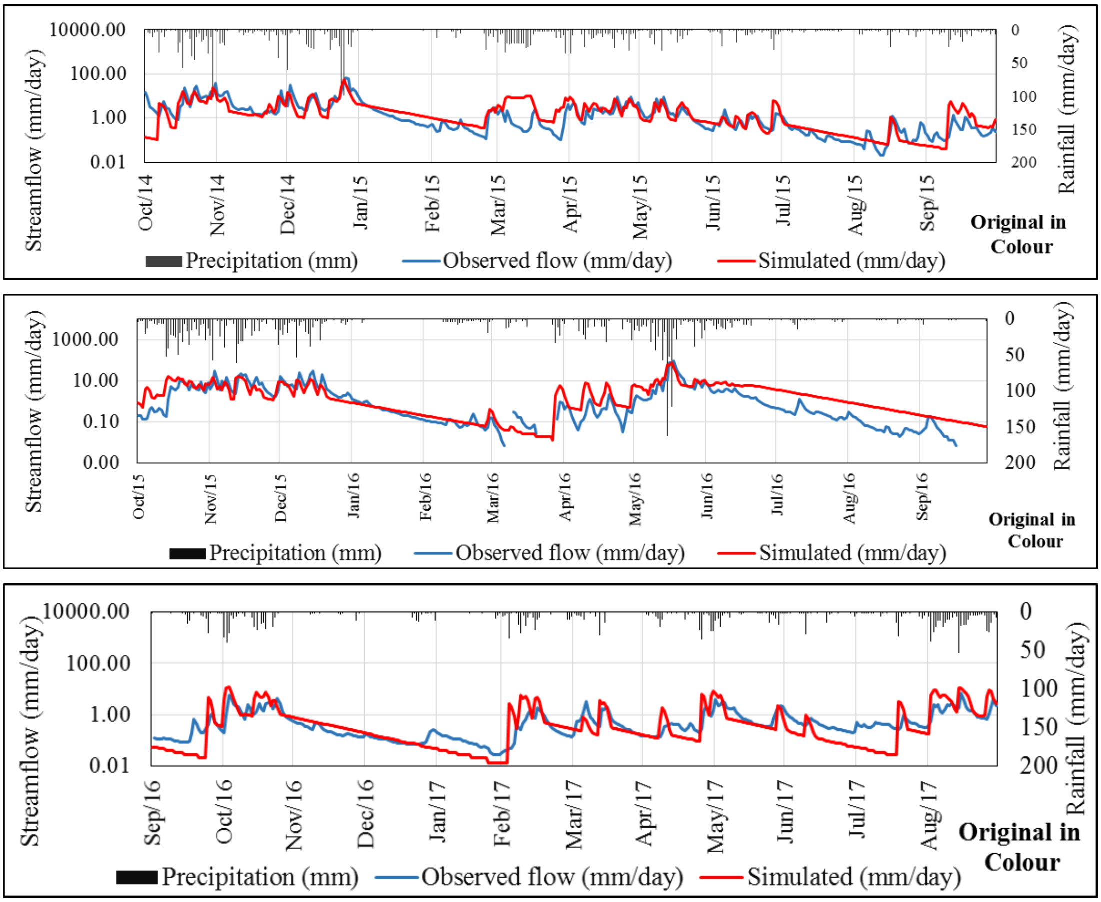
The validation period was selected as 2014/2015 to 2018/2019 in Badalgama watershed. Quantitative model performance for different flow segments are illustrated in Table 5-10.

Table 5-10: Measure of goodness of fit of the model for Badalgama – Validation

Gauging Station	**RMSE (mm/day)**	**MRAE**	**Flow Duration Curve**					
			High		**Medium**		**Low**	
			RMSE (mm/day)	**MRAE**	**RMSE (mm/day)**	**MRAE**	**RMSE (mm/day)**	**MRAE**
Badalgama (Sorted)	1.50	0.19	5.11	0.10	0.59	0.18	0.001	0.46
Badalgama (Unsorted)	4.19	1.56	6.89	0.77	3.96	1.69	4.81	0.73

5.11.2.2 Comparison of Observed and Estimated Streamflow Hydrograph

Figure 5-24 demonstrates the simulated and measured streamflow hydrographs for the period of validation at Badalgama sub-watershed.



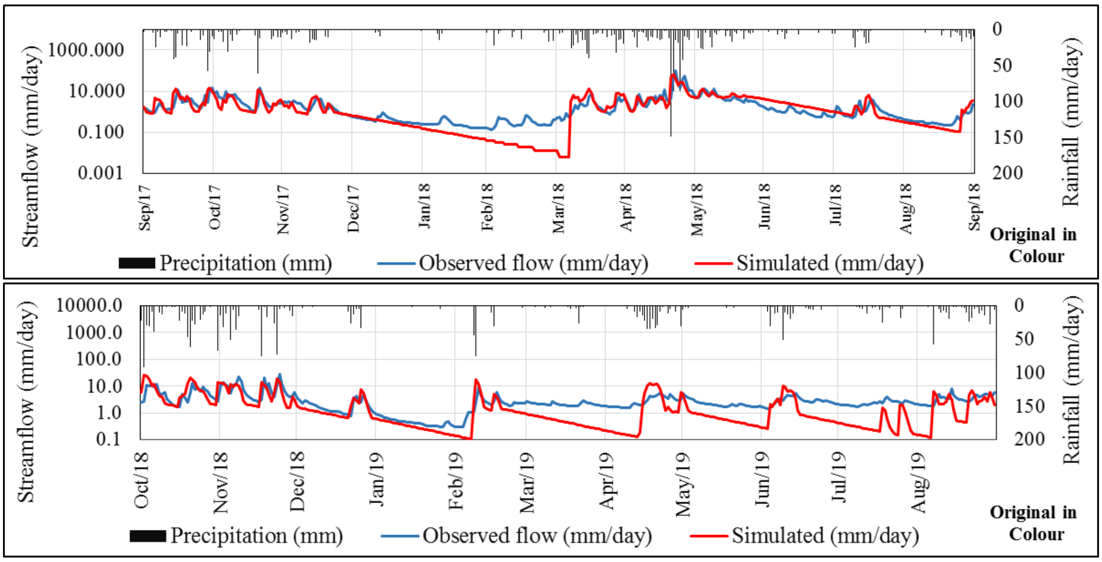


Figure 5-24: Observed and Estimated Flow Hydrograph for Badalgama – Validation

5.11.2.3 Annual Water Balance Error

The Annual and seasonal (Maha and Yala) water balance error for Badalgama watershed are shown in Table 5-11, Figure 5-25, Figure 5-26 and Figure 5-27 correspondingly.

Table 5-11: Annual Water Balance for Badalgama sub-watershed - Validation

Water Year	RF (mm)	Observed SF (mm)	calc. SF (mm)	Pan Evpo. (mm)	AWB for Observe	AWB for Cal.	AWB Error
2014/15	2,671.5	1,119.5	1059.3	1,282.0	1552.0	1612.2	-5%
2015/16	2,594.3	1,183.0	1331.6	1,361.6	1411.3	1262.7	13%
2016/17	1,578.3	254.3	430.4	1,243.3	1323.9	1147.9	69%
2017/18	2,252.3	1,045.1	1050.4	1,107.2	1207.2	1201.9	1%
2018/19	2,167.9	1,090.7	872.7	1,325.0	1077.2	1295.1	-20%
Average	**2252.9**	**938.5**	**948.9**	**1,263.8**	**1314.3**	**1304.0**	**11%**

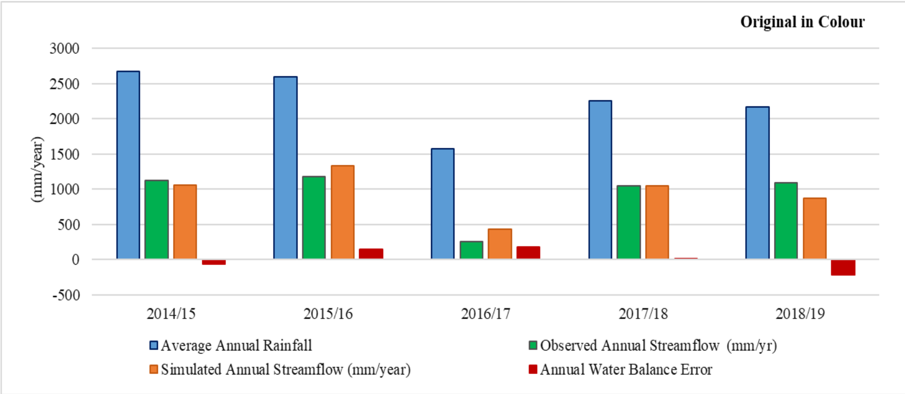


Figure 5-25: Annual water balance for Badalgama Watershed – validation

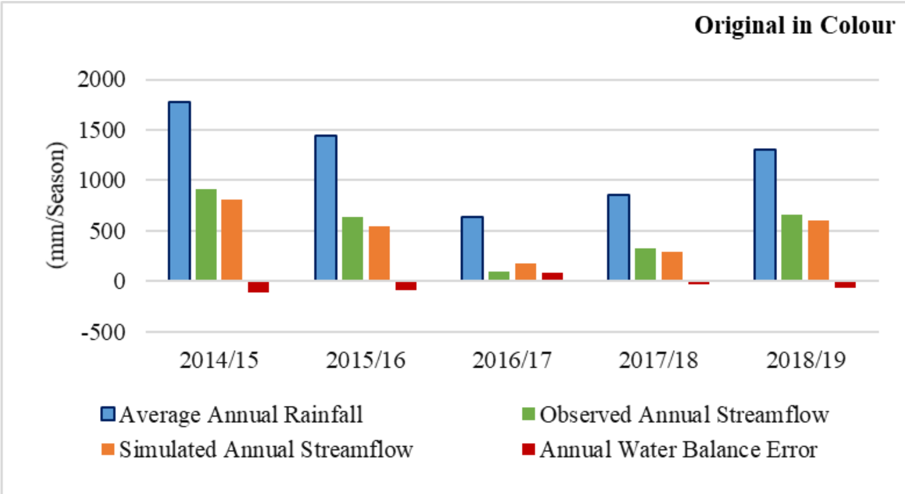


Figure 5-26: Seasonal (Maha) water balance for Badalgama watershed – validation

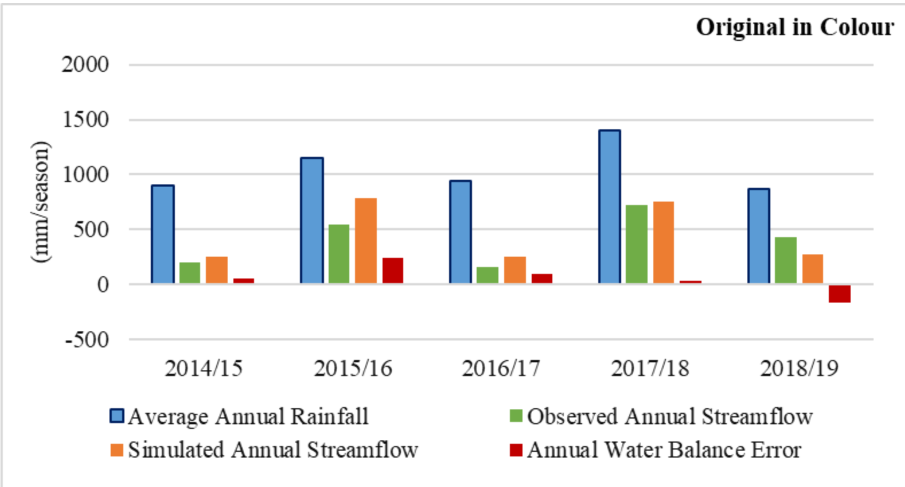


Figure 5-27: Seasonal (Yala) water balance for Badalgama watershed – validation

5.11.2.4 Comparison of Flow Duration Curves

Figure 5-28 and Figure 5-29 demonstrate the performance of sorted and un-sorted FDC respectively for the validation data period of Badalgama watershed.

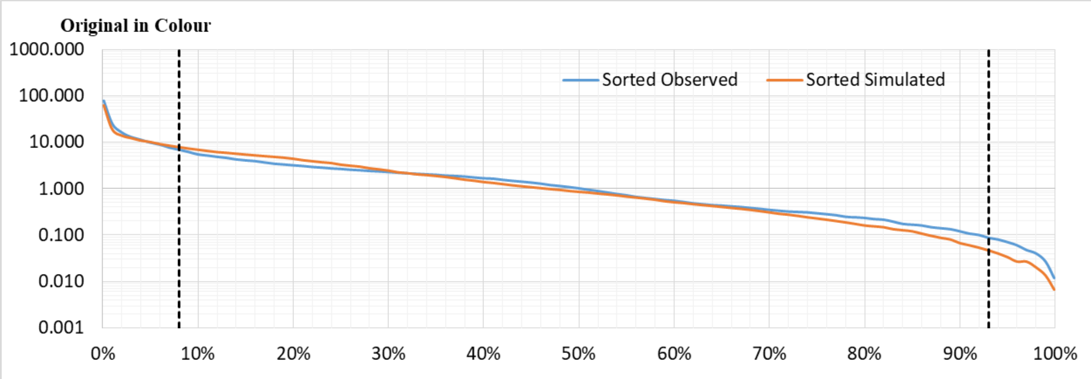


Figure 5-28: Sorted flow duration curve for Badalgama watershed – validation

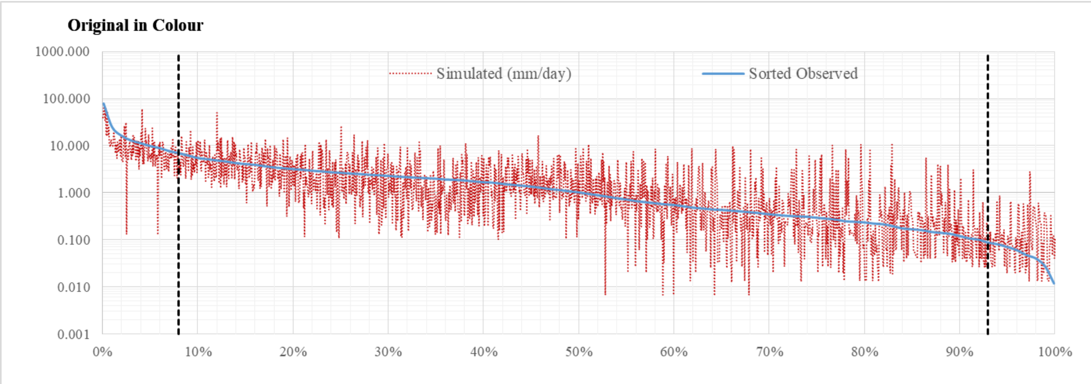


Figure 5-29: Unsorted Flow duration curve for Badalgama watershed – validation

5.12 Optimized HEC-HMS Model Parameters

Once broad spread systematic calibration and validation trials (approximately 200-250 for each catchment) have been conducted, the most promising set of parameters were identified and the model performance of these parameters for both calibration and validation was illustrated in previous sections. Accordingly, the best-optimized set of parameters for both Giriulla and Badalgama Watersheds are demonstrated in Table 5-12.

Table 5-12: Optimized Model Parameters for both catchments

Parameter	Giriulla sub-watershed	Badalgama sub-watershed
Recession - Initial Discharge	25.00	2.00
Recession - Ratio to Peak	0.22	0.09
Recession - Recession Constant	0.98	0.96
SCS Unit Hydrograph - Lag Time	991.10	997.61
Simple Canopy - Initial Storage	2.24	0.56
Simple Canopy - Max Storage	25.00	25.00
Simple Surface - Initial Storage	1.98	0.67
Simple Surface - Max Storage	35.34	39.98
Deficit and Constant - Constant Rate	1.15	0.89
Deficit and Constant - Initial Deficit	24.63	10.28
Deficit and Constant - Maximum Deficit	65.52	33.67

5.13 Automatic Parameter Optimization

Further, optimized parameters were used as initial parameters in automatic calibration, to check whether there is a best set of parameter could be identified from the automatic optimization. The optimized parameters are illustrated in Table 5-13 and Table 5-14, while the sorted flow duration curve as illustrated in Figure 5-30: and Figure 5-31: for Giriulla and Badalgama watersheds respectively. In Table 5-15 and Table 5-16 show the performance indicators, while the flow hydrograph comparison of the automatic calibration is shown in APPENDIX E for the clarity for Giriulla and Badalgama.

Table 5-13: Optimised Parameters from Automatic Calibration - Giriulla

Method	Parameter	Unit	Initial	Automatic Optimized
Baseflow - Recession	Initial Discharge	m^3/s	25.000	34.809
	Ratio to Peak		0.221	0.894
	Recession Constant		0.978	0.846
Transform - SCS Unit Hydrograph	Lag Time	min	900.000	966.470
	Initial Storage	%	2.241	2.714

Method	Parameter	Unit	Initial	Automatic Optimized
Canopy - Simple Canopy	Max Storage	mm	25.000	27.862
Surface - Simple Surface	Initial Storage	%	1.978	2.465
	Max Storage	mm	35.340	57.114
Loss - Deficit and Constant	Deficit and Constant - Constant Rate	mm/hr	1.150	2.956
	Deficit and Constant - Initial Deficit	mm	24.631	49.884
	Deficit and Constant - Maximum Deficit	mm	65.523	103.470

Table 5-14: Optimised Parameters from Automatic Calibration - Badalgama

Method	Parameter	Unit	Initial	Automatic Optimized
Baseflow - Recession	Initial Discharge	m^3/s	2.000	3.403
	Ratio to Peak		0.085	0.421
	Recession Constant		0.995	0.857
Transform - SCS Unit Hydrograph	Lag Time	min	997.610	999.960
Canopy - Simple Canopy	Initial Storage	%	0.560	0.502
	Max Storage	mm	25.000	29.422
Surface - Simple Surface	Initial Storage	%	0.669	0.556
	Max Storage	mm	39.978	39.978
Loss - Deficit and Constant	Deficit and Constant - Constant Rate	mm/hr	0.886	0.775
	Deficit and Constant - Initial Deficit	mm	10.281	10.916
	Deficit and Constant - Maximum Deficit	mm	33.669	32.573

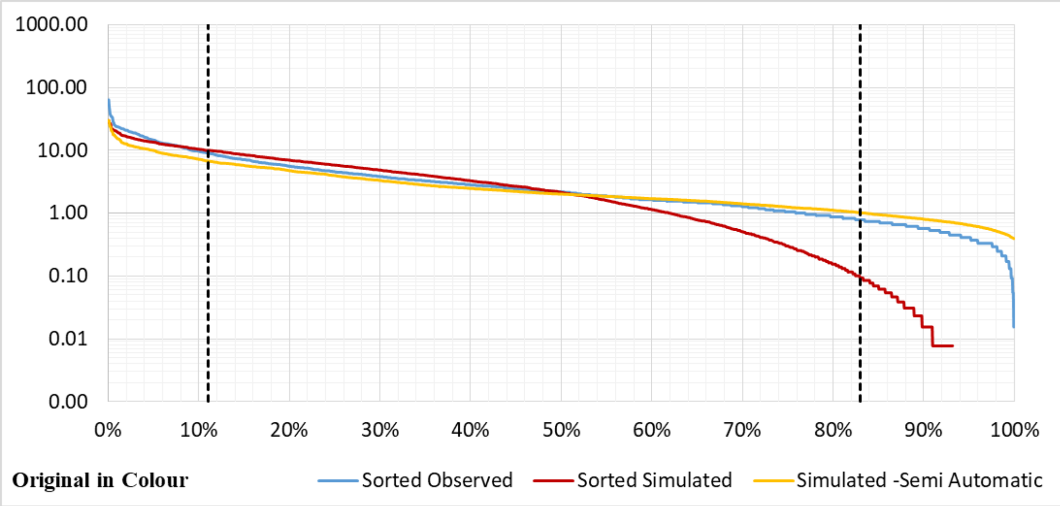


Figure 5-30: Sorted FDC for automatic calibration – Giriulla

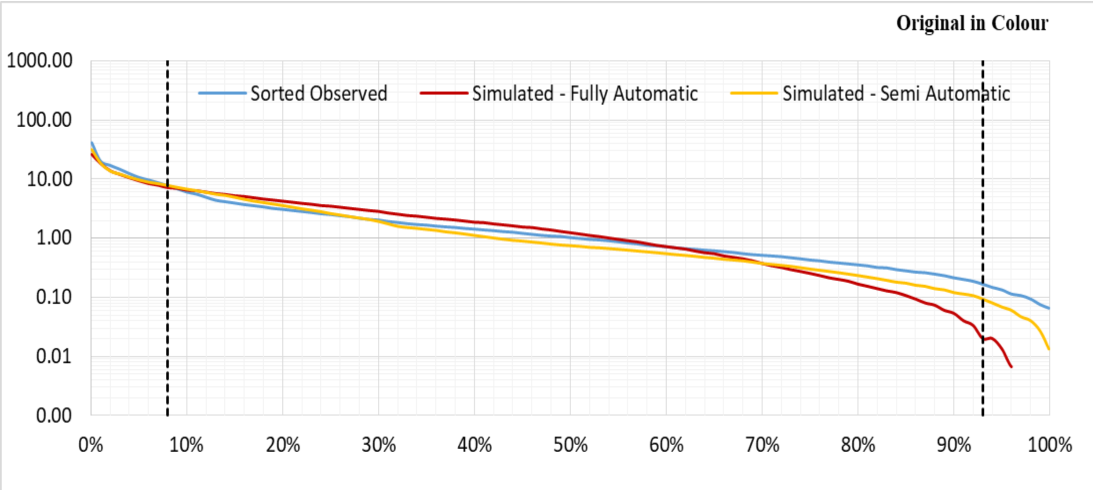


Figure 5-31: Sorted FDC for automatic calibration – Badalgama

Table 5-15: Performance Indicators of Automatic Calibration - Giriulla

Gauging Station	RMSE (mm/day)	MRAE	Flow Duration Curve					
			High		Medium		Low	
			RMSE (mm/day)	MRAE	RMSE (mm/day)	MRAE	RMSE (mm/day)	MRAE
Giriulla (Sorted)	1.17	0.41	3.13	0.11	0.84	0.33	0.22	0.98
Giriulla (Unsorted)	3.39	0.74	3.17	0.56	3.53	0.76	7.21	0.74

Table 5-16: Performance Indicators of Automatic Calibration - Badalgama

Gauging Station	RMSE (mm/day)	MRAE	Flow Duration Curve					
			High		Medium		Low	
			RMSE (mm/day)	MRAE	RMSE (mm/day)	MRAE	RMSE (mm/day)	MRAE
Badalgama (Sorted)	1.38	0.36	4.34	0.15	0.62	0.30	0.02	0.84
Badalgama (Unsorted)	2.52	0.75	2.42	0.59	2.65	0.77	2.95	0.78

5.14 Model parameter Transferability

To facilitate the water resources management activities, it is very important to determine the applicability of the transferability of model parameters from the main catchment area to the sub-catchment area (Badalgama catchment to Giriulla catchment) and vice versa.

In this study, parameter transferability was evaluated under three different schemes of transferability, such as temporal transferability, spatial transferability and spatiotemporal transferability, which were comprehensively discussed in section 2.4. In addition to that, transferability was checked for whole periods, in which two models were calibrated and validated, as Giriulla catchment was checked for 2000/2001 to 2009/2010 with Badalgama parameters and Badalgama catchment was checked for the 2005/2006 to 2018/2019 with Giriulla parameters. The results of the said evaluation are demonstrated in the following subsections.

5.14.1 Temporal Transferability at Giriulla watershed

To investigate the temporal transferability of hydrological parameters in Giriulla catchment, optimized parameters were applied for the period of 2000/2001 to 2003/2004 and results were illustrated in the following subsections.

5.14.1.1 Statistical performance of temporal transferability

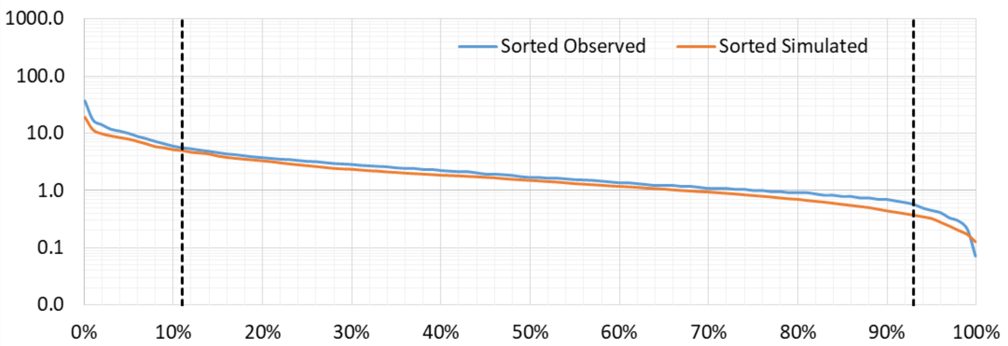
Statistical performance of temporal transferability at Giriulla watershed is numerically shown in Table 5-17 for Giriulla.

Table 5-17: Statistical Performance of Temporal Transferability - Giriulla

Gauging Station	RMSE (mm/day)	MRAE	Flow Duration Curve					
			High		Medium		Low	
			RMSE (mm/day)	MRAE	RMSE (mm/day)	MRAE	RMSE (mm/day)	MRAE
Giriulla (Sorted)	1.45	0.18	4.84	0.24	0.37	0.15	0.17	0.31
Giriulla (Unsorted)	2.34	0.38	3.47	0.38	2.26	0.38	3.34	0.33

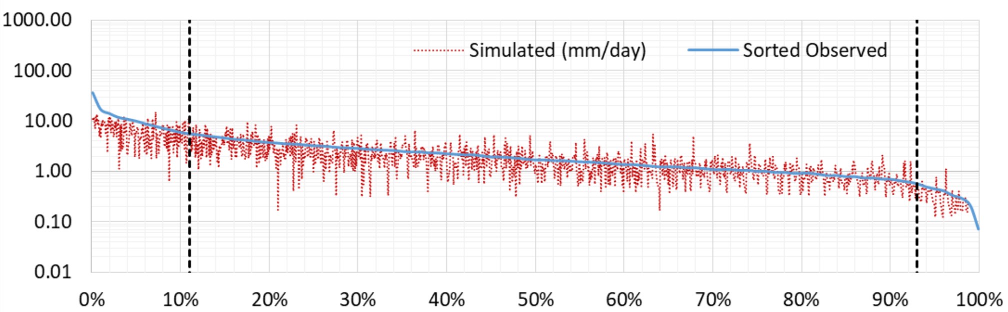
5.14.1.2 Comparison of flow duration curves

Results from Figure 5-32 and Figure 5-33 illustrate the sorted and unsorted flow duration curves by showing the agreement between measured and modeled flows for the entire flow spectrum, including high flows, medium flows and low flows.



Original in Colour

Figure 5-32: Sorted FDC for temporal transferability – Giriulla



Original in Colour

Figure 5-33: Unsorted FDC for temporal transferability – Giriulla

5.14.1.3 Comparison between measured and modeled flow hydrographs

The Figure 5-34 illustrates the simulated and measured flow hydrographs of temporal transferability results at Giriulla watershed.

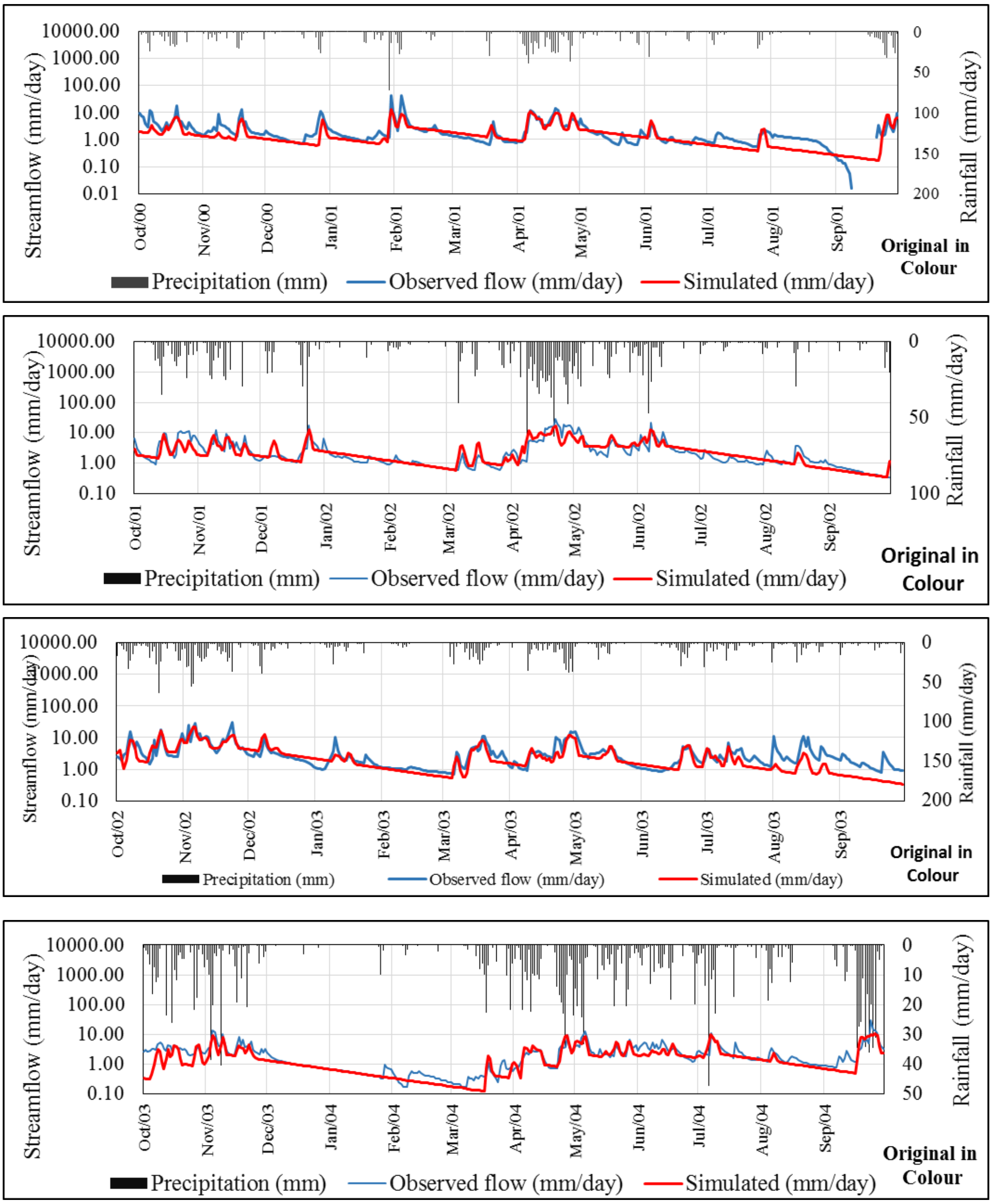


Figure 5-34: Comparison of simulated and observed flow hydrograph - Giriulla

5.14.1.4 Error in Annual and Seasonal Water Balance

Error in annual water balance illustrates in Table 5-18 and the water balance in annually and seasonally are represented graphically in the bar chart in Figure 5-35, Figure 5-36 and Figure 5-37 correspondingly.

Table 5-18: Annual water balance error for temporal transferability at Giriulla

Water Year	RF (mm)	Observed SF (mm)	sim. SF (mm)	Pan Evpo. (mm)	AWB for Observed	AWB for Cal.	AWB Error
2000/01	1487.1	902.1	656.9	1,280.7	584.9	830.2	-27%
2001/02	1928.5	1118.0	978.8	1,311.5	810.5	949.7	-12%
2002/03	2138.8	1304.4	1035.5	1,148.6	834.5	1103.4	-21%
2003/04	1698.6	869.1	696.3	1,331.9	829.5	1002.3	-20%
Avg	**1813.2**	**1048.4**	**841.8**	**1268.2**	**764.8**	**971.4**	**-20%**

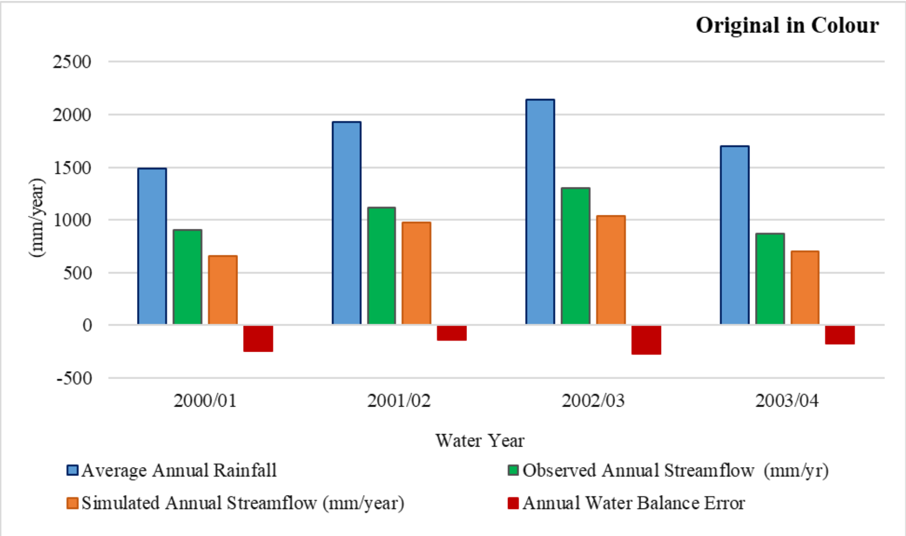


Figure 5-35: Annual water Balance error for temporal transferability – Giriulla

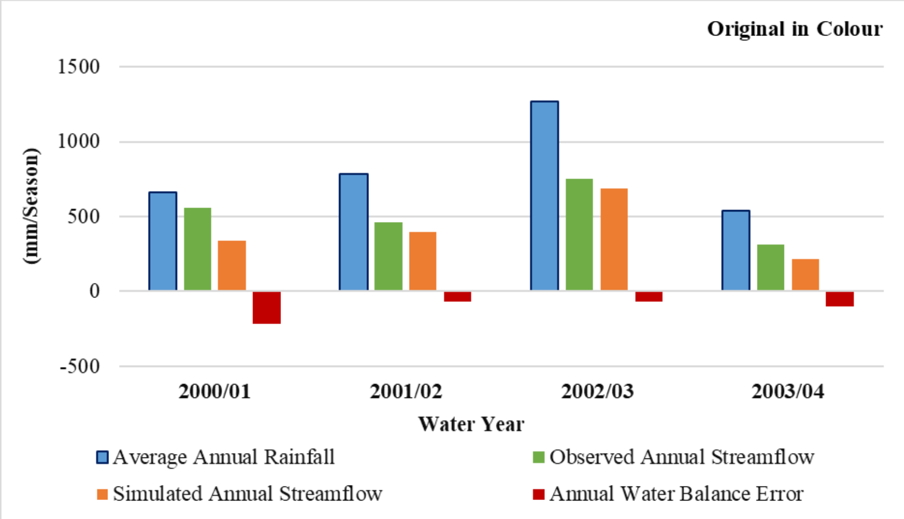


Figure 5-36: Seasonal (Maha) water balance error for temporal transferability – Giriulla

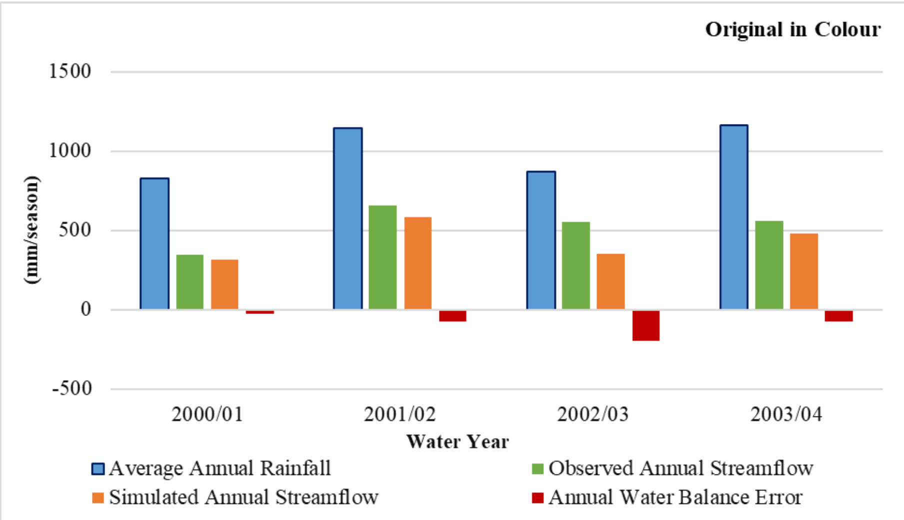


Figure 5-37: Seasonal (Yala) water balance error for temporal transferability – Giriulla

5.14.2 Temporal Transferability at Badalgama watershed

Similarly, for Badalgama watershed, temporal transferability was investigated with the optimized parameters at Giriulla for the period of 2014/2015 to 2018/2019. Accordingly, performance evaluation was conducted and results are illustrated as below.

5.14.2.1 Statistical performance of temporal transferability

In Table 5-19 statistical performance of temporal transferability at Badalgama was shown.

Table 5-19: Statistical Performance of Temporal Transferability - Badalgama

Gauging Station	RMSE (mm/day)	MRAE	Flow Duration Curve					
			High		Medium		Low	
			RMSE (mm/day)	MRAE	RMSE (mm/day)	MRAE	RMSE (mm/day)	MRAE
Badalgama (Sorted)	1.50	0.19	4.79	0.11	0.61	0.16	0.001	0.40
Badalgama (Unsorted)	4.19	1.56	6.48	0.88	4.09	1.77	5.53	0.73

5.14.2.2 Comparison of flow duration curves

Sorted (Figure 5-38) and unsorted (Figure 5-39) flow duration curves at Badalgama, show the comparison of performance of low, medium and high flows.

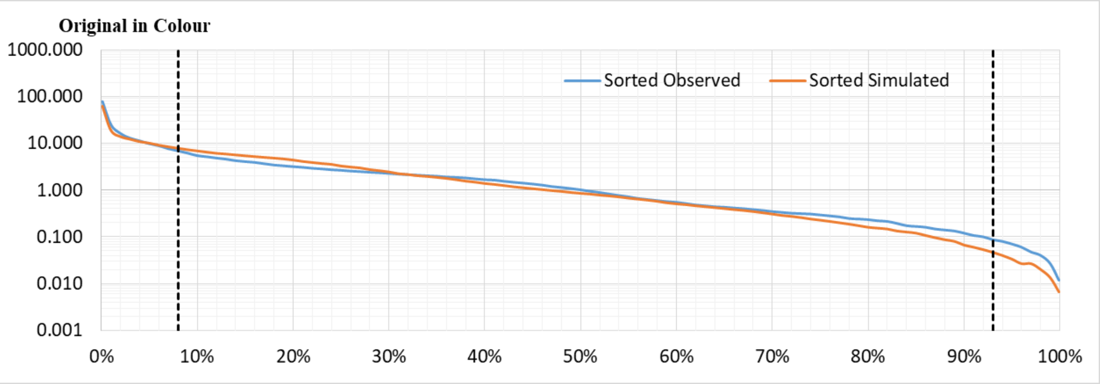


Figure 5-38: Sorted flow duration curve for temporal transferability – Badalgma

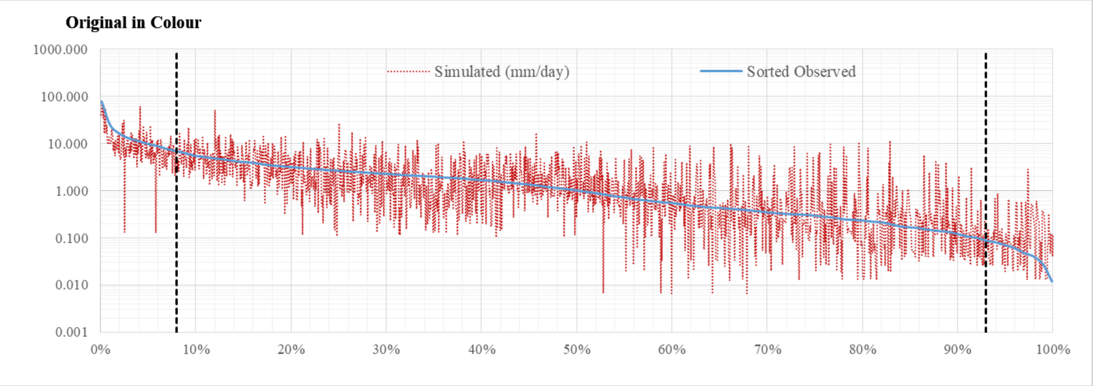


Figure 5-39: Unsorted flow duration curve for temporal transferability – Badalgma

5.14.2.3 Comparison between measured and modelled flow hydrographs

The comparison between observed flow hydrographs at Badalgama for the temporal transferability is shown in Figure 5-40.

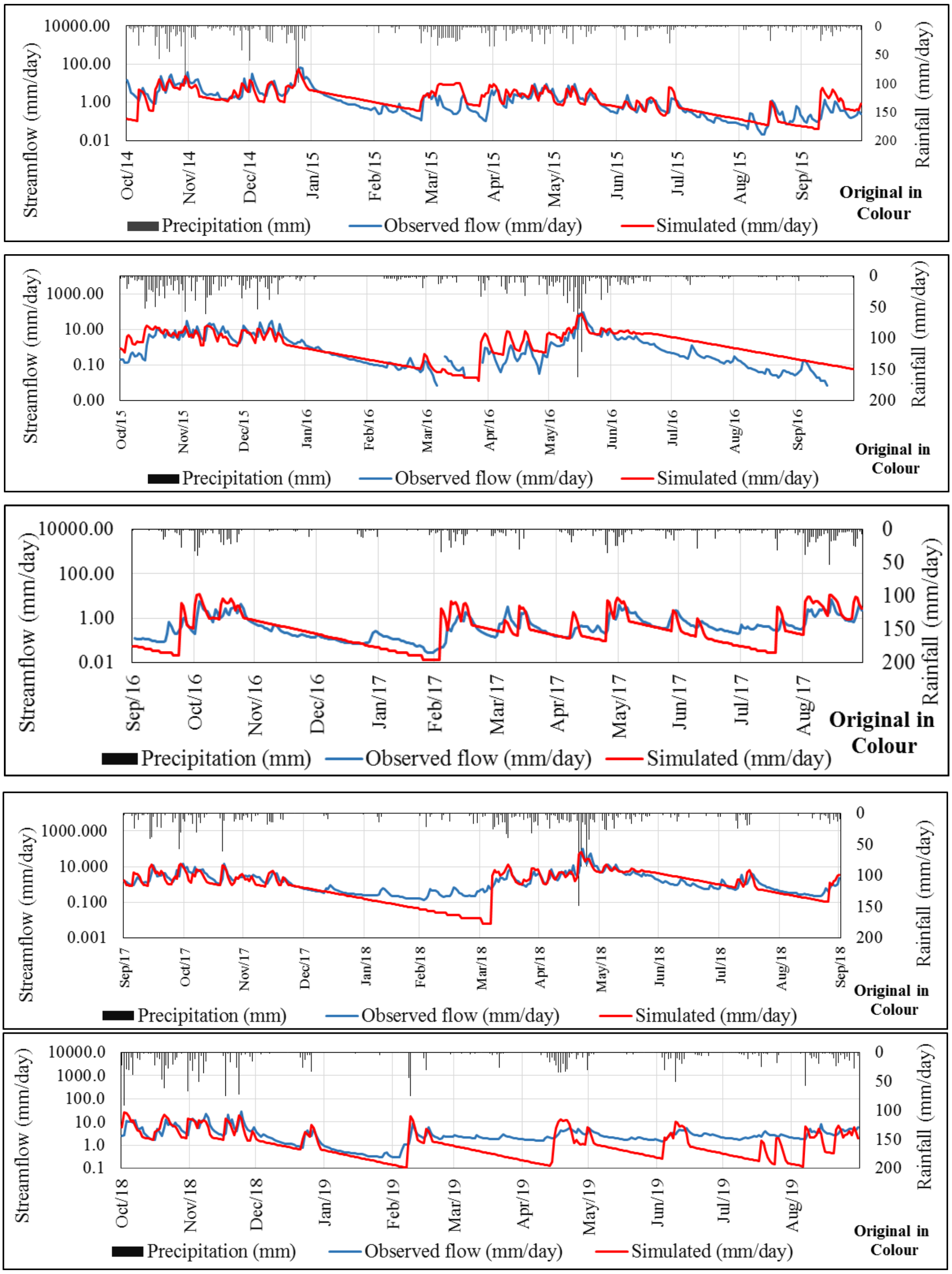


Figure 5-40: Comparison of flow hydrograph of temporal transferability - Badalgama

5.14.2.4 Error in Annual and Seasonal Water Balance

Water balance in annually and seasonally from the temporal transferability at Badalgama is illustrated in Table 5-20 and the annual and the seasonal water balance are represented graphically in the bar chart in Figure 5-41, Figure 5-42 and Figure 5-43.

Table 5-20: Annual water balance error for temporal transferability at Badalgama

Water Year	RF (mm)	Observed SF (mm)	calc. SF (mm)	Pan Evpo. (mm)	AWB for Observed	AWB for Calc.	AWB Error
2014/15	2,671.5	1,119.5	1,612.2	1,282.0	1,552.0	1,612.2	-5%
2015/16	2,594.3	1,183.0	1,262.7	1,361.6	1,411.3	1,262.7	13%
2016/17	1,578.3	254.3	1,147.9	1,243.3	1,323.9	1,147.9	69%
2017/18	2,252.3	1,045.1	1,201.9	1,107.2	1,207.2	1,201.9	1%
2018/19	2,167.9	1,090.7	1,295.1	1,325.0	1,077.2	1,295.1	-20%
Average	**2,252.86**	**938.52**	**1,303.96**	**1,263.82**	**1,314.32**	**1,303.9**	**11%**

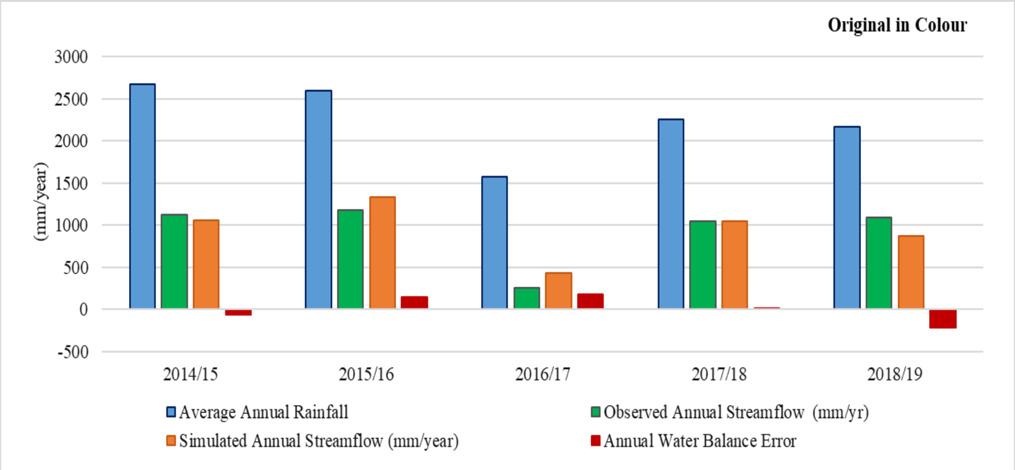


Figure 5-41: Annual water balance error for temporal transferability at Badalgama

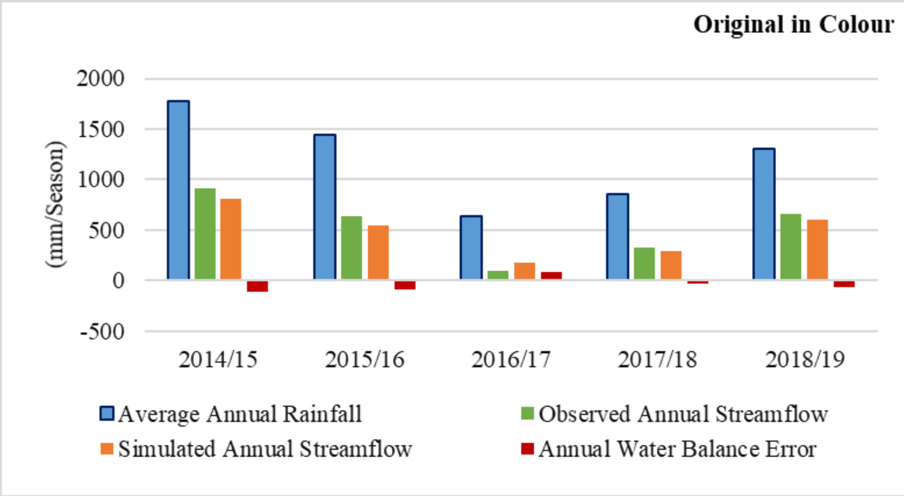


Figure 5-42: Seasonal (Maha) water balance error for temporal transferability at Badalgama

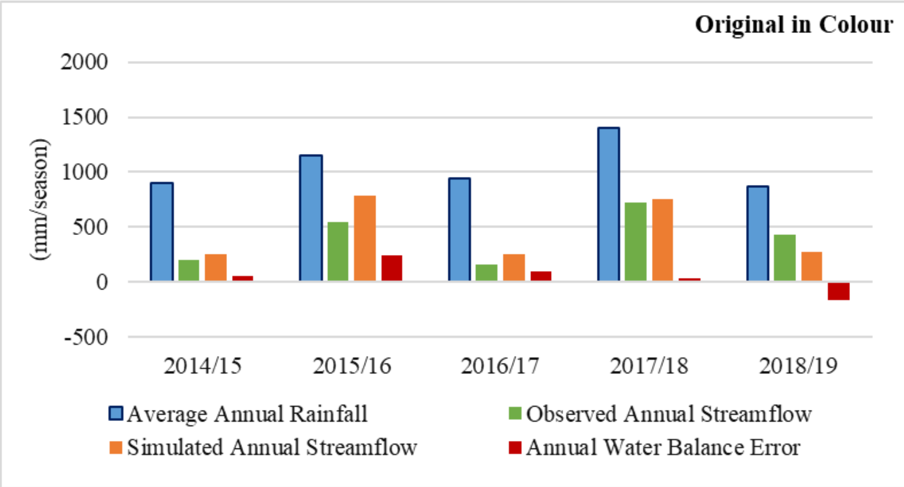


Figure 5-43: Seasonal (Yala) water balance error for temporal transferability at Badalgama

5.14.3 Spatial Transferability at Giriulla Watershed

To perform the investigation of spatial transferability at Giriulla, optimized parameters at Badalgama watershed were directly applied to the Giriulla watershed for the period of 2005/2006 to 2009/2010. Accordingly, the obtained result is explained in the below sub-sections.

5.14.3.1 Statistical performance of spatial transferability

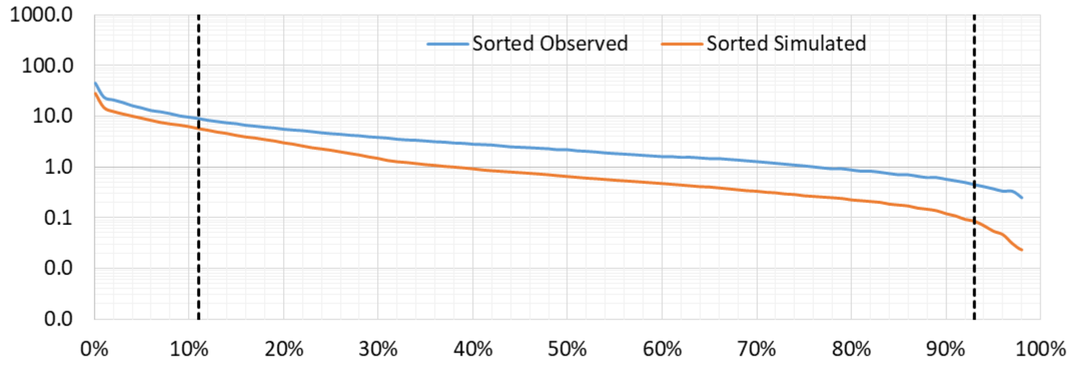
In Table 5-21, model performance was demonstrated statistically to determine the applicability of transferability of model parameter.

Table 5-21: Statistical Performance of Spatial Transferability - Giriulla

Gauging Station	RMSE (mm/day)	MRAE	Flow Duration Curve					
			High		Medium		Low	
			RMSE (mm/day)	MRAE	RMSE (mm/day)	MRAE	RMSE (mm/day)	MRAE
Giriulla (Sorted)	2.54	0.64	6.71	0.38	1.89	0.64	0.15	0.82
Giriulla (Unsorted)	4.40	0.74	4.75	0.75	4.52	0.72	11.64	0.79

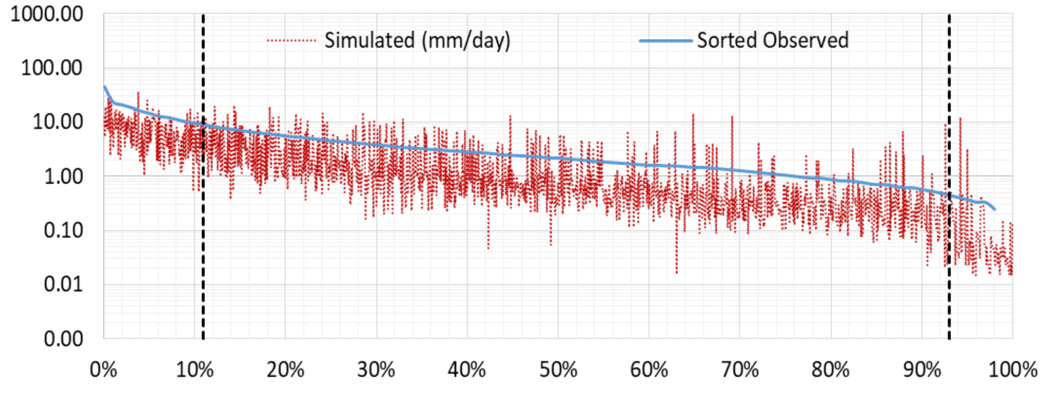
5.14.3.2 Comparison of flow duration curves

The sorted and unsorted flow duration curves graphically illustrate the behavior of high medium and low flow performance in Figure 5-44 and Figure 5-45 separately.



Original in Colour

Figure 5-44: Sorted FDC curve for spatial transferability - Giriulla



Original in Colour

Figure 5-45: Unsorted FDC curve for Spatial Transferability – Giriulla

5.14.3.3 Comparison between measured and modeled flow hydrographs

Figure 5-46 clearly illustrate the evaluation of measured and modeled flow hydrographs for the spatial transferability at Giriulla.

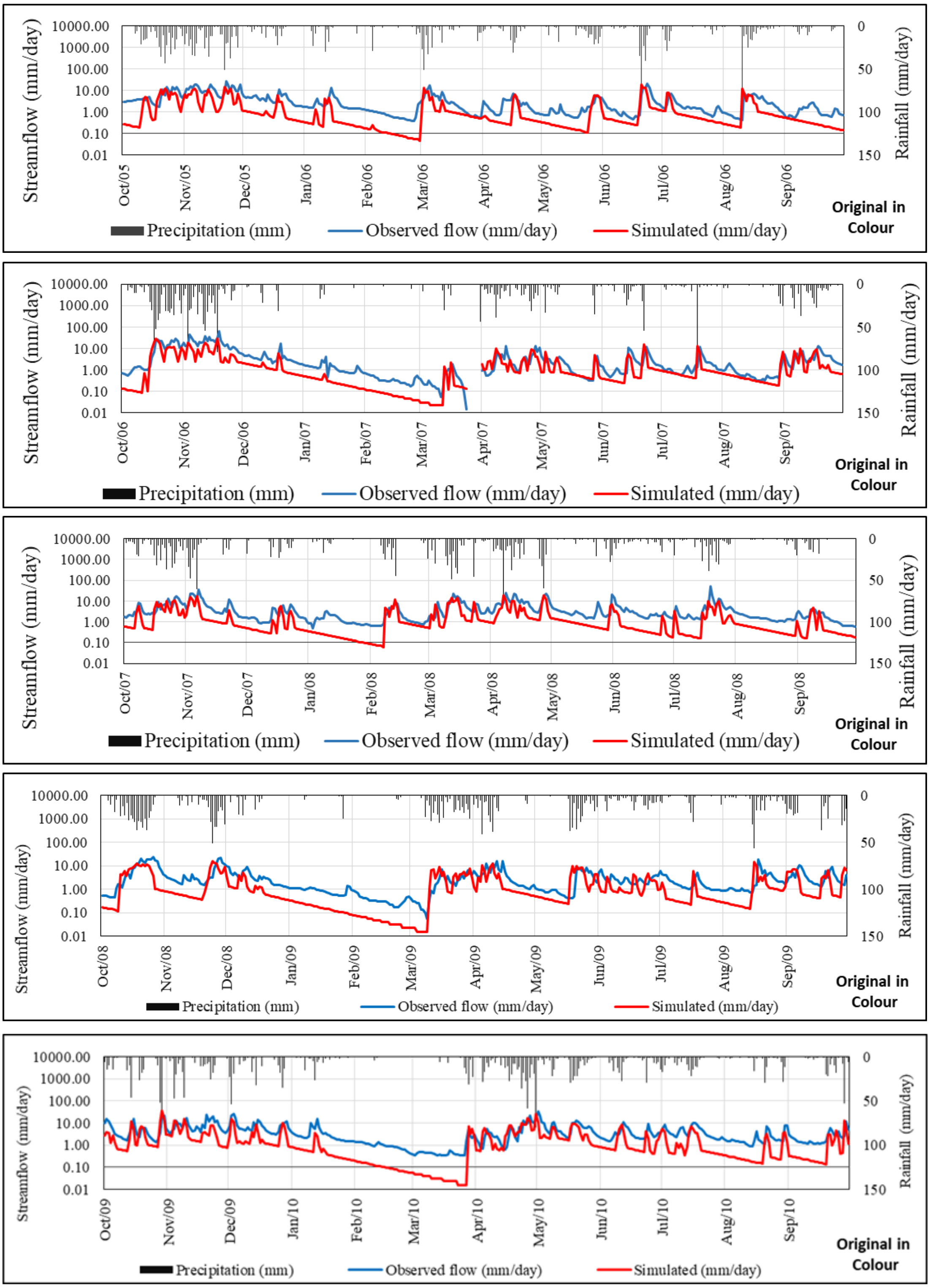


Figure 5-46: Comparison between observed and simulated for spatial transferability – Giriulla

5.14.3.4 Error in Annual and Seasonal Water Balance

The annual and seasonal water balance of spatial transferability is given in Table 5-22 and graphical demonstration in bar chart are given in Figure 5-47, Figure 5-48 and Figure 5-49 correspondingly.

Table 5-22: Annual Water Balance error for Spatial Transferability - Giriulla

Water Year	Annual RF (mm/yr)	Annual Observe SF (mm/yr)	Annual Sim. SF (mm/yr)	Annual Pan Evpo. (mm/yr)	AWB for Observe Data	AWB for Cal.	AWB Error
2005/06	2,117	1,322	640	1,281	796	1,477	-52%
2006/07	2,344	1,572	817	1,312	772	1,527	-48%
2007/08	2,257	1,567	707	1,149	690	1,550	-55%
2008/09	2,349	1,184	724	1,332	1,165	1,625	-39%
2009/10	2,318	1,606	808	1,375	712	1,510	-50%
Average	**2,277**	**1,450**	**739**	**1,289**	**827**	**1,538**	**-49%**

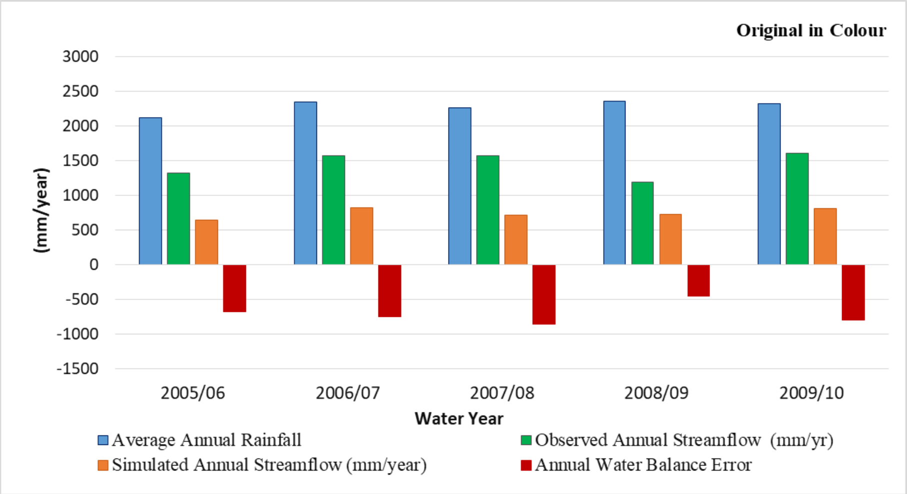


Figure 5-47: Annual Water Balance for spatial Transferability – Giriulla

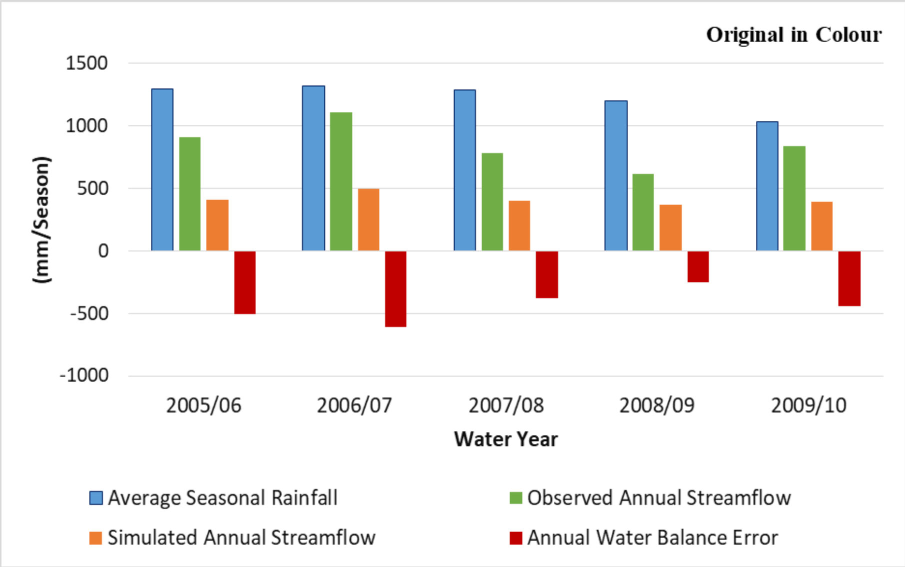


Figure 5-48: Seasonal (Maha) water balance error for spatial transferability - Giriulla

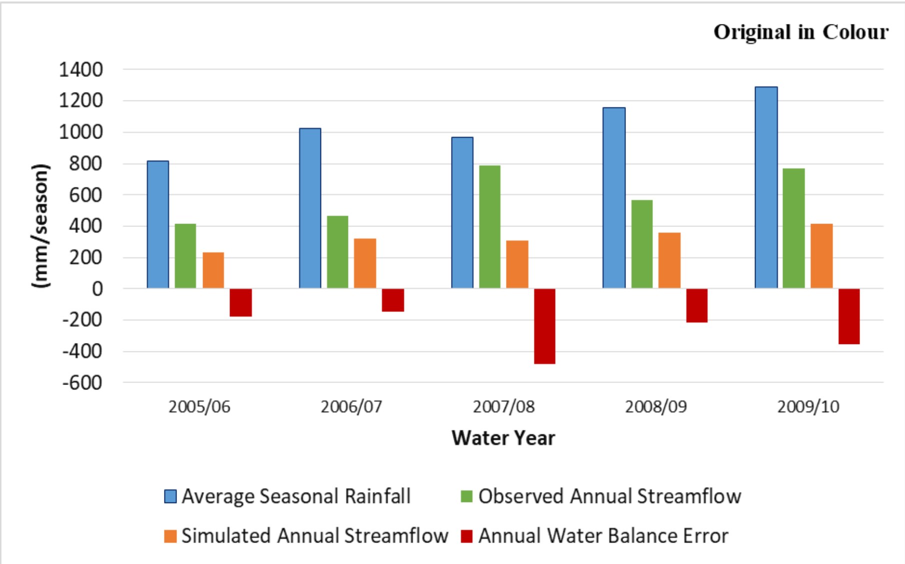


Figure 5-49: Seasonal (Yala) water balance error for spatial transferability - Giriulla

5.14.4 Spatial Transferability at Badalgama Watershed

To evaluate the spatial transferability at Badalgama, optimized parameters at Giriulla were applied to the model developed for Badalgama directly for the period of 2005/2006 to 2009/2010. The results obtained during this analysis was revealed below.

5.14.4.1 Statistical performance of spatial transferability

The statistical performance of the spatial transferability at Badalgama watershed is shown in the Table 5-23. Further, it illustrate the performance of the different flow regimes.

Table 5-23: Statistical Performance of spatial transferability - Badalgama

Gauging Station	RMSE (mm/day)	MRAE	Flow Duration Curve					
			High		Medium		Low	
			RMSE (mm/day)	MRAE	RMSE (mm/day)	MRAE	RMSE (mm/day)	MRAE
Badalgama (Sorted)	1.13	1.06	2.38	0.10	1.01	0.85	0.17	2.70
Badalgama (Unsorted)	2.52	1.73	2.56	1.10	2.58	1.72	4.51	2.16

5.14.4.2 Comparison of flow duration curves

Sorted and unsorted flow duration curves are shown in Figure 5-50 and Figure 5-51, which further illustrated the behavior of different flow spectrum including, high medium and low flows.

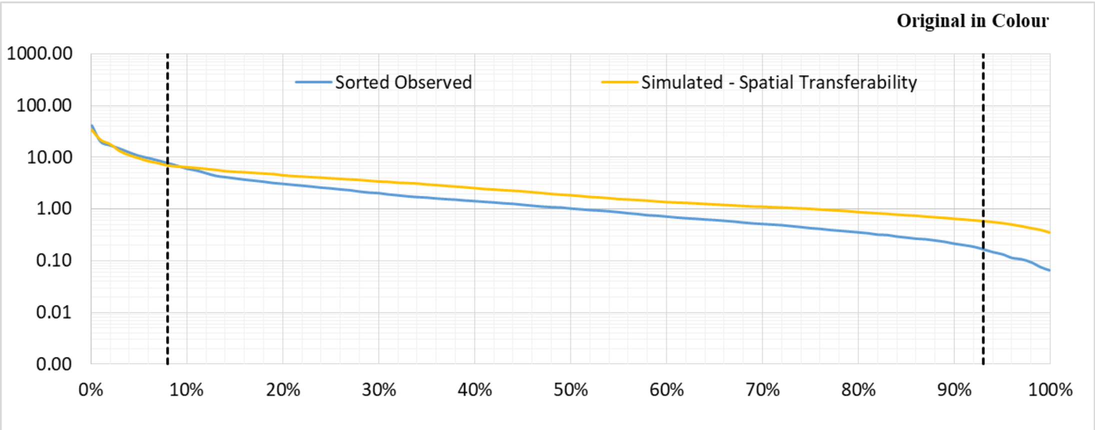


Figure 5-50: Sorted FDC for spatial transferability - Badalgama

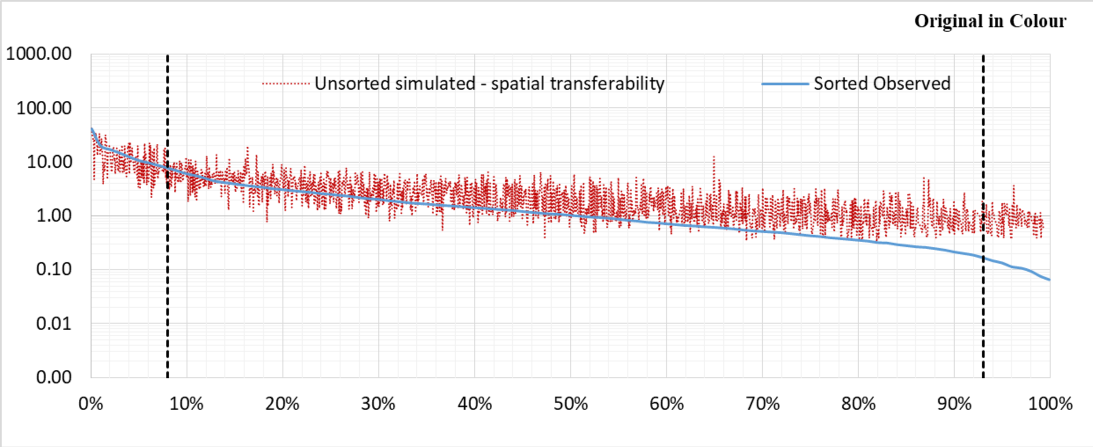
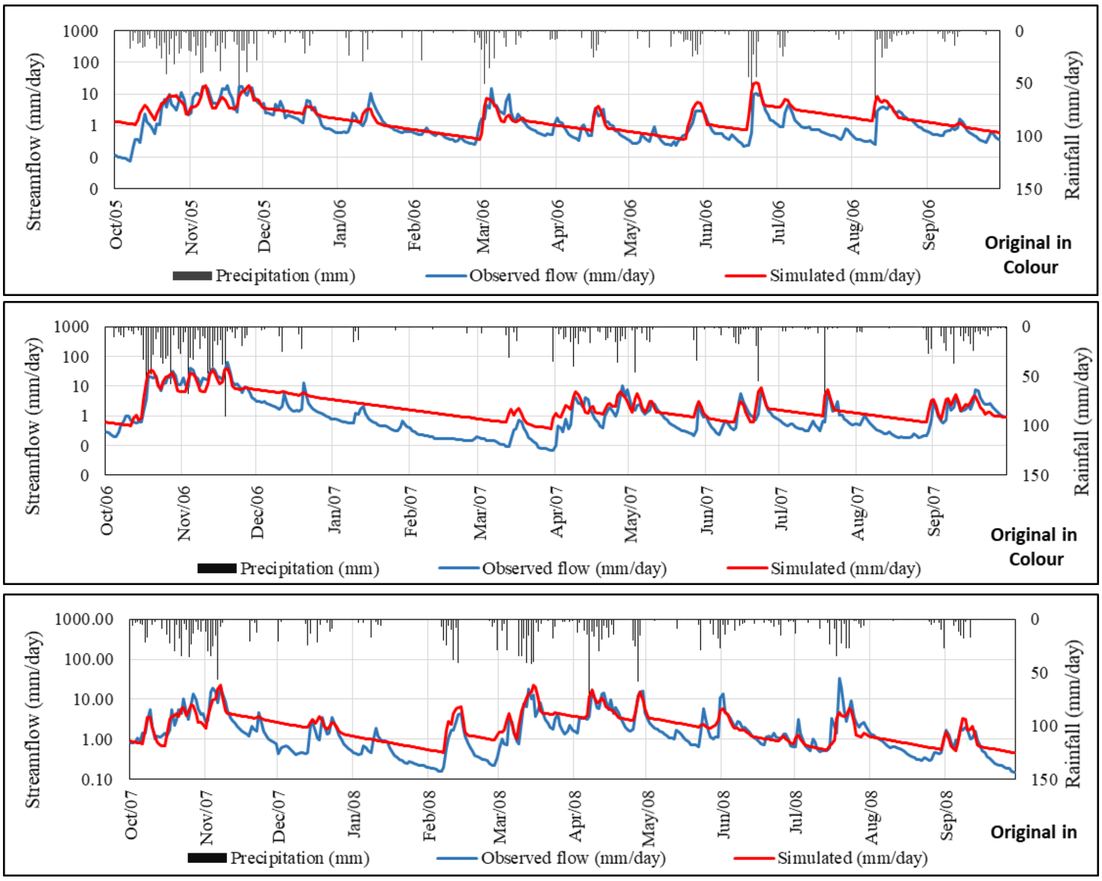


Figure 5-51: Unsorted FDC for spatial transferability – Badalgama

5.14.4.3 Comparison between measured and modeled flow hydrographs

The Figure 5-52 clearly shows the comparison between measured and modeled river flow hydrographs at Badalgama with spatially transferred parameters from Giriulla watershed.



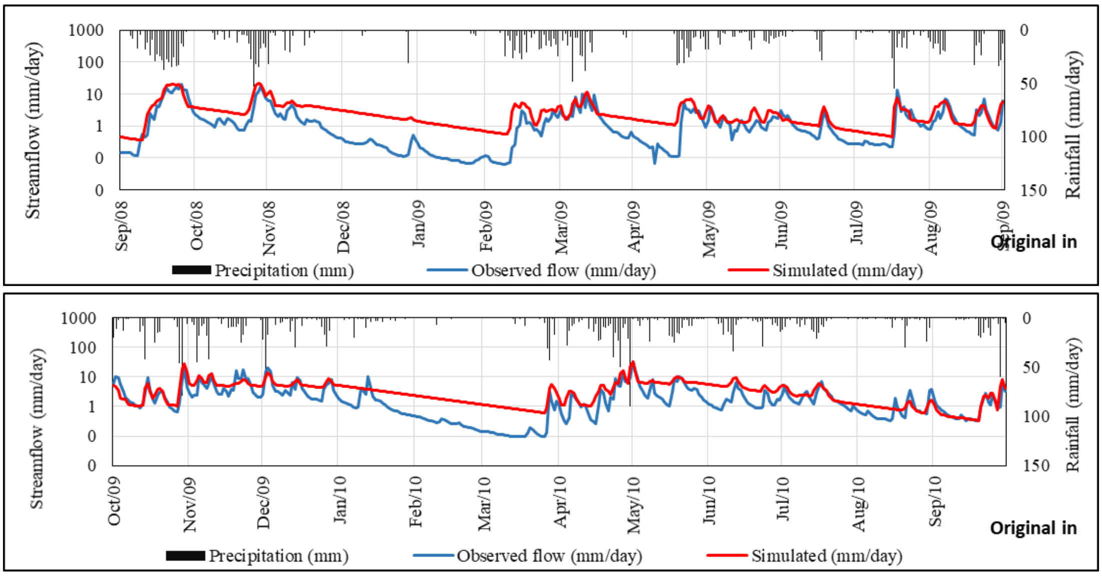


Figure 5-52: Comparison between observed and simulated streamflow for spatial transferability – Badalgama

5.14.4.4 Error in Annual and Seasonal Water Balance

Estimation of annual water balance error for the spatially transferred parameter to Badalgama catchment with optimized model parameter at Giriulla catchment is shown in Table 5-24 with equivalent graphical illustration in Figure 5-53. The minimum annual water balance error is recorded for water year 2007/2008 as 10%. Further, Seasonal water balance for Maha and Yala seasons are shown in Figure 5-54 and Figure 5-55 respectively.

Table 5-24: Annual water Balance for the spatial transferability - Badalgama

Water Year	RF (mm/yr)	Observed SF (mm/yr)	Sim. SF (mm/yr)	Pan Evpo. (mm/yr)	AWB for Observed Data	AWB for simulated data	AWB Error
2005/06	2,122	823	958	1,281	1,298	1,164	16%
2006/07	2,406	1,209	1,392	1,312	1,197	1,015	15%
2007/08	2,144	924	1,013	1,149	1,220	1,131	10%
2008/09	2,361	679	1,105	1,332	1,682	1,256	63%
2009/10	2,189	943	1,395	1,375	1,246	794	48%
Average	**2,244**	**916**	**1,173**	**1,289**	**1,329**	**1,072**	**30%**

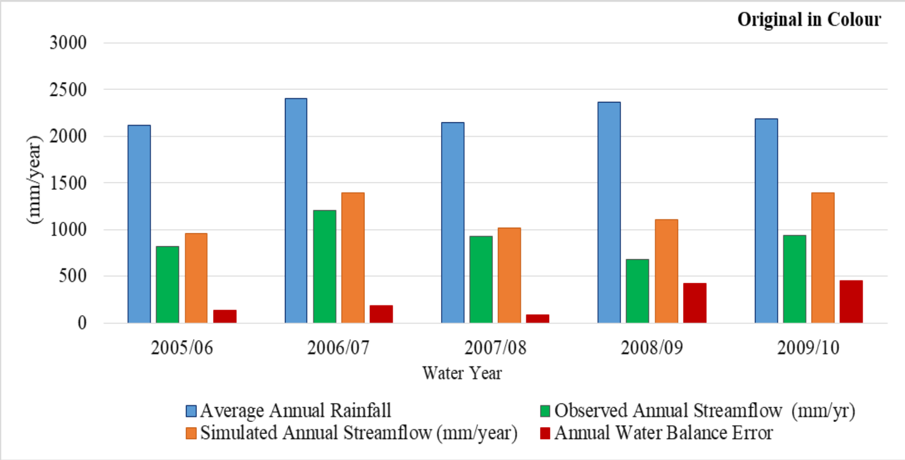


Figure 5-53: Annual water Balance for the spatial transferability – Badalgama

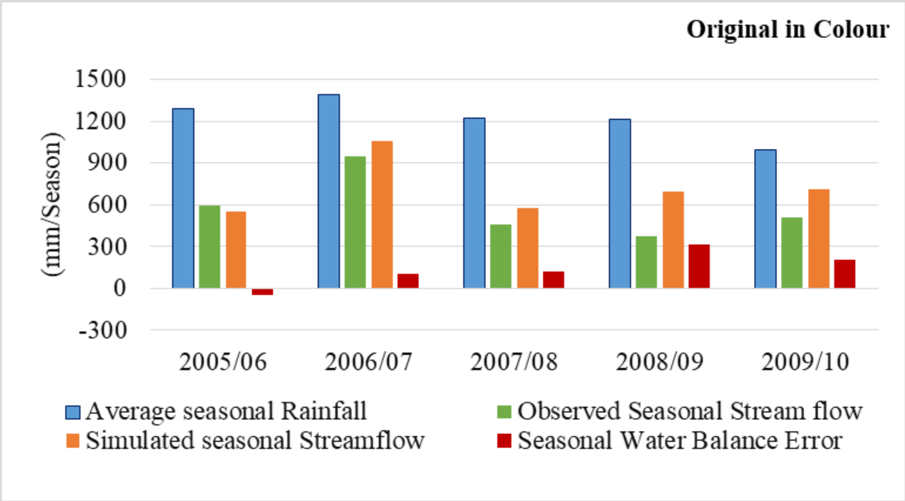


Figure 5-54: Seasonal (Maha) Water Balance for the spatial transferability – Badalgama

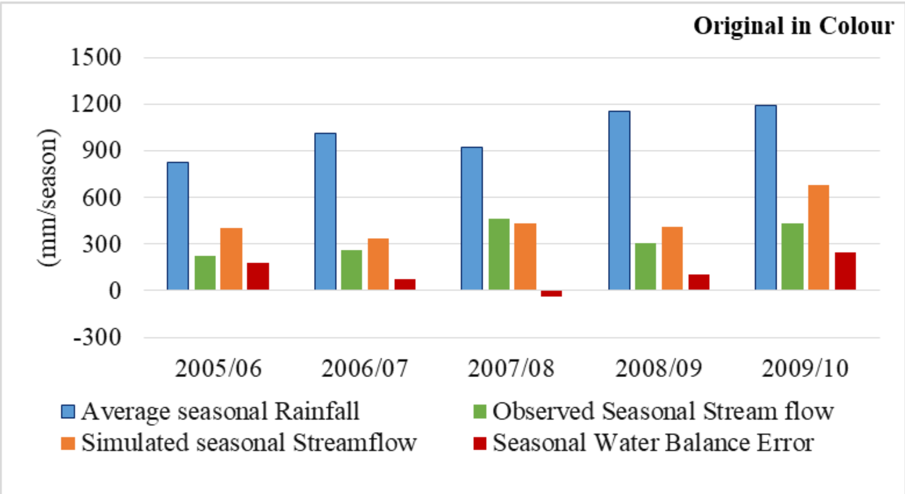


Figure 5-55: Seasonal (Yala) water Balance for the Spatial Transferability – Badalgama

5.14.5 Spatiotemporal Transferability at Giriulla Watershed

Spatiotemporal transferability of the model parameter is another method, which has been used in this study. Accordingly, to investigate the applicability of this method, was carried out by directly applying optimized parameters of Badalgama catchment to the spatially and temporally (2000/2001 to 2003/2004) different data set for Giriulla watershed. The corresponding results have been detailed in the flowing sub-sections for the clarity.

5.14.5.1 Statistical performance

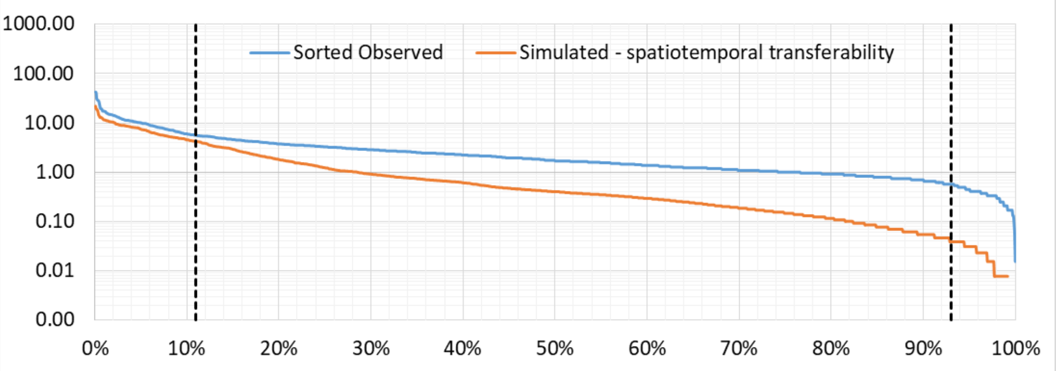
Numerical measures of model performance for spatiotemporal transferability at Giriulla is given in Table 5-25 as shown below. Accordingly, it shows that, MRAE and RMSE for the overall period of sorted series are 0.7 and 1.92 mm/day.

Table 5-25: Statistical model performance for Spatiotemporal transferability - Giriulla

Gauging Station	RMSE (mm/day)	MRAE	Flow Duration Curve					
			High		Medium		Low	
			RMSE (mm/day)	MRAE	RMSE (mm/day)	MRAE	RMSE (mm/day)	MRAE
Giriulla (Sorted)	1.92	0.70	4.24	0.27	1.41	0.74	0.37	0.95
Giriulla (Unsorted)	3.16	0.79	4.71	0.81	2.86	0.78	9.64	0.82

5.14.5.2 Comparison of flow duration curves of

The sorted and unsorted FDC for the spatiotemporal transferability at Giriulla is illustrated in Figure 5-56 and Figure 5-57.



Original in Colour

Figure 5-56: Sorted FDC curve for spatiotemporal transferability - Giriulla

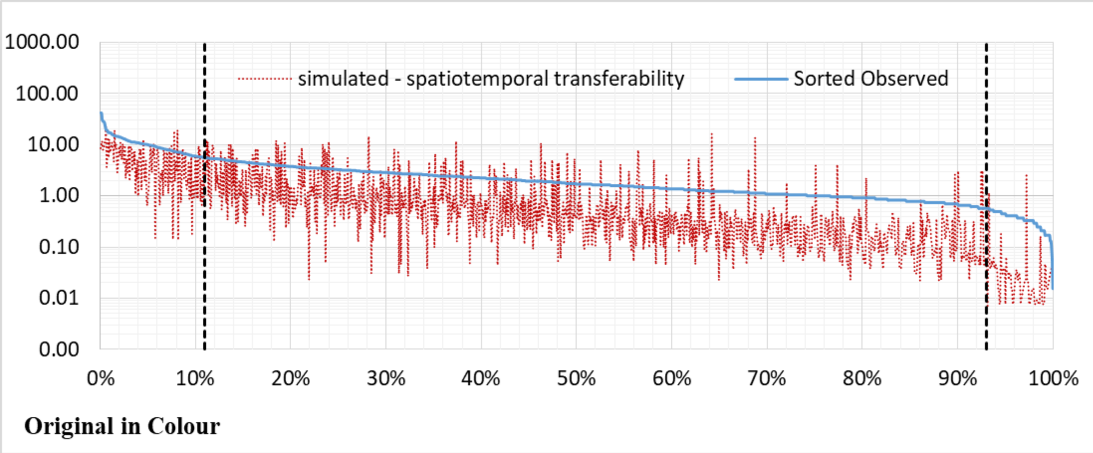
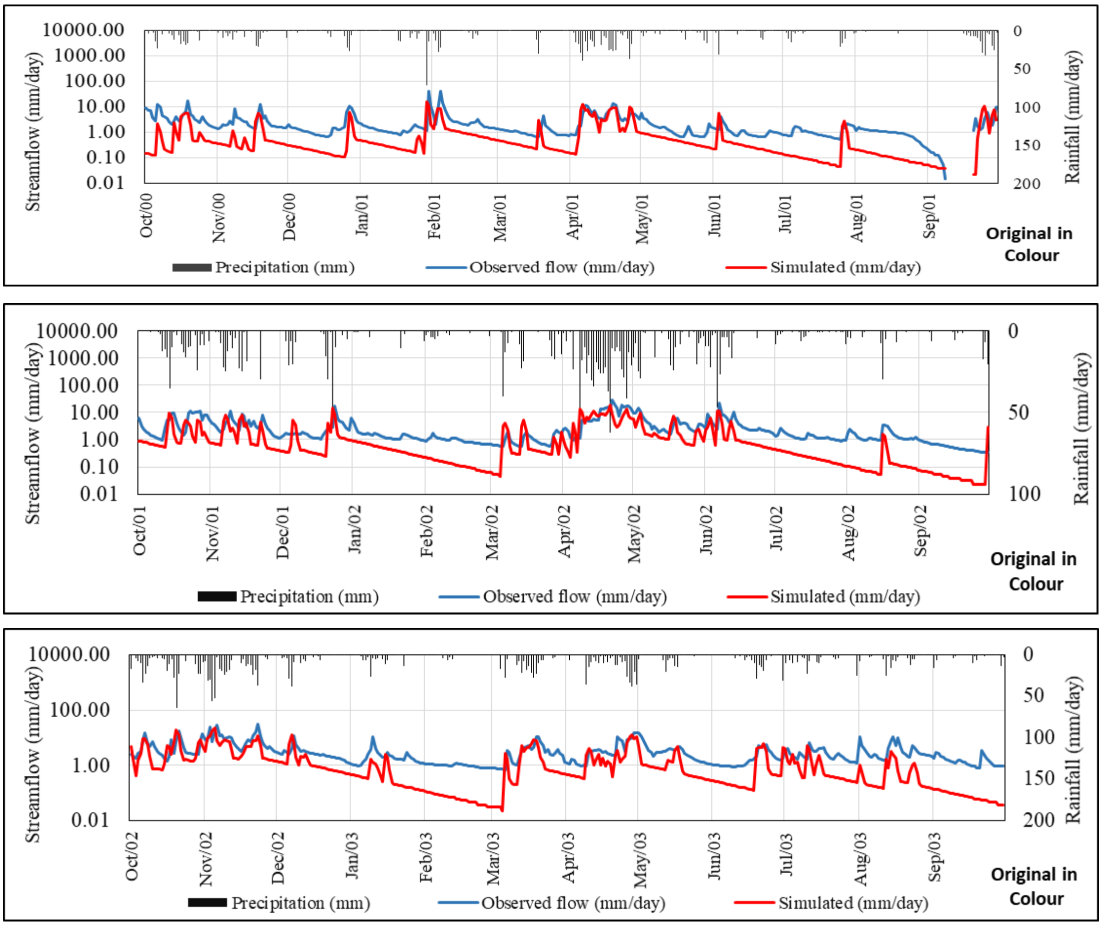


Figure 5-57: Un-sorted FDC curve for spatiotemporal transferability – Giriulla

5.14.5.3 Comparison between measured and modeled flow hydrographs

The Figure 5-58 showed the comparison between observed flow hydrograph and the modeled flow hydrograph for the spatiotemporal transferability at Giriulla with parameters optimized to the Badalgama catchment.



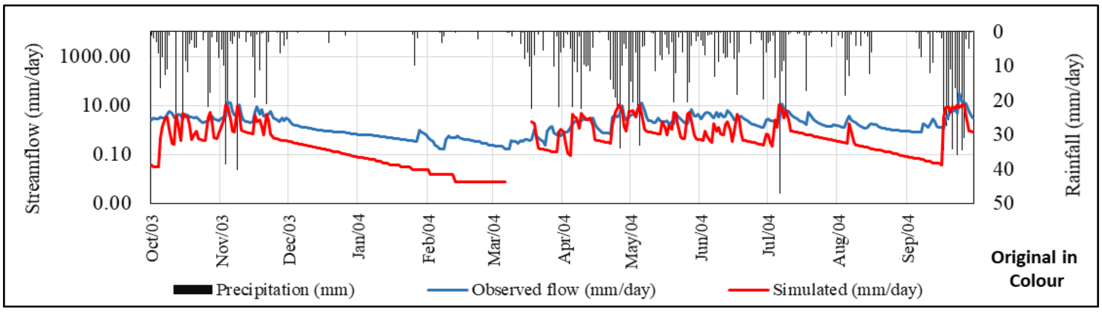


Figure 5-58: Comparison between observed and simulated streamflow for spatiotemporal transferability – Giriulla

5.14.5.4 Error in Annual and Seasonal Water Balance

Error in annual water balance for the spatiotemporal transferability at Giriulla is further given in Table 5-26 and Figure 5-59, while seasonal variation illustrated in Figure 5-60 and Figure 5-61.

Table 5-26: Annual water Balance for the Spatiotemporal transferability - Giriulla

Water Year	RF (mm/yr)	Observed SF (mm/yr)	Sim. SF (mm/yr)	Pan Evpo. (mm/yr)	AWB for Observed Data	AWB for Cal.	AWB Error
2000/2001	285	901	396	1,281	-616	-111	-56%
2001/2002	453	1,118	586	1,312	-665	-133	-48%
2002/2003	494	1,304	647	1,149	-810	-153	-50%
2003/2004	365	869	447	1,332	-504	-82	-49%
Average	**399**	**1,048**	**519**	**1,268**	**-649**	**-120**	**-51%**

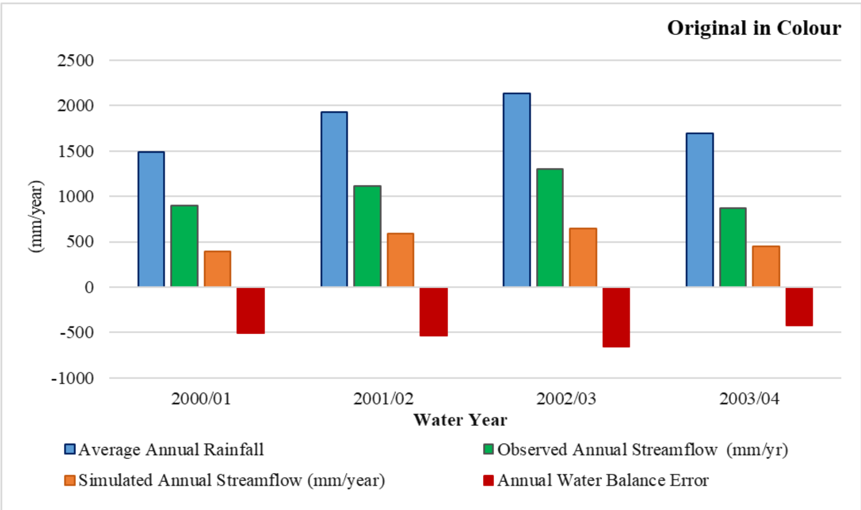


Figure 5-59: Annual water balance error for spatiotemporal transferability - Giriulla

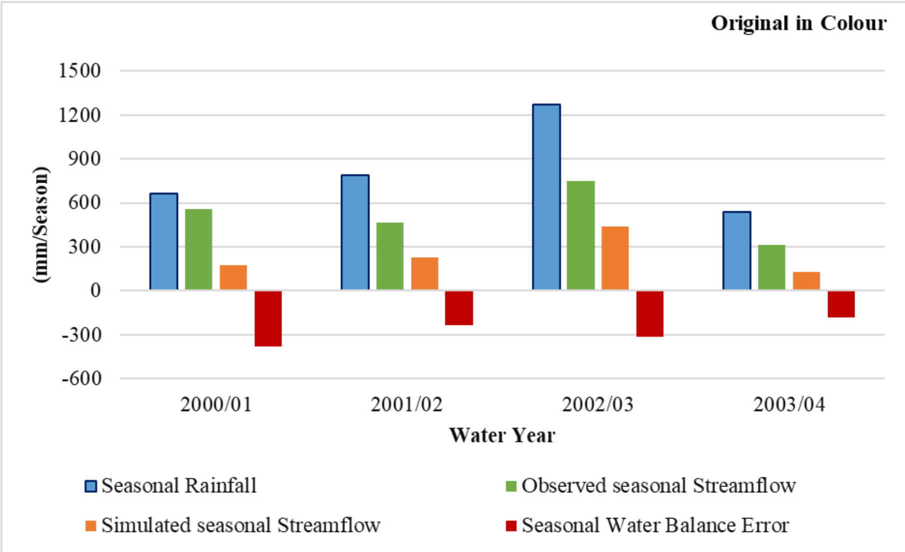


Figure 5-60: Seasonal (Maha) water balance error for spatiotemporal transferability – Giriulla

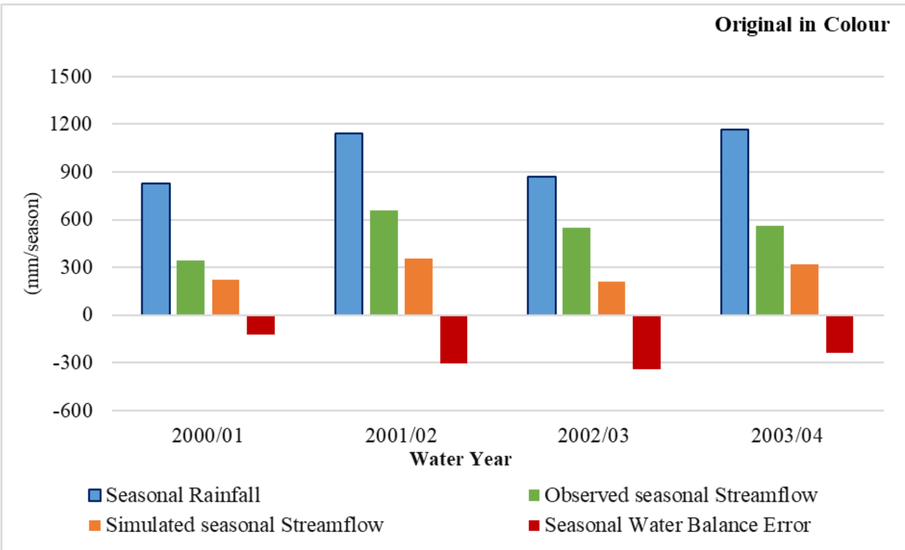


Figure 5-61: Seasonal (Yala) water balance error for spatiotemporal transferability - Giriulla

5.14.6 Spatiotemporal Transferability at Badalgama Watershed

As elaborated in section 5.14.5, spatiotemporal transferability has been investigated for the Badalgama watershed as well, by applying optimized parameters of Giriulla to Badalgama for the period of 2014/2015 to 2018/2019. The corresponding results have been comprehensively presented in the flowing sub-sections for the clarity.

5.14.6.1 Statistical performance

The performance of spatiotemporal transferability is numerically illustrated in Table 5-27 for the Badalgama watershed.

Table 5-27: Statistical performance of spatiotemporal transferability - Badalgama

Gauging Station	RMSE (mm/day)	MRAE	Flow Duration Curve					
			High		Medium		Low	
			RMSE (mm/day)	MRAE	RMSE (mm/day)	MRAE	RMSE (mm/day)	MRAE
Badalgama (Sorted)	2.01	1.59	4.26	0.28	1.78	1.48	0.04	4.14
Badalgama (Unsorted)	3.90	4.54	5.50	2.60	3.86	5.08	3.83	0.44

5.14.6.2 Comparison of flow duration curves

The following sorted (Figure 5-62) and unsorted (Figure 5-63) flow duration curves explained the behavior of all flow regimes for spatiotemporal transferability.

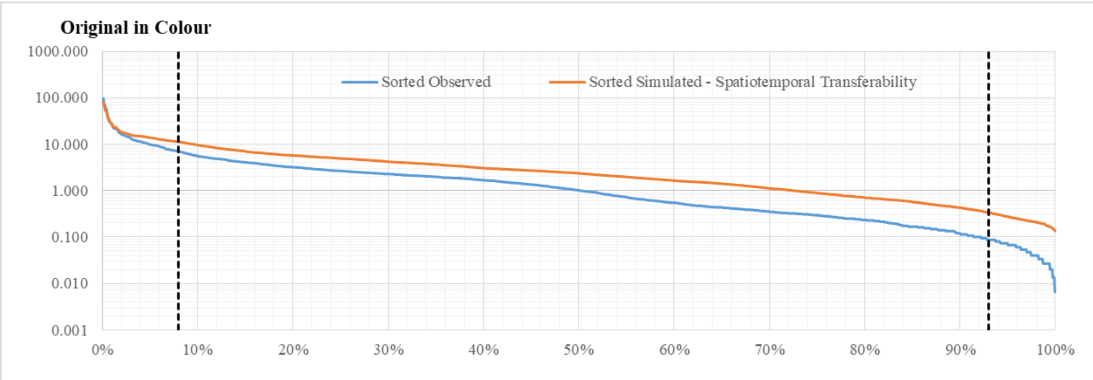


Figure 5-62: Sorted FDC curve for the spatiotemporal transferability – Badalgama

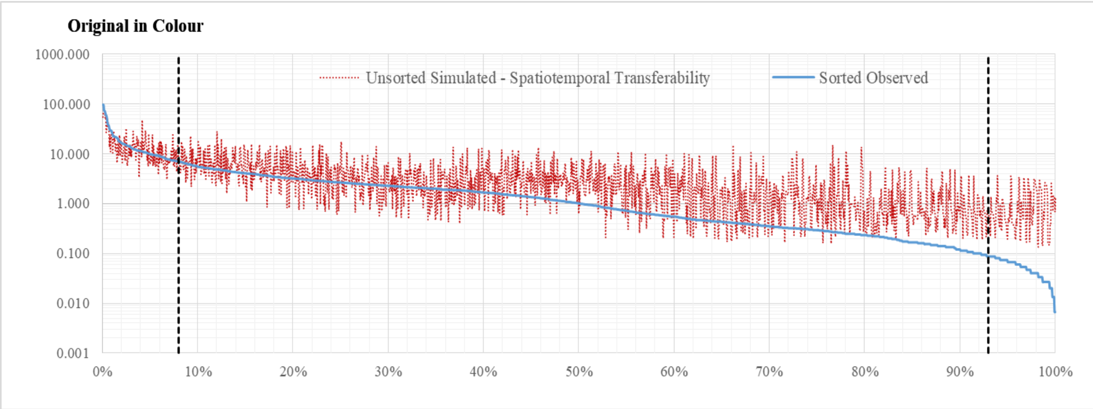
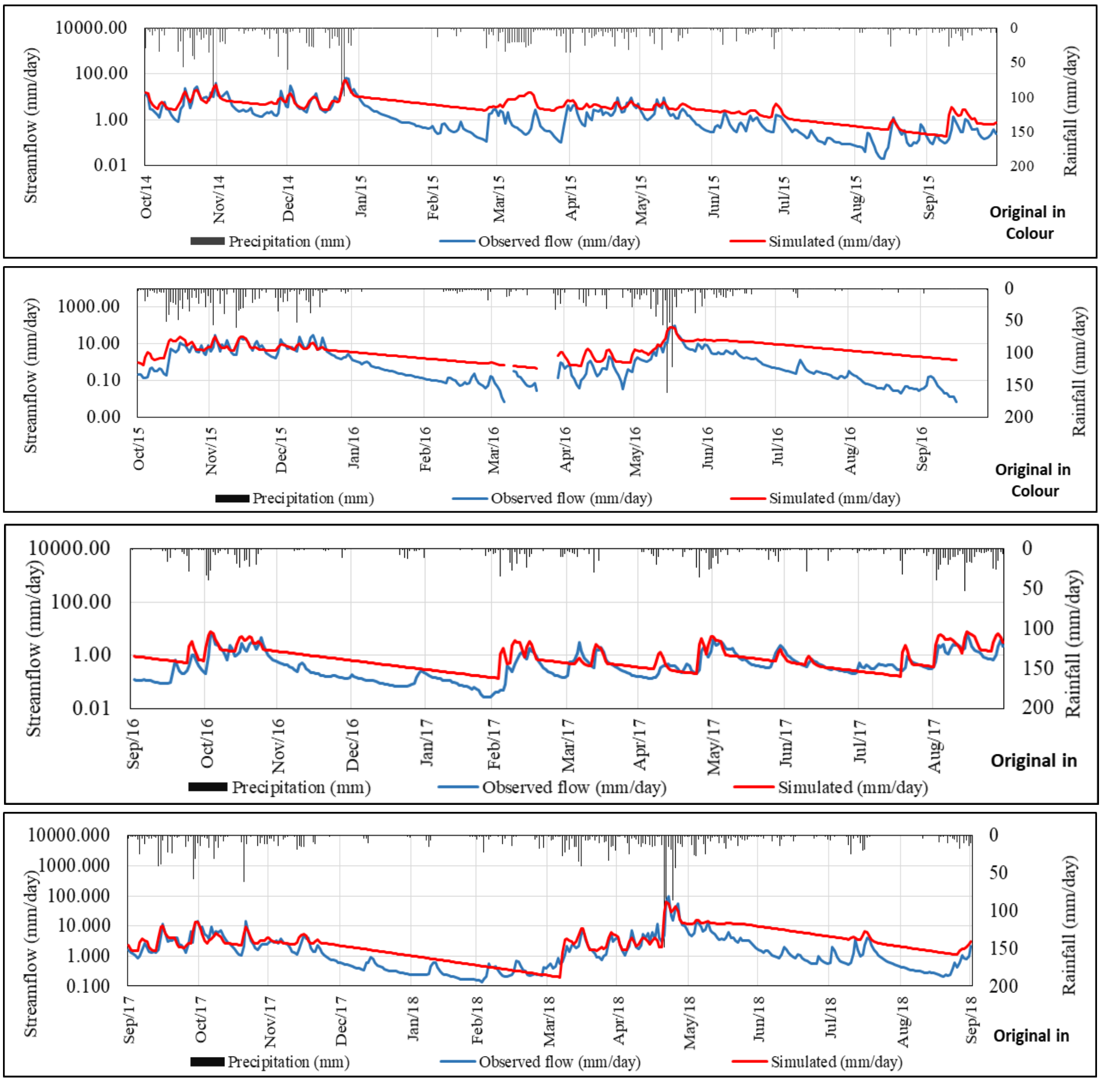


Figure 5-63: Unsorted FDC curve for the spatiotemporal transferability – Badalgama

5.14.6.3 Comparison between measured and modeled flow hydrographs

The simulated and measured flow hydrographs for the spatiotemporal transferability is shown in Figure 5-64: for the transferred parameters from Giriulla watershed.



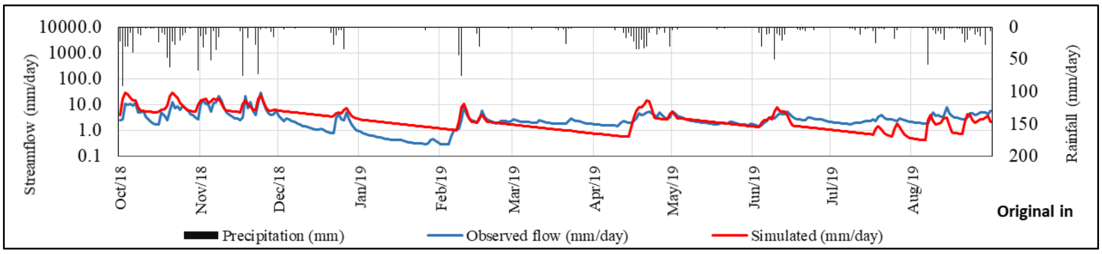


Figure 5-64: Comparison between observed and simulated streamflow for spatiotemporal transferability – Badalgama

5.14.6.4 Error in Annual and Seasonal Water Balance

Error in annual water balance for the spatiotemporal transferability was shown in Table 5-28 and Figure 5-65, while the seasonal water balance error were shown in Figure 5-66 and Figure 5-67.

Table 5-28 Annual water Balance for spatiotemporal transferability - Badalgama

Water Year	RF (mm/yr)	Observed SF (mm/yr)	Sim. SF (mm/yr)	Pan Evpo. (mm/yr)	AWB for Observe Data	AWB for Sim	AWB Error
2014/2015	2,701	1,119	1,697	1,281	1,581	1,004	52%
2015/2016	2,594	1,183	2,162	1,312	1,411	432	83%
2016/2017	1,578	254	425	1,149	1,324	1,153	67%
2017/2018	2,252	1,045	1,628	1,332	1,207	625	56%
2018/2019	2,168	1,091	1,317	1,375	1,077	851	21%
Average	**2,259**	**939**	**1,446**	**1,289**	**1,320**	**813**	**56%**

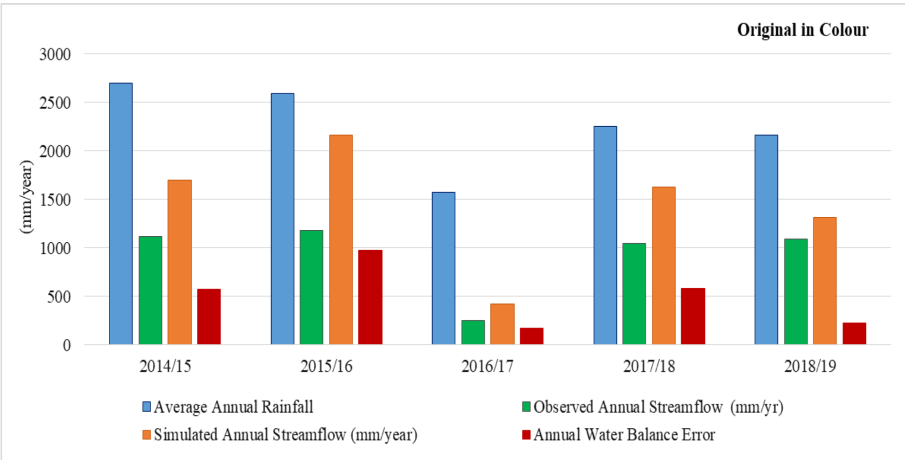


Figure 5-65: Annual water Balance error for spatiotemporal transferability – Badalgama

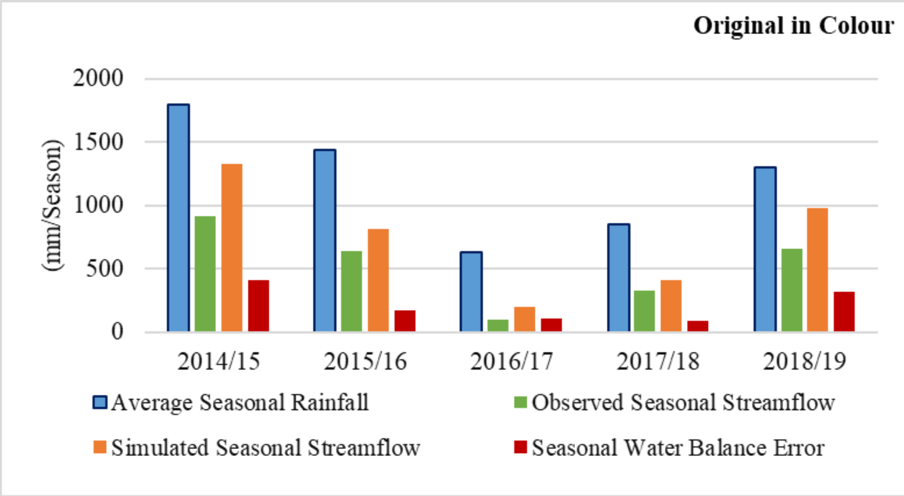


Figure 5-66: Seasonal (Maha) water Balance error for spatiotemporal transferability – Badalgama

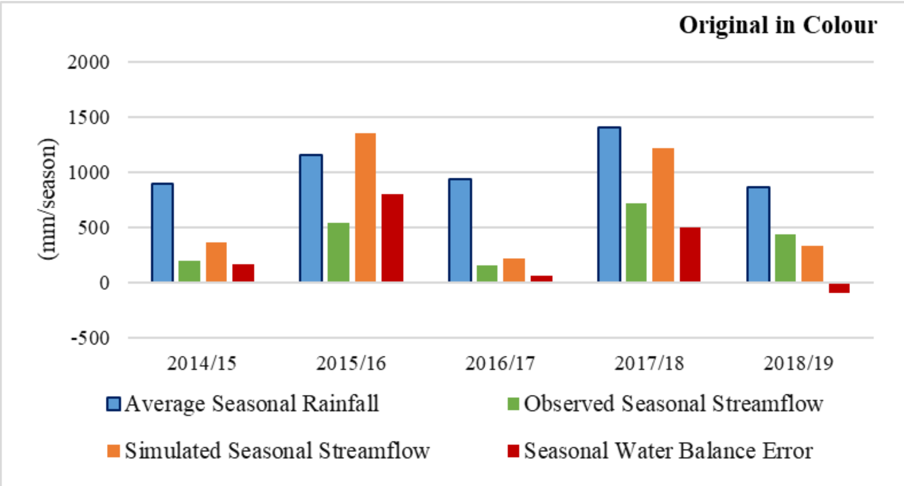


Figure 5-67: Seasonal (Yala) water Balance error for spatiotemporal transferability – Badalgama

5.14.7 Transferability of Parameters from main catchment to Sub-catchment

To check the parameter transferability, optimized parameters of Badalgama catchment was directly applied to the Giriulla catchment. The parameter transferability model performance at the Giriulla sub-catchment were illustrated in Table 5-29 as below.

5.14.7.1 Statistical Measure of Goodness of Fit

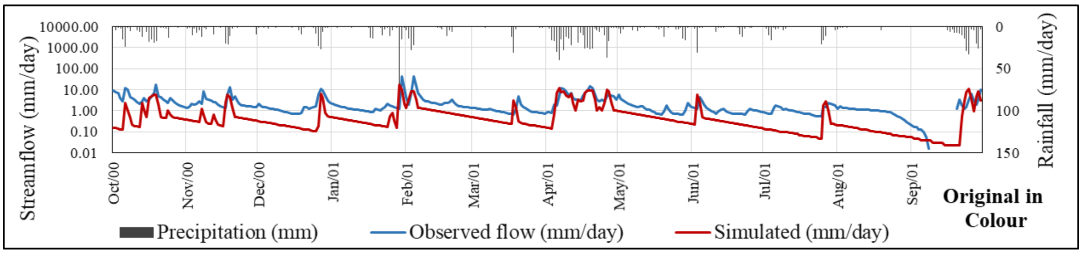
The numerical measurements of the model performance for the entire flow regime and three different flow segments such as low, medium and high flow regimes are illustrated in Table 5-29.

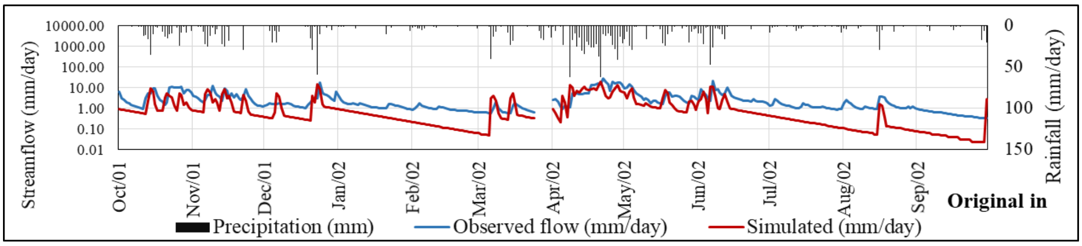
Table 5-29: Measure of goodness of fit of the model for Giriulla with transferred parameters

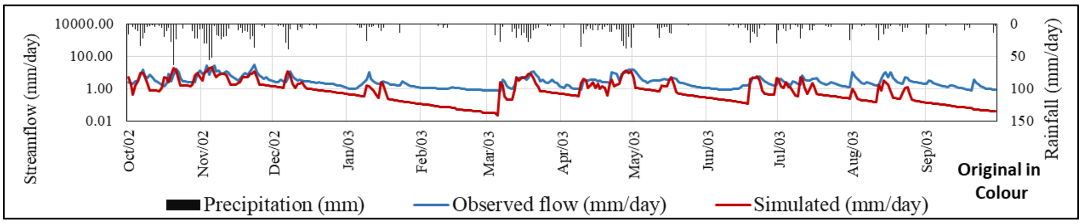
Gauging Station	**RMSE (mm/day)**	**MRAE**	**Flow Duration Curve**					
			High		**Medium**		**Low**	
			RMSE (mm/day)	**MRAE**	**RMSE (mm/day)**	**MRAE**	**RMSE (mm/day)**	**MRAE**
Giriulla (Sorted)	2.44	0.67	44.46	0.35	2.77	0.66	0.23	0.89
Giriulla (Unsorted)	3.90	0.75	13.36	0.78	15.51	0.75	14.44	0.77

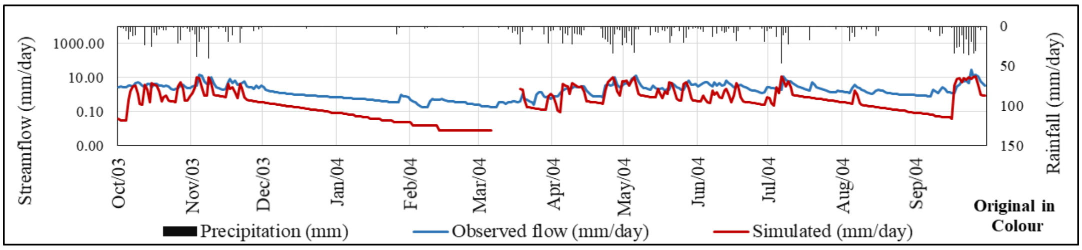
5.14.7.2 Comparison of measured and modeled streamflow hydrograph

The Figure 5-68 and Figure 5-69 shows the comparison between the measured vs modeled streamflow hydrographs.









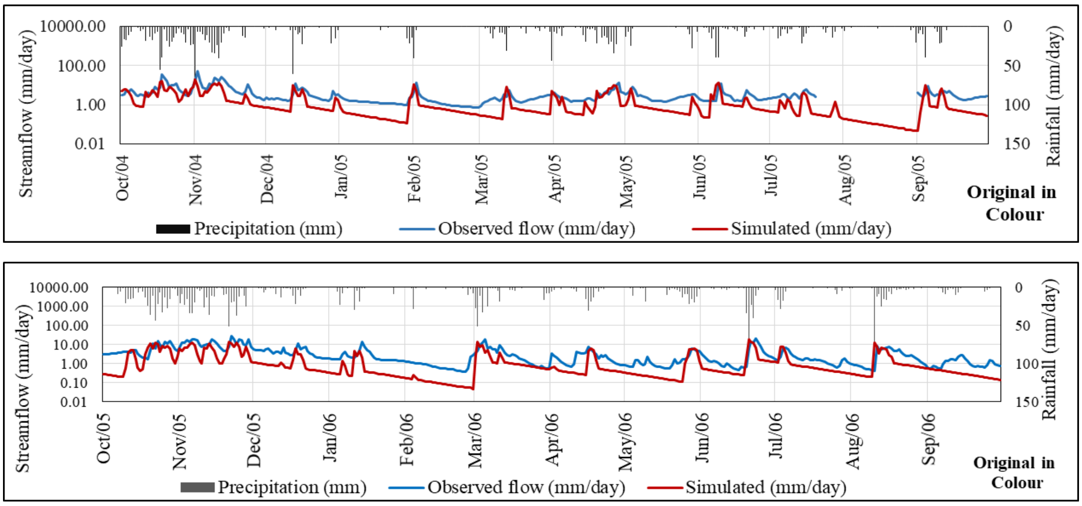


Figure 5-68: Flow Hydrograph for Giriulla with transferred parameters from 2000/2001 to 2005/2006

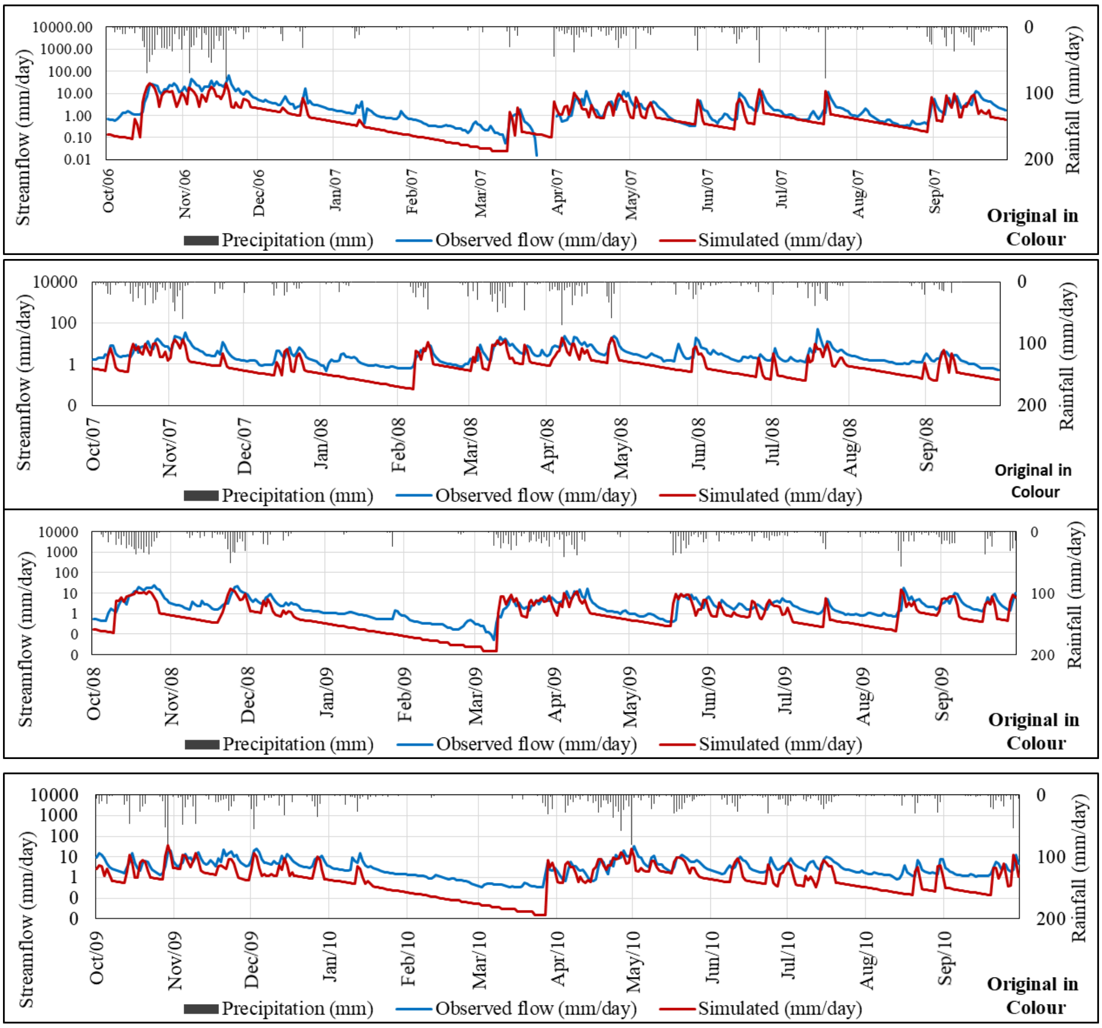


Figure 5-69: Flow Hydrograph for Giriulla with transferred parameters from 2006/2007 to 2008/2009

5.14.7.3 Error in annual and seasonal water balance

Error in annual water balance for the entire period is illustrated in Table 5-30, and graphically shown in Figure 5-70, while the seasonal water balance shown in Figure 5-71 and Figure 5-72.

Table 5-30: Annual water Balance error for the entire period with transferability – Giriulla

Water Year	RF (mm)	Observed SF (mm)	cal. SF (mm)	AWB for Observe	AWB for Cal.	AWB Error
2000/01	1487.1	902.1	396.5	584.9	1090.5	-56%
2001/02	1888.6	1109.4	581.3	779.2	1307.3	-48%
2002/03	2137.8	1301.8	647.1	836.0	1490.7	-50%
2003/04	1699.6	871.7	447.1	828.0	1252.6	-49%
2004/05	1955.0	1243.3	621.3	711.6	1333.7	-50%
2005/06	2117.2	1321.5	639.7	795.7	1477.5	-52%
2006/07	2344.4	1572.1	817.3	772.3	1527.1	-48%
2007/08	2256.8	1567.1	706.6	689.7	1550.2	-55%
2008/09	2349.0	1184.0	723.7	1165.0	1625.3	-39%
2009/10	2318.3	1606.0	808.3	712.3	1510.0	-50%
Average	**2026.2**	**1230.3**	**620.1**	**795.8**	**1406.1**	**-50%**

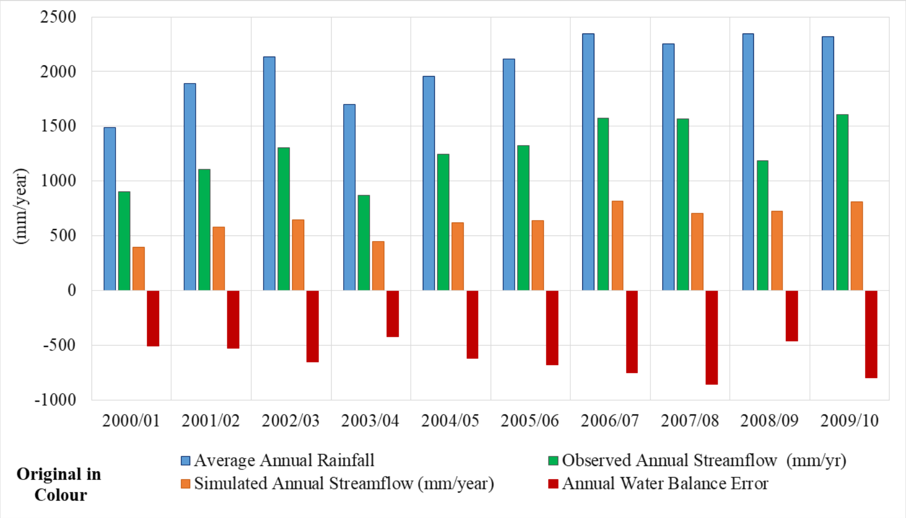


Figure 5-70: Annual Water Balance error for the entire period with transferability – Giriulla

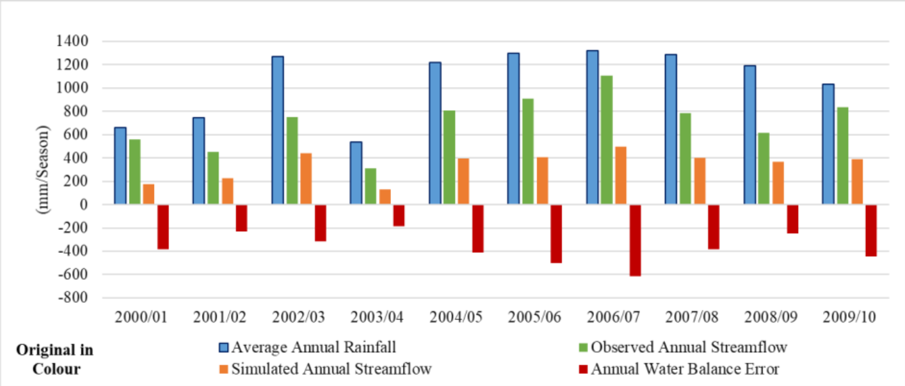


Figure 5-71: Seasonal (Maha) Water Balance error for the entire period with transferability – Giriulla

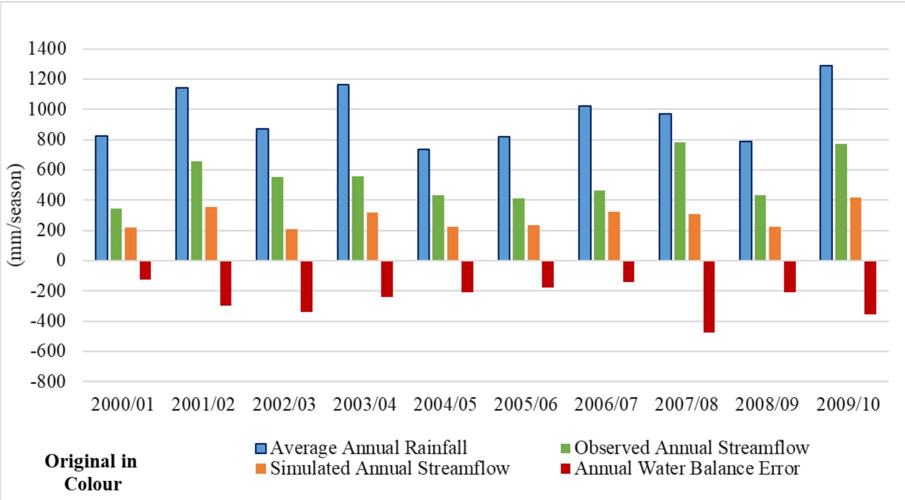


Figure 5-72: Seasonal (Yala) Water Balance error for the entire period with transferability – Giriulla

5.14.7.4 Comparison of Flow Duration Curves

Figure 5-73 and Figure 5-74 illustrate the sorted and unsorted flow duration curve for the whole period, while showing the distribution of observed flows vs simulated flows for the entire period.

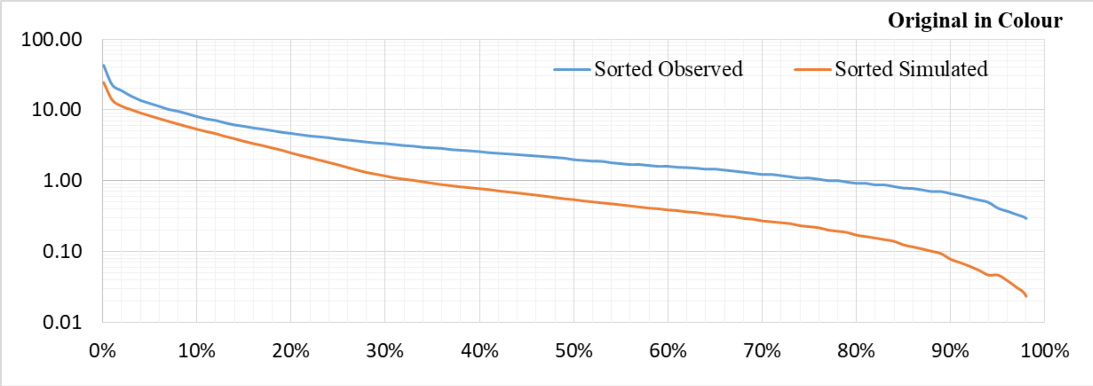


Figure 5-73: Sorted FDC for the entire period with transferred parameters - Giriulla catchment

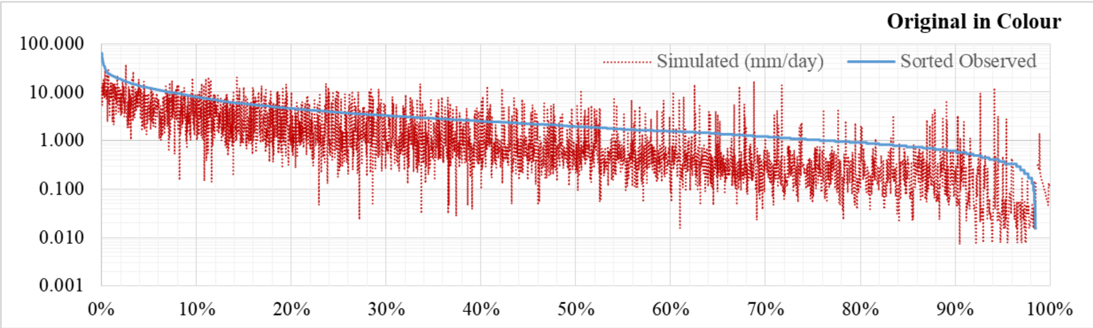


Figure 5-74: Unsorted FDC for the entire period with transferred parameters – Giriulla catchment

5.14.8 Transferability of parameter from sub-catchment to main catchment

Similarly stated in section 5.14.1, to check the parameter transferability, optimized parameters of Giriulla catchment is directly applied to the Badalgama main catchment.

5.14.8.1 Statistical Measure of Goodness of Fit

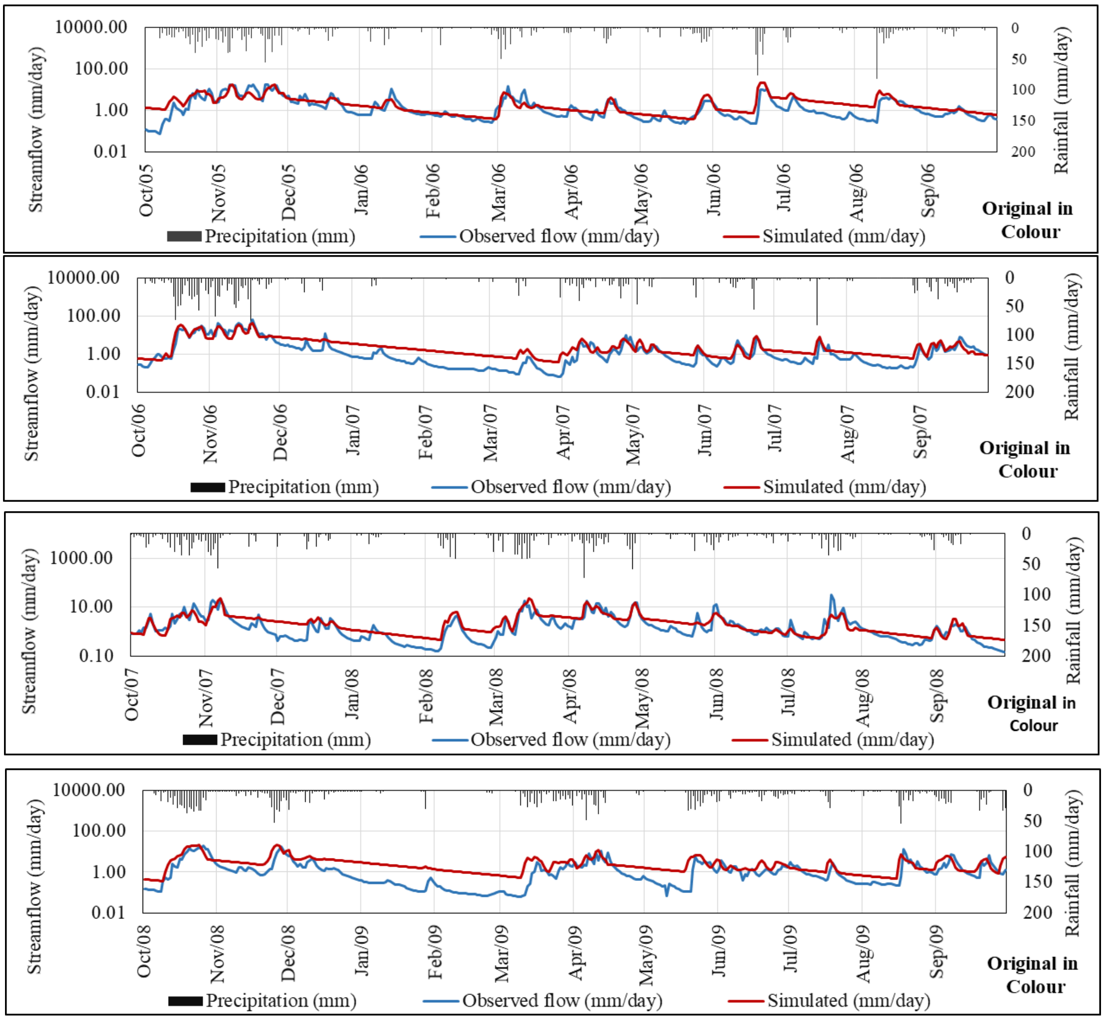
The parameter transferability model performance at the Badalgama main-catchment is illustrated in Table 5-31 as below.

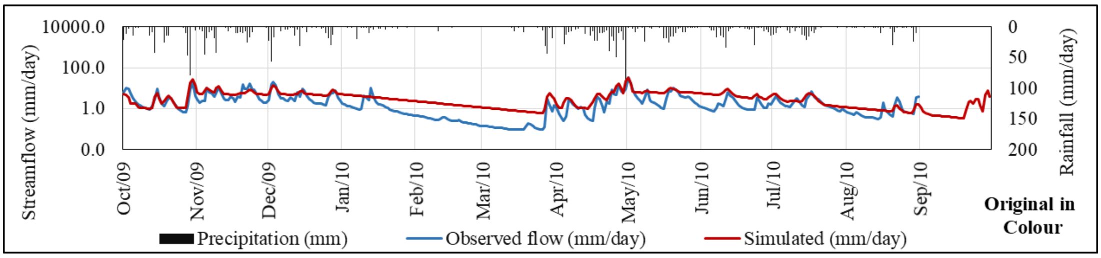
Table 5-31: Measure of goodness of fit of the model for Badalgama with transferred parameters

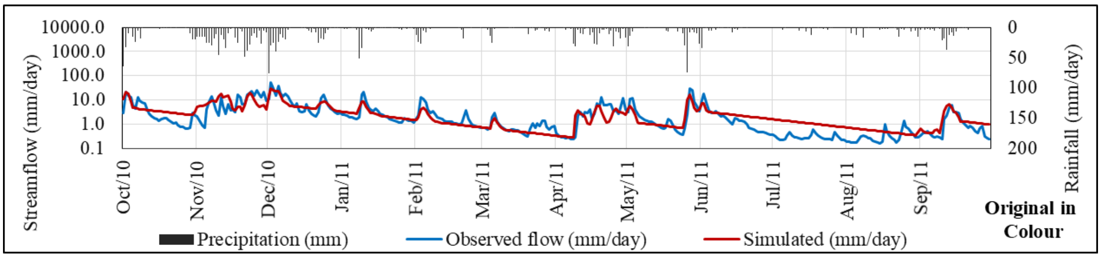
Gauging Station	RMSE (mm/day)	MRAE	Flow Duration Curve					
			High		Medium		Low	
			RMSE (mm/day)	MRAE	RMSE (mm/day)	MRAE	RMSE (mm/day)	MRAE
Badalgama (Sorted)	3.23	3.989	3.22	1.107	3.14	4.816	13.42	1.388
Badalgama (Unsorted)	3.23	3.648	7.57	0.387	2.63	1.905	1.64	14.81

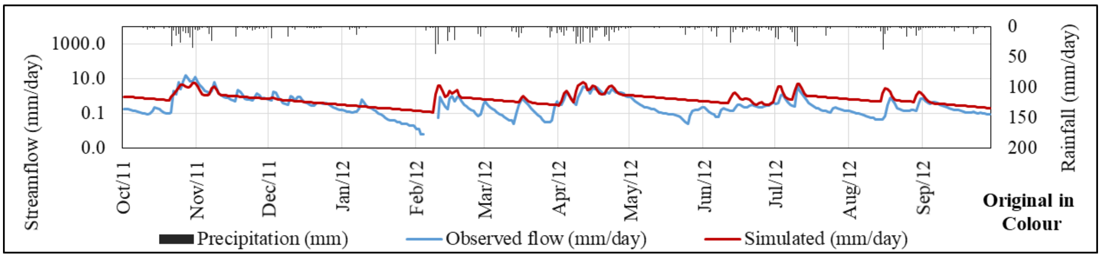
5.14.8.2 Comparison of Observed and Estimated Streamflow Hydrograph

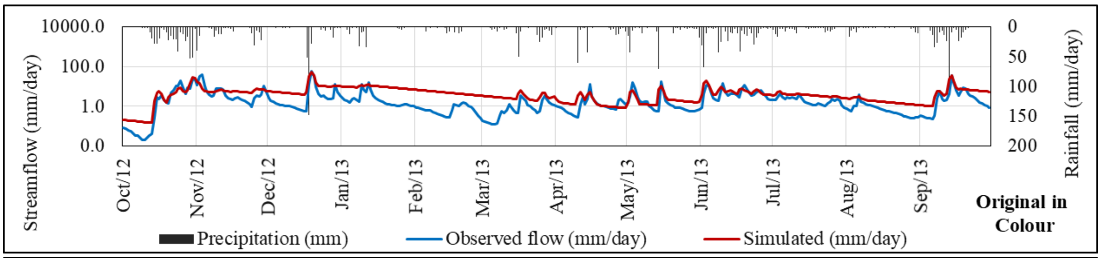
A comparison of measured flow and simulated flow hydrographs with transferred parameters from Giriulla catchment to Badalgama catchment is shown in Figure 5-75.

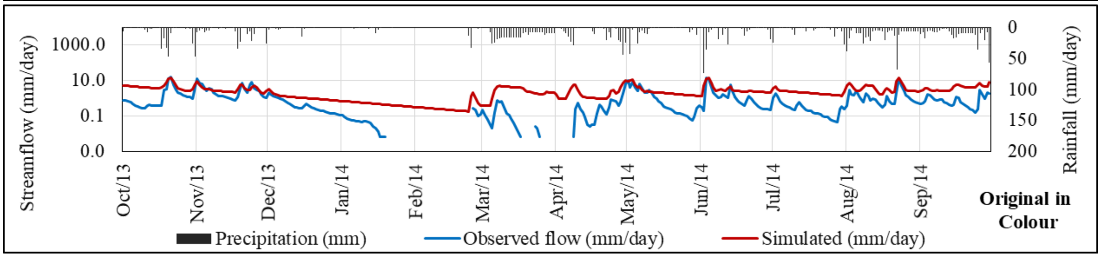


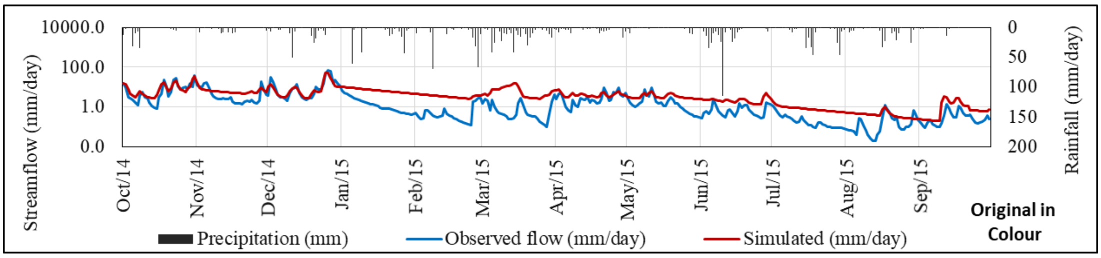

Streamflow (mm/day)
10000.0
100.0
1.0
0.0
0
50
100
150
200
Rainfall (mm/day)
Oct/09
Nov/09
Dec/09
Jan/10
Feb/10
Mar/10
Apr/10
May/10
Jun/10
Jul/10
Aug/10
Sep/10
Precipitation (mm)
Observed flow (mm/day)
Simulated (mm/day)
Original in Colour

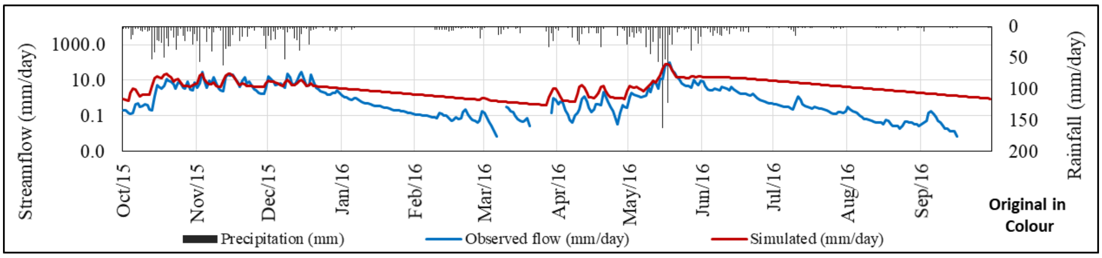

Streamflow (mm/day)
10000.0
1000.0
100.0
10.0
1.0
0.1
0
50
100
150
200
Rainfall (mm/day)
Oct/10
Nov/10
Dec/10
Jan/11
Feb/11
Mar/11
Apr/11
May/11
Jun/11
Jul/11
Aug/11
Sep/11
Precipitation (mm)
Observed flow (mm/day)
Simulated (mm/day)
Original in Colour


Streamflow (mm/day)
1000.0
10.0
0.1
0.0
0
50
100
150
200
Rainfall (mm/day)
Oct/11
Nov/11
Dec/11
Jan/12
Feb/12
Mar/12
Apr/12
May/12
Jun/12
Jul/12
Aug/12
Sep/12
Precipitation (mm)
Observed flow (mm/day)
Simulated (mm/day)
Original in Colour


Streamflow (mm/day)
10000.0
100.0
1.0
0.0
0
50
100
150
200
Rainfall (mm/day)
Oct/12
Nov/12
Dec/12
Jan/13
Feb/13
Mar/13
Apr/13
May/13
Jun/13
Jul/13
Aug/13
Sep/13
Precipitation (mm)
Observed flow (mm/day)
Simulated (mm/day)
Original in Colour


Streamflow (mm/day)
1000.0
10.0
0.1
0.0
0
50
100
150
200
Rainfall (mm/day)
Oct/13
Nov/13
Dec/13
Jan/14
Feb/14
Mar/14
Apr/14
May/14
Jun/14
Jul/14
Aug/14
Sep/14
Precipitation (mm)
Observed flow (mm/day)
Simulated (mm/day)
Original in Colour


Streamflow (mm/day)
10000.0
100.0
1.0
0.0
0
50
100
150
200
Rainfall (mm/day)
Oct/14
Nov/14
Dec/14
Jan/15
Feb/15
Mar/15
Apr/15
May/15
Jun/15
Jul/15
Aug/15
Sep/15
Precipitation (mm)
Observed flow (mm/day)
Simulated (mm/day)
Original in Colour


Streamflow (mm/day)
1000.0
10.0
0.1
0.0
0
50
100
150
200
Rainfall (mm/day)
Oct/15
Nov/15
Dec/15
Jan/16
Feb/16
Mar/16
Apr/16
May/16
Jun/16
Jul/16
Aug/16
Sep/16
Precipitation (mm)
Observed flow (mm/day)
Simulated (mm/day)
Original in Colour

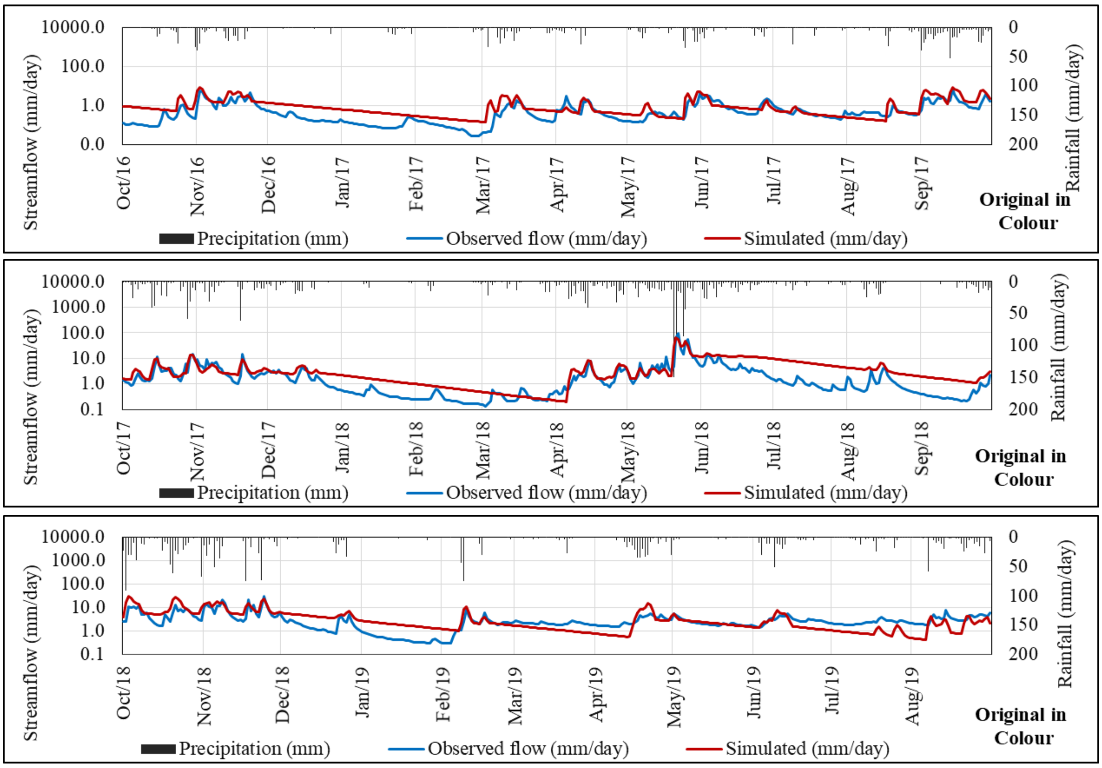


Figure 5-75: comparison of observed and simulated Flow Hydrographs for Badalgama with transferred parameters

5.14.8.3 Error in Annual Water Balance

Error in annual water balance between measured and modeled streamflow series for the entire period with transferred parameters from Giriulla sub-watershed to Badalgama main watershed is shown in the Table 5-32 and Figure 5-76, while seasonal water balance shown in the Figure 5-77 and Figure 5-78.

Table 5-32: Annual water Balance for Badalgama with Parameter Transferability

Water Year	RF (mm)	Observed SF (mm)	sim. SF (mm)	Pan Evpo. (mm)	AWB for Observe	AWB for Cal.	AWB Error
2005/06	2,121.7	823.4	958.0	1,280.8	1,298.3	1,163.7	16%
2006/07	2,406.4	1,209.1	1,391.9	1,311.6	1,197.3	1,014.5	15%
2007/08	2,144.1	923.6	1,012.2	1,148.7	1,220.6	1,131.9	10%
2008/09	2,382.0	685.3	1,110.5	1,331.9	1,696.7	1,271.5	62%
2009/10	2,188.6	942.8	1,394.9	1,374.7	1,245.8	793.7	48%
2010/11	2,405.2	1,321.1	1,158.0	1,287.4	1,084.1	1,247.2	-12%

Water Year	RF (mm)	Observed SF (mm)	sim. SF (mm)	Pan Evpo. (mm)	AWB for Observe	AWB for Cal.	AWB Error
2011/12	1,271.6	253.5	353.3	1,401.9	1,018.1	918.3	39%
2012/13	2,547.6	1,158.8	1,920.2	1,322.3	1,388.8	627.4	66%
2013/14	2,206.9	400.3	953.7	1,403.3	1,806.6	1,253.2	138%
2014/15	2,700.7	1,119.5	1,697.1	1,282.0	1,581.2	1,003.6	52%
2015/16	2,594.3	1,183.0	2,162.0	1,361.7	1,411.3	432.3	83%
2016/17	1,578.3	254.3	424.9	1,243.3	1,323.9	1,153.4	67%
2017/18	2,252.3	1,045.1	1,627.7	1,107.2	1,207.2	624.6	56%
2018/19	2,167.9	1,090.7	1,317.3	1,325.0	1,077.2	850.6	21%
Average	**2212.0**	**886.5**	**1,248.7**	**1,298.7**	**1,325.5**	**963.3**	**47%**

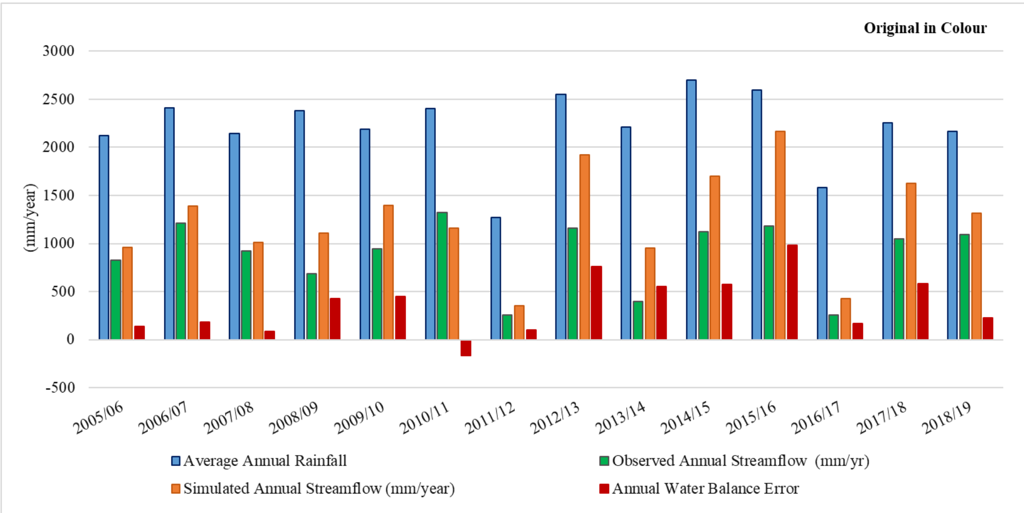


Figure 5-76: Annual water Balance for Badalgama with Parameter Transferability

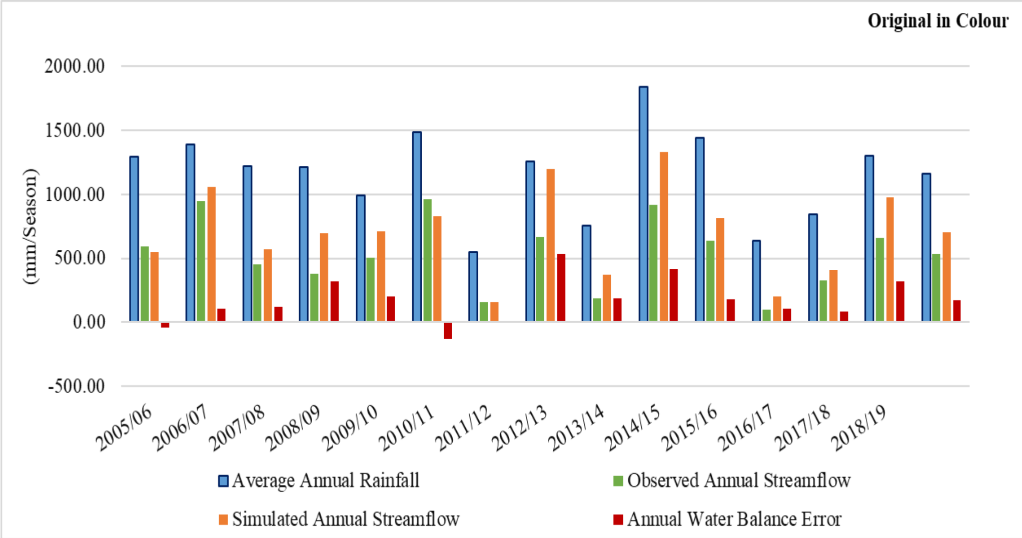


Figure 5-77: Seasonal (Maha) water balance for Badalgama with Parameter Transferability

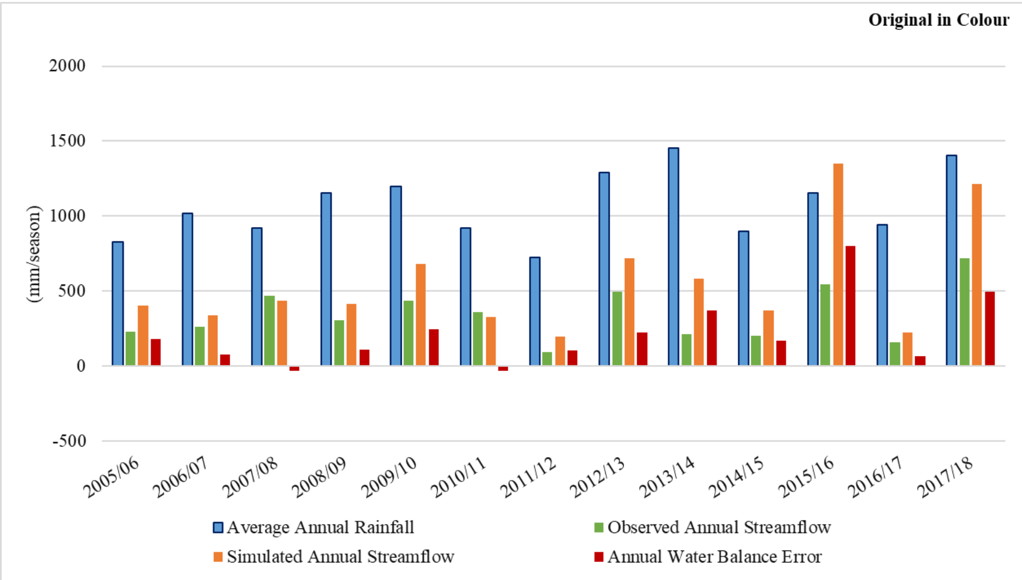


Figure 5-78: Seasonal (Yala) water balance for Badalgama with Parameter Transferability

5.14.8.4 Comparison of Flow Duration Curves

Sorted and unsorted flow duration curves are illustrated in Figure 5-79 and Figure 5-80, while showing distribution between observed flows and simulated flows with transferability of parameter from Giriulla watershed to Badalgama watershed.

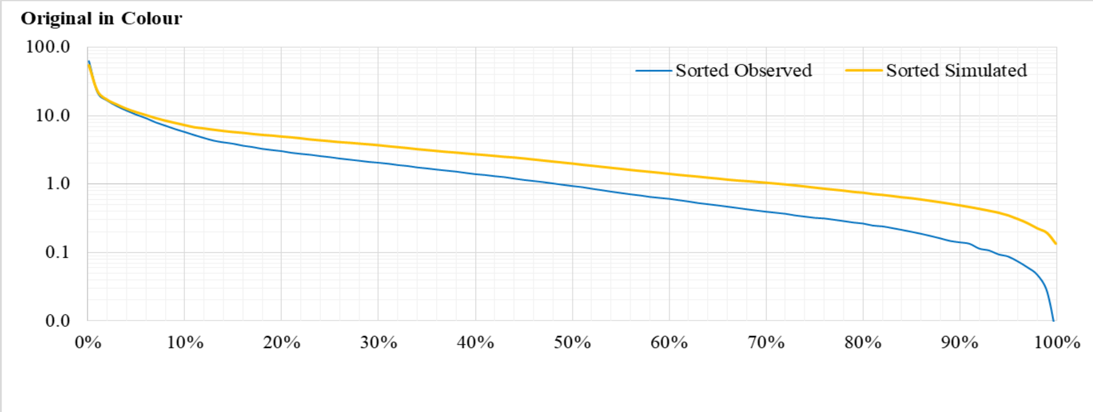


Figure 5-79: Sorted FDC for Badalgama catchment with transferred parameters from Giriulla catchment

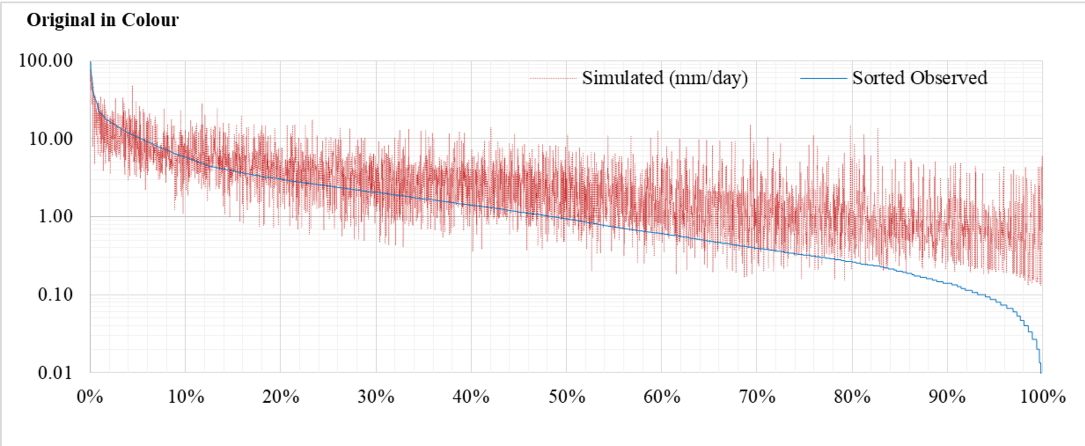


Figure 5-80: Unsorted FDC for Badalgama catchment with transferred parameters from Giriulla catchment

6 DISCUSSION

6.1 Selections of stations and Data

6.1.1 Gauging Stations and Data Period Selection

Based on the extensive literature survey, it was found that consideration of data selection strategies is very important, including the availability of long series of daily data, representative hydrological variability such as mean and extreme (drought and flood), and maximum spatial-temporal data density (Cunderlik & Simonvic, 2004). Further, it was recognized that the availability of five to ten years of continuous data series is adequate to effectively develop a daily lumped hydrological model with the representation of catchment processes.

When considering the hydrometric stations established in the Maha Oya basin, only two stations are functioning well, which are Giriulla Gauging Station and the Badalgama Gauging Station. In addition to that, there was another hydrometric station called Alawwa, which has been closed in the year 2005. According to the Irrigation Department (Sri Lanka), Giriulla and Badalgama stations have been established in 1958 at the Pasyala –Griulla Bridge and in 1953 at the Makandura – Badalgama Road Bridge respectively. To represent the prevailing hydrological conditions and catchment behaviors, data reliability and the accuracy was checked in recent 20 year to select the data period.

Accordingly, for the Giriulla gauging station, 2005/2006 to 2009/2010 period was selected as calibration period, while 2000/2001 to 2004/2005 was selected as verification period, since data availability was much better than with compared to most recent period as seen in Table 4-7. Similarly data availability at Badalgama station is comparatively good in recent years, hence it was decided to select 2005/2006 to 2009/2010 period as calibration period and 2014/2015 to 2018/2019 period as validation period as can be seen in Table 4-9. Although these periods are complied with the data selection strategies, the reliability of these data was uncertain, since Giriulla flow series is much higher than the Badalgama flow series, even though Badalgama gauging station is located in far downstream of the Giriulla gauging station, which comparison can be seen visually from the APPENDIX C.

Concerning the rain gauging station selection, spatiotemporal density is a very important factor and with the consideration of this as a key factor six rainfall stations with good spatial distribution and greater than 10% raw data availability (Table 4-3) were selected. The selected precipitation stations also meet the requirements listed in WMO Guide No. 168, Indian Standard: 4987 (WMO, 2011). Thiessen weights were used to fill the gaps, although external stations were selected, the influence of the Thiessen weights was minimal (Kodippili, 2019).

6.1.2 Selection of spatial averaging method

During the literature survey, it was revealed that there are many spatial averaging methods are available and with the advancement of GIS technologies, many spatial interpolation methods have been introduced. However majority of researches had been used Thiessen averaging method (Kodippili, 2019; Teegavarapu & Chandramouli, 2005; Jayadeera, 2016), which includes regional researches as well. Further Sugawara et al. (1984), also stated that the use of weighted mean rainfall from several spatially distributed stations will effective for accurate runoff analysis. Accordingly, Thiessen averaging method has been adopted in this study as well.

Once spatial averaging has been completed, visual data checking has been initialized and an insignificant number of non-responsive rainfall events were identified, hence the selection of rain gauge stations are well representative for the Maha Oya basin. Further, based on the visual data checking, it was confident on the selection of rain gauging stations.

6.1.3 Existence of Data Errors

Only two functioning hydrometric stations are available in Maha Oya basin and Badalgama gauging station has been established in far downstream of the Giriulla Gauging station. However, Giriulla observed flow series is significantly higher than the Badalgama flow series, and comparison of flow duration curved at both locations is shown below in Figure 6-1, which clearly shows that Badalgama flows are underestimated and comparison of observed streamflow measurements of both stations are illustrated annually in APPENDIX C.

In addition to that, during the literature review, it was observed that there are some geological fault zones are exist within the Maha Oya Catchment (Gomez, Kodippili, 1998). Hence there are some uncertainties on the reduction of observed streamflow at Badalgama catchment with compared to Giriulla catchment. Rainfall non-responses are further shown in APPENDIX A and APPENDIX B for more information.

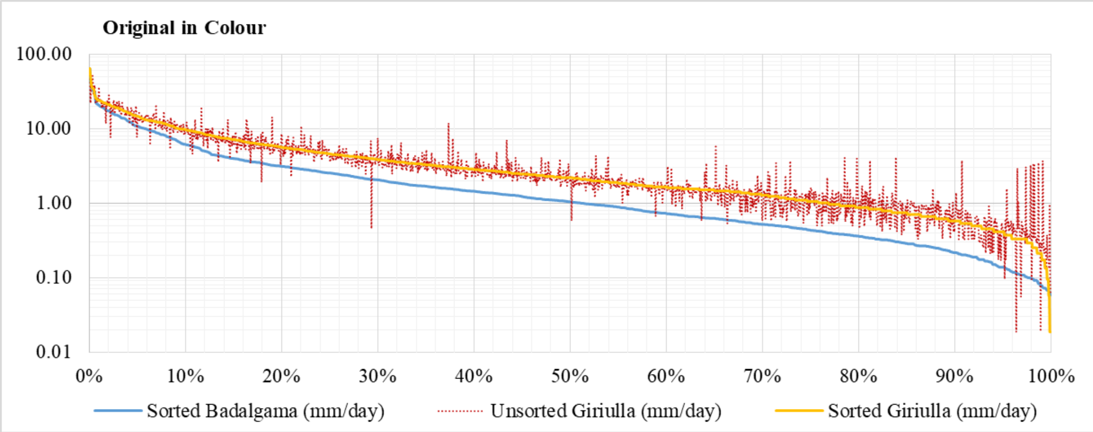


Figure 6-1: Comparison of flow duration curve in both Badalgama and Giriulla watersheds

6.2 Selection of Model and Objective function

6.2.1 Model Selection

Ample literature survey discovered that there are significant number of hydrological models are exist to model the hydrological processes in the catchments. However model selection greatly depends on the availability of data, the complication of the model development and the purpose of the modeling (Garcia et al., 2017, Chandra et al., 2000). Further, it was observed that, various types of rainfall-runoff models have been used in parameter transferability as well, to predict the streamflow in ungauged watersheds. However water managers and planners preferred to work with simple models, which required a lesser number of parameters and accessible to the modeling software to model the catchments. Hence, to select the most appropriate model, the comprehensive model review has been carried out based on identified ten criteria as illustrated in Table 2-3. Accordingly, HEC-HMS model has been prioritized as a most appropriate model to carry out this research, since it is freely available Physics-based model, which able to simulate with limited data available situations and the model application has been proven in the region including Sri Lanka. The other advantage of this model is that it can also represent the physical characteristics of the catchment area.

Although HEC-HMS is a physically distributed model, it is capable to model lumped catchments as well (Kamran & Rajapakse, 2018). Similarly it has the ability to model the catchment by applying the number of parameters in a data-rich situation, as well as with lesser parameters in data scare situations. As part of this research, the focus is on modeling the continuous series for water management purposes that require an overall spectrum of the flow regime in a data anxiety situation. In addition, the lumped model also increases simplicity. Accordingly, the HEC-HMS model was developed for selected catchments as lumped models with limited parameter applicability.

6.2.2 Objective Function Selection

During the literature survey, it was revealed that there are number of objective functions (Table 2-7) used in the field of hydrological studies (Garcia et al., 2017), which sometimes focuses on different flow regimes and it is important to identify the robustness of the objective function in terms of the water resources management activities. There are fourteen different minimization objective functions and eight maximization objective functions are introduced in the HEC-HMS model (Mike Bartles, Tom Brauer, Bill Scharffenberg, Matt Fleming, 2018).

Based on the literature, Root Mean Square Error (RMSE) has been chosen as an Objective function for the current study, which was facilitated to optimize the model performance. In addition to that, main objective of the study is to facilitate the decision making in the water resources management activities, hence it was focused on high and intermediate flow. Accordingly as discussed in section 2.7, most popular and best performing objective function in HEC-HMS model was selected as RMSE for this study.

In addition to that, Mean Ratio Absolute Error (MRAE) has been used as numerical model evaluation criteria to evaluate the model results, because it gives a relative error and spreads the error across the entire data set, which is considered ideal for high, medium and low flow conditions in the data set. In addition to that, the primary purpose of this research is to facilitate the management of water resources in ungauged watersheds, hence key focus has been given to evaluate medium flows. And successful application of MRAE in studies carried out in Sri Lanka was further enhance the confidence to use it as an objective function (M Kamran & Rajapakse, 2018; Jayadeera, 2016; Kodippili, 2019).

6.3 Model Development

During the HEC-HMS model development, the realistic catchment parameters were derived for both catchments as discussed in Section 5.3.

6.3.1 Selection of model components and parameters

Model components were selected to represent the hydrological processes of the selected catchment areas. Accordingly, surface and Canopy models were selected to represent the hydrological processes related to the precipitation interception and loss model to represent the infiltration processes, while the transform model and baseflow model were selected to represent the overland runoff generation processes and baseflow processors respectively. These simple selection of model component has been considered, since in this study it was needed to address data scare situations, hence model with lesser parameters were chosen in this study. The simple schematic diagram for the processes are shown in the Figure 5-3.

When deriving the model parameters, hydrological properties of the catchment were considered including, Land use, prevailing soil types, stream length, slope, etc… However due to lesser number of layers in precipitation loss method in the selected model and inability to continue that performance through baseflow model caused low performance in low flows, by giving considerably high mass balance error. As the main purpose of this study is to facilitate the water resources planning activities, in which targeted flow is medium and high flows in the entire flow regime, especially for hydropower projects and water extraction projects. Therefore, this model schematization is sufficient to achieve the study objective.

6.3.2 Model simulation and optimization

Once initial parameters have been derived model simulation was performed. Though the HEC-HMS model has introduced two optimization methods as deterministic and and stochastic, deterministic optimization has been chosen to use in this study, since this optimization method facilitates, to begin with the initial parameters and change them. Accordingly, it will be searched to the best parameter set, which minimized the difference between the simulated streamflow series vs observed streamflow series (Scharffenberg, Bartles, Brauer, Fleming, 2018). During the process of parameter optimization, it was essentially required to ensure that, unrealistic parameters were not used.

During the optimization, the search method was selected as Simplex as, it allows the modeler to optimize the number of parameters at once and at least two parameters have been selected to optimize. Moreover, other method called Univariate allows to optimize one parameter at once. Based on the aforementioned details, approximately 250 trial simulations were done, while using the semi-automatic optimization approach, though there were other two approaches as manual and automatic.

However before proceeding with a semi-automatic approach, a fully automatic approach was also tested, but it was not able to converge model to optimize the parameters, while discontinuing the model with local minimum. Further Manual method was not used, since it was not found systematic approach to perform this method and it was highly time-consuming. Finally again, automatic optimization was applied, by using optimized parameters as initial parameters, which obtained through semi-automatic optimization. But this was also not provided better parameters with compared to optimized parameters through semi-automatic optimization approach.

6.4 Model performance Evaluation

To assess model performance, both statistical and graphical model assessment techniques were used in this study, as mentioned in the previous sections. The model evaluation statistics including Mean Ratio Absolute Error (MRAE) and the Root Mean Square Error (RMSE) have been used and the equations for these functions are illustrated in Table 2-7. The subject of these statistics has been selected and is being used in this research was to facilitate the water resources planning and management.

Further as a graphical model performance evaluation, combined hydrographs of HEC-HMS model simulated streamflow and daily observed streamflow were plotted against daily average precipitation. Visual checking of hydrographs were performed for each of the water year, which including both calibration and validation period. Moreover, a comparison of flow hydrographs, provide an overall idea on the behavior of low and high flow magnitude variation over the time and occurrence of actual events and simulated events. In addition to that, annual and seasonal water balance has been done to check the annual and seasonal mass balance of the model for all calibration, validation periods and the separate transferability approaches including the entire period for transferability. Moreover, sorted and unsorted Flow Duration Curve (FDC) has been utilized for visual checking of model performance in different three flow regimes including low, medium and high flows. Since the main purpose of this study was water resources management, the behavior of sorted flow duration curves are very important, while changing magnitudes are not very significant. These techniques are widely used in the field of hydrological model performance evaluation.

6.4.1 Model calibration and validation

The key objective of the hydrological model calibration was to optimize the difference between observed flows and simulated flows, including high flows, low flows, and timing, while identifying the best set of model parameters. In this study model parameters were further verified by applying those in fully automatic calibration with the use of Nelder and Mead search algorithm (Simplex). This was further illustrated in section 5.13. However, in some instances, the difference might be occurred due to imprecise representation of spatial distribution and used spatial averaging of rainfall within the watershed. In order to the validation of the model, optimized parameters identified during calibration was kept constant for the verification period, to check the performance of model.

6.4.1.1 Model performance in Calibration period

As mentioned in the previous sections (Section 5.10), the calibration period was selected as 2005/2006 to 2009/2010 for both catchments. During this period it includes extreme events such as floods and droughts, by enabling the model to be exited. At the Giriulla Gauging station observed flow varies between 0.2 m^3/s to 831 m^3/s, while the same at Badalgama watershed streamflow varies from 0.9 m^3/s to 944 m^3/s. The MRAE and RMSE values for the entire sorted flow regimes at Giriulla are 0.24 and 2.24 mm/day and same for the Badalgama watershed are 0.25 and 0.96 mm/day as illustrated in Table 5-4 and Table 5-6. Similarly, for the unsorted flow series overall MRAE and RMSE values of Giriulla are 0.58 and 3.14 mm/day respectively and same for the Badalgama are 0.86 and 3.07 mm/day. The reasons for the higher variation in

RMSE in Giriulla is error contribution from high flows and low flows. According to both model results, it was shown more than 75% accuracy, by confirming the good model performance during calibration periods for both watersheds.

Further when considering the visual checking of annual hydrographs at Giriulla (Figure 5-6) time of occurrence is at an acceptable level and it was revealed that model response with wet conditions is high compared to dry conditions. Moreover, similar behavior has been observed in the Badalgama catchment (Figure 5-12) as well. Instead of one layer loss model, the five-layer SMA Loss model shall provide good performance in low flow simulation. However, the main objective of the study was to facilitate water resources management and planning, hence performance of the FDC is very important. Therefore sorted and unsorted flow duration curves were checked for both watersheds in calibration period (Figure 5-10, Figure 5-11, Figure 5-16, and Figure 5-17), which Giriulla showed underestimation in high flows, while slightly overestimation in low flows and Badalgama showed good agreement in high flows while underestimating low flows. However, based on the study objectives the achieved level of accuracy was sufficient for the water resources management with prevailing data uncertainties. Based on all criteria, both models could be considered as an accurately calibrated model.

Further, in terms of water resources management, a medium flow regime has been given high consideration, accordingly for the Giriulla watershed, MRAE and RMSE values for the medium flow spectrum were 0.13 and 0.62 mm/day respectively (Table 5-4). Likewise, for the Badalgama same values were 0.23 and 0.36 mm/day respectively (Table 5-6).

Investigation of annual variation of statistical measures at Giriulla was indicated in Table 6-1, which provides a better understand on model behavior for separate water years. According to the table MRAE value varied between 0.19 in 2009/2010 to 0.78 in 2006/2007, while RMSE values varied from 1.3 mm/day and 3.59 mm/day for the respective years as MRAE.

Table 6-1: Comparison of annual MRAE and RMSE variation - Giriulla

Water Year	Calibration Results (Sorted)	
	MRAE	RMSE
2005/06	0.20	1.69
2006/07	0.78	3.59
2007/08	0.22	2.44
2008/09	0.41	1.44
2009/10	0.19	1.30

Although, Table 6-1 showed that the highest MRAE was indicated in the year 2006/2007, the highest annual water balance error indicated in the year 2007/2008 as shown in Table 5-5 and Figure 5-7.

Further according to the water balance analysis, the annual average water balance error for the Giriulla watershed was -19%, while the lowest water balance error occurred in the year 2008/2009 as 6%. Figure 5-6 showed a good high and low flow simulation inflow hydrograph of 2008/2009, which leads to the lowest water balance error. When visually check the 2006/2007 flow hydrograph, which presented that low flow simulation was not performed well in the model, leading to occur highest MRAE value in the calibration period.

Similarly annual variation in statistical indicators is shown in Table 6-2 for a better understanding of the model performance in each year at Badalgama catchment. Based on the below table, the highest and lowest MRAE values were obtained in 2009/2010 and 2006/2007 correspondingly.

Table 6-2: Comparison of annual MRAE and RMSE variation - Badalgama

Water Year	Calibration Results (Sorted)	
	MRAE	RMSE
2005/06	0.34	0.66
2006/07	0.17	2.16
2007/08	0.33	0.77
2008/09	0.32	1.05
2009/10	0.35	0.64

Based on Figure 5-12 of the flow hydrograph for the 2006/2007 year, there was a good agreement between observed flows and simulated flows, which leads towards the lowest MRAE value in the same year.

Further, when considering the annual water balance error at Badalgama watershed, as indicated in Table 5-7 and Figure 5-13, annual average water balance error was -7%, while the highest and lowest annual water balance error was indicated as 29% and -7% respectively. Accordingly, it was shown good model performance to use in water resources management activities.

6.4.1.2 Model performance in Validation period

Though same period was selected for the calibration for both catchments, separate validation periods were selected, due to unavailability of good observed streamflow series at Giriulla catchment in recent years as shown in Table 4-7. Accordingly, validation period was selected as 2000/2001 to 2004/2005 for Giriulla and 2014/2015 to 2018/2019 for Badalgama catchments (Table 4-9). At the Giriulla Gauging station observed flows during the validation period vary between 0.1 m^3/s to 548 m^3/s, while the same at Badalgama watershed streamflow varies from 0.1 m^3/s to 1,447 m^3/s during the validation period.

The MRAE and RMSE values for the entire sorted flow regimes of Giriulla are 0.18 and 1.45 mm/day and same for the Badalgama watershed are 0.19 and 1.5 mm/day as illustrated in Table 5-8 and Table 5-10. Accordingly, it showed approximately 80% of accuracy in sorted flows. Further when considering the visual checking of annual hydrographs (Figure 5-18 and Figure 5-24), magnitudes and time of occurrence in high flows have been shown good agreement, while low flow magnitudes has been shown higher variation. Further, sorted and unsorted flow duration curves (Figure 5-22, Figure 5-23, Figure 5-28, and Figure 5-29), has been illustrated good agreement between observed and simulated streamflow. According to the statistical indicators, it was shown quite low accuracy due to poor low flow estimation within the model.

Besides, when considering the different flow spectrums, statistical indicators showed that, MRAE and RMSE values for the medium flows were 0.15 and 0.36 mm/day for the Giriulla and 0.18 and 0.59 mm/day for the Badalgama watershed. Accordingly, it indicates more than 80% of accuracy for both catchments in the medium flow spectrum, hence these models are accurate enough to use in water resources management activities.

As discussed in the above section 6.4.1.1, analysis on MRAE and RMSE values on an Annual basis were provided a better understanding of model behavior throughout the validation period. As shown in Table 6-3, highest and lowest MRAE values obtained at Giriulla gauging station in year 2000/2001 (0.27) and 2001/2002 (0.11). Similarly highest RMSE value indicated as 2.41 mm/day in 2000/2001 and the same for the lowest was 1.11 mm/day in the year 2002/2003. However, all the MRAE values indicated that, this model was well performed during the validation period as well, maintaining the highest MRAE value at 0.27. Further flow duration curves are given in APPENDIX E to further illustrate the behavior of flows spectrum in annually.

Table 6-3: Comparison of annual MRAE and RMSE variation in the validation period - Giriulla

Water Year	**Validation Results (Sorted)**	
	MRAE	**RMSE**
2000/01	0.27	2.41
2001/02	0.11	1.48
2002/03	0.24	1.11
2003/04	0.23	1.19

On the other hand, the annual water balance error at Giriulla catchment for the validation period was -20% as indicated in Table 5-9 and Figure 5-19. Lowest water balance error indicated in 2001/2002 as -12%, which further confirmed from the visual checking of flow hydrograph for the year 2001/2002 from the Figure 5-18.

Consequently, for the Badalgama Catchment annual variation of performance indicators including MRAE and RMSE were illustrated in Table 6-4 below. According to the aforementioned table, the lowest MRAE value was indicated in the year 2017/2018 as 0.31, which further confirmed through the visual checking of flow Hydrograph at Badalgama in Figure 5-24, though it underestimate low flows from January to March in 2017. Further flow duration curves are given in APPENDIX E to further illustrate the behavior of flows spectrum in annually.

Table 6-4: Comparison of annual MRAE and RMSE variation in the validation period - Badalgama

Water Year	Validation Results (Sorted)	
	MRAE	**RMSE**
2014/2015	0.34	2.47
2015/2016	1.31	2.42
2016/2017	0.51	1.32
2017/2018	0.31	2.03
2018/2019	0.53	1.41

In addition to that, the annual water balance error for the validation period of Badalgama was 11%, while the highest water balance error indicated in the 2016/2017 water year as 69%. The huge error occurred due to the presence of very low observed streamflow values in that particular year compared to the annual average rainfall. Based on all criteria, both models could be considered as satisfactorily validated models.

Figure 6-2 and Figure 6-3 illustrate the graphical representation of MRAE variation based on both unsorted and sorted flow duration curves in the entire period and different flow regimes including high, medium and low flow for both catchments. When considering unsorted FDC, at Giriulla, MRAE indicators for both calibration and validation for overall, high and medium flow phases show a good level of accuracy, while the same for the low flow shows high MRAE value for calibration and reasonably well indication in the validation.

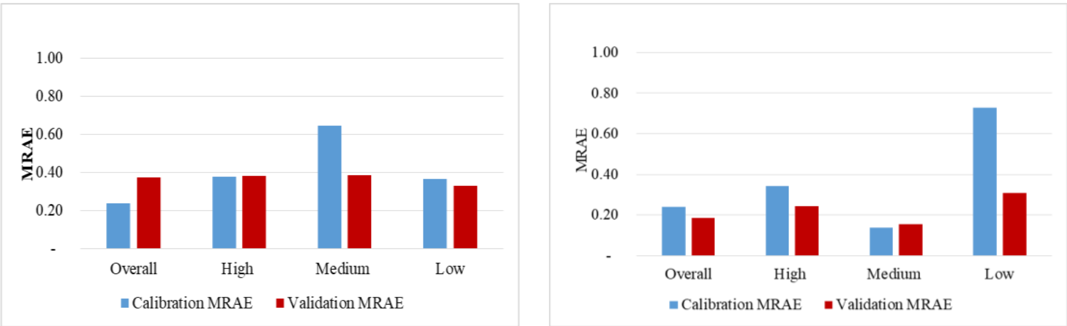


Figure 6-2: Unsorted (Left) and sorted (Right) performance indicators – Giriulla

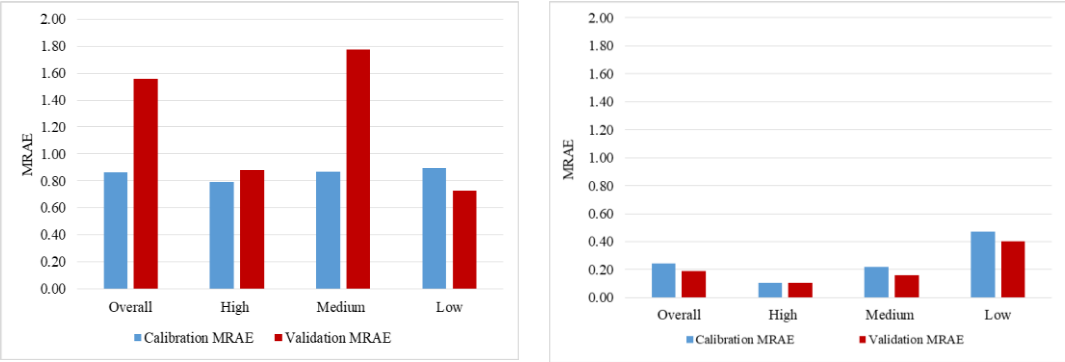


Figure 6-3: Unsorted (Left) and sorted (Right) Performance Indicators – Badalgama

In addition to that, Figure 6-4 shows the scatterplot of measured and modeled streamflow with the 1:1 line, which indicates the simulated streamflow distribution over observed streamflow at Giriulla and Badalgama catchments calibration period, while Figure 6-5 shows same for the validation period.

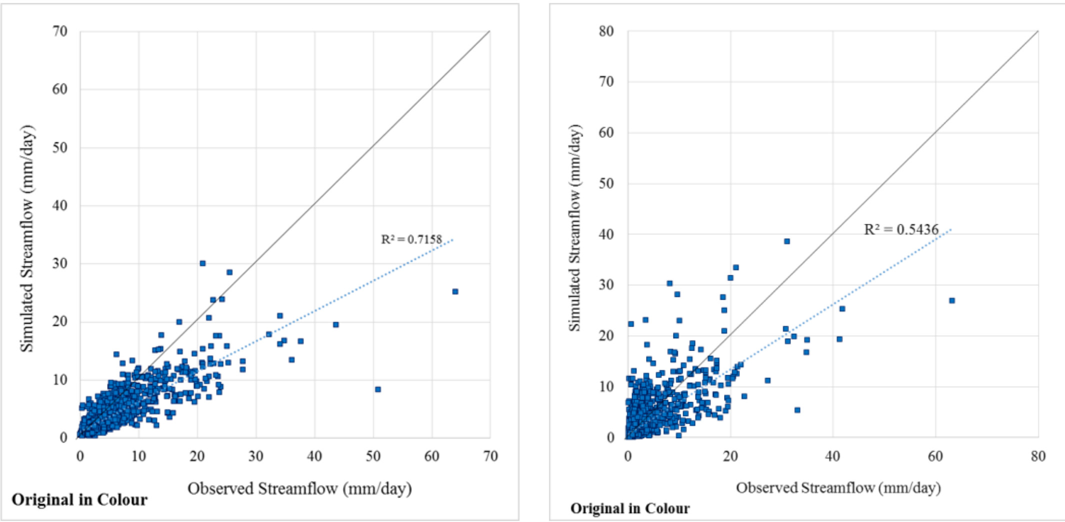


Figure 6-4: Observed streamflow vs, simulated streamflow for calibration period - Giriulla (Left) and Badalgama (Right)

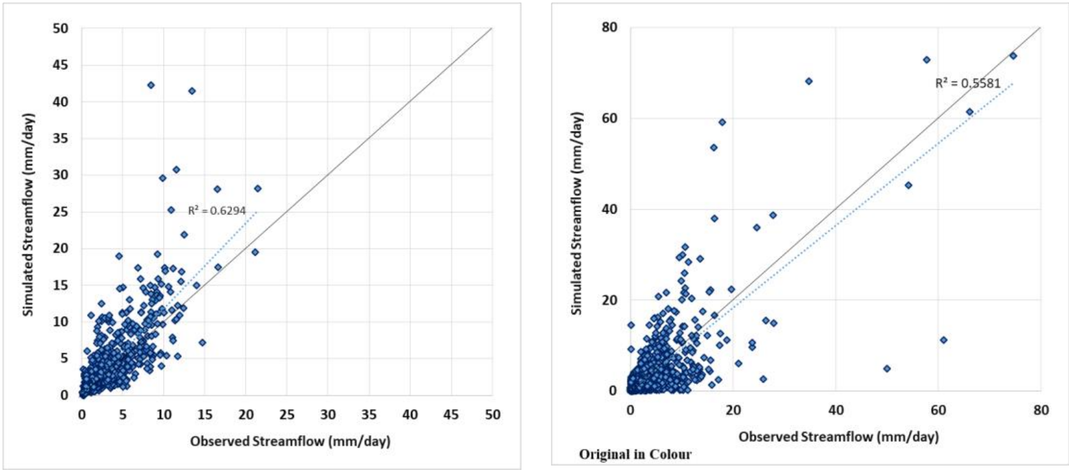


Figure 6-5: Observed streamflow vs, simulated streamflow for the validation period - Giriulla (Left) and Badalgama (Right)

According to the scatter plot in Figure 6-4, Giriulla and Badalgama watersheds, underestimated the simulated flow and R^2 value for both watersheds are 0.72 and 0.54 respectively. Similarly, the validation scatter plot Figure 6-5 shows that estimated streamflow at Griulla is slightly overestimated while the same for the Badalgama slightly underestimate the simulated flow. The R^2 value for both catchments are 0.63 and 0.56. However according to the observed vs simulated streamflow distribution, for both calibration and validation period is adequate for management and development of water resources activities.

6.5 Parameter Transferability

The primary objective of this study was to investigate the applicability of parameter transferability in the Maha Oya basin in data uncertain conditions. Accordingly, two gauged catchments were selected as Giriulla and Badalgama to perform this study, which was also associated with measured flow uncertainties. In the literature review, it was observed that, there are several transferability methods used globally (Patil & Stieglitz, 2015; Kokkonen et al. 2003). Based on the Shrestha et al., (2007), it was concluded that temporal transferability, spatial transferability and spatiotemporal transferability of parameters were the most promising methods to reproduce the runoff components, while capturing seasonal variations and annual variations in runoff. Further he stated that, this was associated with a donor catchment approach based on the similarity index. Besides Patil and Stieglitz, (2015), has confirmed that, spatiotemporal transferability also applicable to predict streamflow in ungauged catchments.

6.5.1 Selection of Parameter Transferability Approach

As stated in section 2.4, hydrological communities have been adopted different methodologies, to transfer the hydrological parameters to predict streamflow in ungauged catchments, since water resources management in ungauged watersheds are being a crucial requirement in developing world. Accordingly, hydrological model parameters are used as key instruments to predict hydrological responses and streamflow at the ungauged catchments (Razavi & Coulibaly, 2013). In that context, the majority of water resource planners and managers are preferred to adopt simple understandable methods. Loukas and Vasiliades (2014), highlighted that model parameter transferability from gauged catchment to ungauged catchment would satisfy this requirement.

Although, during the literature review, different approaches have been identified and listed out in Table 2-2, and among those none of the methods had been recommended to use worldwide. However according to Razavi and Coulibaly (2013), it was highlighted that, spatial proximity and physical similarity approach have been shown satisfactory performance for the warm temperature climates. Therefore, spatial transferability, which refers to transform parameters from one gauged catchment to ungauged catchment, was selected as one method to use in this study. In addition to that, temporal transferability and spatiotemporal transferability approaches were used to investigate the applicability of these methods.

6.5.2 Temporal Transferability

In this approach, the same model was tested with temporally different data sets. Accordingly, the Model developed for the Giriulla was tested for the period of 2000/2001 to 2003/2004 while the Badalgama model was tested for the period of 2014/2015 to 2018/2019.

According to the results, both models reproduced the streamflow with a good level of accuracy as shown in Table 5-17 and Table 5-19. Both Giriulla and Badalgama models showed that, more than 80% of overall accuracy for the temporal transferability, while showing approximately 85% of accuracy in medium flow spectrum. As the study concern was to perform water resources management activities, behavior of flow duration curve is very important, which sorted and unsorted FDC were shown in Figure 5-32, Figure 5-33, Figure 5-38 and Figure 5-39 for the Giriulla and Badalgama Catchments. Accordingly, it shows that, both models reproduce stream flows with a good accuracy level. Figure 6-6 and Figure 6-7 further illustrated the MRAE variation in graphically for the Giriulla and Badalgama respectively. It was further confirmed that, temporal transferability was at an acceptable level of accuracy.

When checking the annual average water balance as shown in the Table 5-18, Table 5-20, Figure 5-35, and Figure 5-41, it shows the -20% of annual water balance error at Giriulla and 11% of annual water balance error in Badalgama watershed separately, which further provide good confidence on temporal parameter transferability in both models. Similarly, when considering the seasonal scale, both models provided good temporal transferability results for the maha and Yala seasons as indicated in Figure 5-37 and Figure 5-42. Moreover, visual checking of annual flow hydrographs were shown in Figure 5-34 and Figure 5-40, which was demonstrated that, magnitude and time of occurrences of high flows were good enough to carry out water resources management activities.

6.5.3 Spatial Transferability

In this approach parameters were transferred spatially, with the same temporal similarity. Accordingly, optimized parameters at Giriulla watershed were directly applied in the Badalgama watershed for the period of 2005/2006 to 2009/2010, while optimized parameters of Badalgama were directly applied to the Giriulla model for the same period.

Statistical model performance at Giriulla showed as, in Table 5-21, the overall MRAE and RMSE values were 0.64 and 2.54 mm/day respectively. Similarly, for the Badalgama numerical indicators as MRAE and RMSE showed that 1.06 and 1.13 mm/day respectively. Based on the statistical indicators both models did not reproduce the streamflow in a good level of accuracy with the spatially transferred parameters. However, both models showed a good level of accuracies in high flow regimes, such as MRAE for Giriulla was 0.38, and the same for the Badalgama was 0.1.

When checking the yearly performance in Spatial Transferability, as illustrated in Table 6-5, the highest MRAE value indicated in the year 2007/2008 as 0.674. Most of the years indicated less than 40% of accuracy at Giriulla. Similarly annual variation of MRAE and RMSE values at Badalgama are indicated in Table 6-6, which shows very high MRAE values 2006/2007, 2008/2009 and 2009/2010.

Table 6-5: Annual model performance for Spatial Transferability - Giriulla

Water Year	**Spatial Transferability Results (Sorted)**	
	MRAE	**RMSE**
2005/06	0.668	2.338
2006/07	0.553	3.988
2007/08	0.674	2.947
2008/09	0.578	1.718
2009/10	0.673	2.548

Table 6-6: Annual model performance for Spatial Transferability - Badalgama

Water Year	**Spatial Transferability Results (Sorted)**	
	MRAE	**RMSE**
2005/06	0.52	0.84
2006/07	1.37	1.84
2007/08	0.52	0.85
2008/09	2.07	1.36
2009/10	1.17	1.50

In addition to that, it can be seen in sorted and unsorted flow duration curves as indicated in Figure 5-44, Figure 5-45 at Giriulla, simulated flows were highly underestimated with compared to observed flows, while same for the Badalgama watershed was highly overestimated as signposted in Figure 5-50 and Figure 5-51. However, this, variation in simulated flows occurred due to observed flow uncertainties.

For the spatial transferability, the Giriulla watershed shows that the Annual average water balance error as -49% as indicated in Table 5-22 and Figure 5-47 while the same for the Badalgama was indicated the 30% as shown in Table 5-24 and Figure 5-53.

The magnitude of high and low flows were not shown good agreement with observed flows, but the time of occurrence was at a satisfactory level of accuracy.

Moreover, high and medium flow prediction accuracy of spatial transferability at Giriulla is 62% and 56%, while same at Badalgama watershed shows 90% and 15% accuracies respectively.

6.5.4 Spatiotemporal Transferability

In this approach, optimized model parameters at Giriulla Catchment were directly applied to the Badalgama watershed, under temporally different condition. Consequently, optimized parameters at Badalgama catchment were directly applied to the Giriulla catchment for different periods. Accordingly, spatiotemporal transferability was checked from 2000/2001 to 2003/2004 for Giriulla catchment and 2014/2015 to 2018/2019 was checked for the Badalgama Watershed.

Based on the statistical model performance evaluation as shown in Table 5-23 and Table 5-25 for Giriulla and Badalgama, streamflow were reproduced at a very low level of accuracy as indicated in the spatial transferability section. Under this approach, also similar behavior has been shown likely spatial transferability. As stated in the previous section, in this approach also high flows (83% at Giriulla) regimes have been shown comparatively good agreement with compared to medium and low flows, which can be seen in Figure 6-6 and Figure 6-7 for further understanding. The annual flow hydrographs confirmed that the magnitude of high and low flows was not re-produced correctly by the model, though the time of occurrence showed an acceptable level of agreement. Numerical performance on an annual basis was shown in Table 6-7 and Table 6-8 showed best MRAE value as 0.28. As shown in APPENDIX E, 2005/2006 to 2014/2015 observed flows at Giriulla watershed was higher than the Badalgama Watershed, though Giriulla Gauging station located far upstream of the catchment.

Table 6-7: Annual model performance for spatiotemporal transferability - Giriulla

Water Year	Spatiotemporal Transferability Results (Sorted)	
	MRAE	RMSE
2000/01	0.72	2.52
2001/02	0.67	1.85
2002/03	0.69	1.99
2003/04	0.71	1.61

Table 6-8: Annual model performance for spatiotemporal transferability – Badalgama

Water Year	Spatiotemporal Transferability Results (Sorted)	
	MRAE	RMSE
2014/15	2.50	2.54
2015/16	8.59	3.62
2016/17	0.98	0.70
2017/18	1.22	2.98
2018/19	0.28	1.83

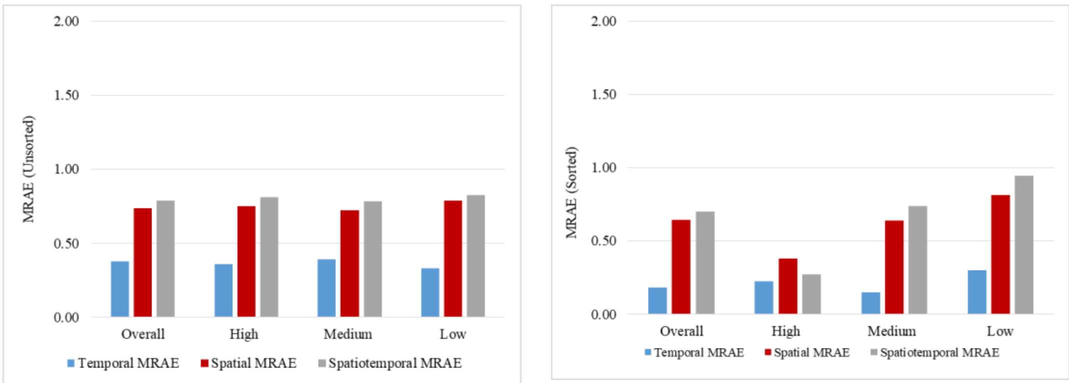
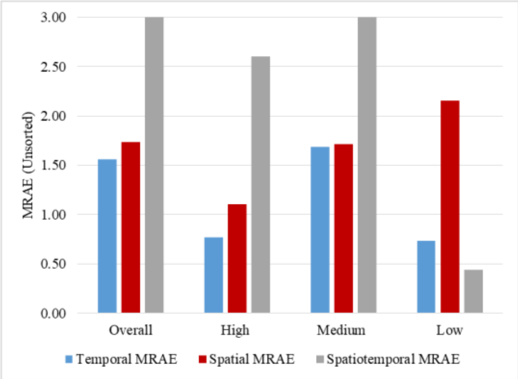


Figure 6-6: Performance Indicators for parameter Transferability - Giriulla



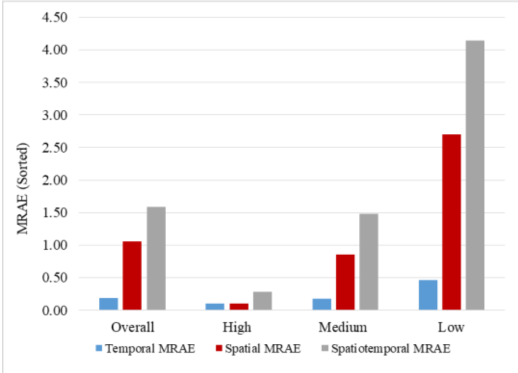


Figure 6-7: Performance indicators for parameter transferability - Badalgama

6.5.5 Transferability of model parameters for the entire period

In this approach, entire periods were considered to evaluate the parameter transferability in temporally, spatially and spatiotemporally, using two gauged catchments such as Badalgama and Giriulla. One reason to select those watersheds that are most similar to the site of interest and common area percentage of the catchment is 86%. By using available time-series data both models have been satisfactorily calibrated and validated as demonstrated in the above sections. Following that, optimized parameters of Badalgama catchment (main) were applied to the Giriulla catchment (sub-catchment) for the period of 2000/2001 to 2009/2010. Similarly, optimized parameters of Giriulla catchment was applied for the Badalgama catchment for the period of 2005/2006 to 2018/2019.

The graphical representation of flow hydrographs with transferred parameters at Giriulla watershed indicated an underestimation of simulated flows (Figure 5-68 and Figure 5-69). Similarly FDC curve in Figure 5-73 also clearly shows that, estimated flows are underestimated and the magnitude of discrepancies is increased from high flows to low flows.

Disparately, flow hydrographs at Badalgama catchments with transferred parameters show that, estimated flows are overestimated, especially in low flows. The sorted and unsorted flow duration curves also have been shown similar variation in Figure 5-73 and Figure 5-74. These FDC curves show good agreement in high flows, which might be occurred due to the saturation condition of the catchments. The scatter plot further demonstrate the observed flows vs simulated flows with transferred parameters in

Figure 6-8: Overall MRAE values for the entire flow spectrum is 0.66 for the Giriulla and 1.42 for the Badalgama, which is not acceptable.

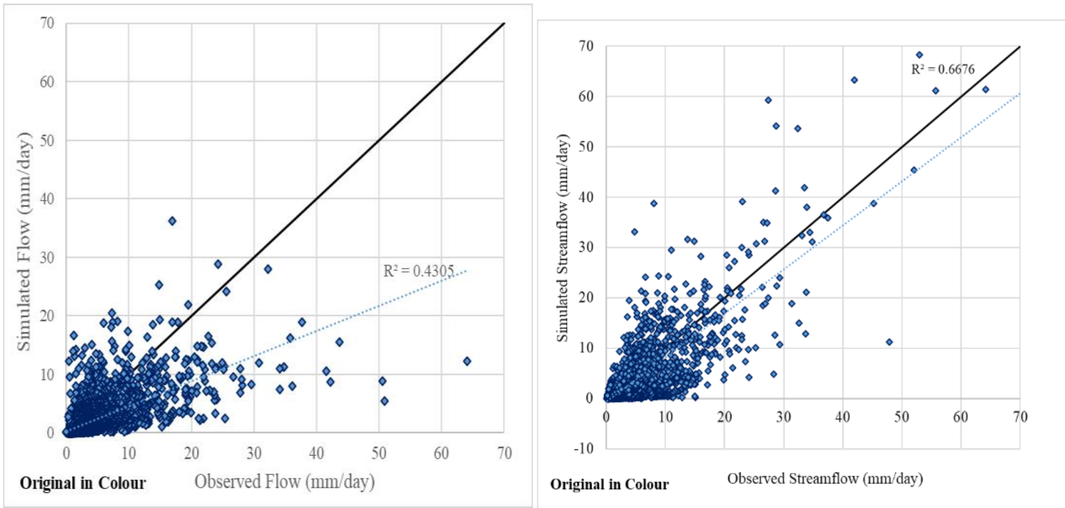


Figure 6-8: Scatter plot of observed vs simulated streamflow with transferred parameters - Giriulla (Left) and Badalgama (Right)

Moreover, according to the model results, it only shows less than 40% of overall accuracy level and yearly performance of transferability results with respect to numerical indicators of RMSE and MRAE values of Giriulla watershed as shown in the Table 6-9. But accuracy of Badalgama was shown in Table 6-10. According to the MRAE values in the table, it clearly shows these values are not in the acceptable level, especially in the Badalgama catchment. The uncertainties in observed flows might significantly influence the model results as well.

Table 6-9:Comparison of annual MRAE and RMSE values with transferred parameters at Giriulla catchment

Water Year	**Transferability Results (Sorted)**	
	MRAE	**RMSE**
2000/01	0.72	2.52
2001/02	0.67	1.85
2002/03	0.69	1.99
2003/04	0.71	1.61
2004/05	0.63	3.01
2005/06	0.67	2.34
2006/07	0.56	4.02
2007/08	0.67	3.39
2008/09	0.58	1.72
2009/10	0.67	2.55

Table 6-10: Comparison of annual MRAE and RMSE values with transferred parameters at Badalgama catchment

Water Year	Transferability Results (Sorted)	
	MRAE	**RMSE**
2005/06	0.60	0.79
2006/07	1.37	1.84
2007/08	0.52	0.85
2008/09	2.96	2.08
2009/10	1.17	1.50
2010/11	0.93	3.54
2011/12	1.94	0.83
2012/13	1.70	2.39
2013/14	6.29	1.92
2014/15	2.50	2.54
2015/16	8.59	3.62
2016/17	0.98	0.70
2017/18	1.22	2.98
2018/19	0.28	1.83

The error in average annual water balance at Giriulla watershed was 50%, with underestimated streamflow as shown in Table 5-30 and the lowest water balance error occurred in the year 2008/2009 as -39%. Similarly, for Badalgama watershed with transferability parameters, annual water balance error was 47% with overestimated streamflow. The yearly water balance errors are indicated in Table 5-32 and the lowest error occurred in the year 2007/2008 as 10%, while showing a very high annual water balance error in 2013/2014.

7 CONCLUSION AND RECOMMENDATION

7.1 Conclusion

1. The lumped model has been developed for Giriulla and Badalgama watersheds in Maha Oya Basin, which was underpinned in the HEC-HMS model platform. Accordingly HEC-HMS hydrological model could be used to simulate streamflow at selected gauging stations with approximately 75% of overall accuracy for water resources management activities, while showing comparatively good confidence in high flow (68% in Giriulla and 88% in Badalgama) and medium flow (87% in Giriulla and 77% in Badalgama) regimes.

2. SCS Unit hydrograph transform method was used to estimate direct runoff, deficit and constant loss method was used to estimate the runoff volume and recession method was used as baseflow estimation method in this study. Based on the model results, it was revealed that the recession method is not much suitable to reproduce the low flows in this catchment.

3. Semi-automatic optimization approach showed over 75% of accuracy with compared to automatic optimization, which showed approximately 60% of accuracy for both catchments.

4. This study results further revealed that, temporal transferability is the best approach to transfer the hydrological parameters to reproduce the streamflow in daily time steps at Giriulla and Badalgama watersheds by capturing approximately 80% of overall accuracy level.

5. Accordingly, at Giriulla watershed high and medium flow prediction accuracy for temporal transferability are 76% and 85%, while same for Badalgama watershed are 89% and 84%. However low flow prediction accuracy maintained approximately less than 60% for both watersheds.

6. Annual water balance error at Giriulla is over estimated 20%, while indicating seasonal water balance errors are overestimated 23% (Maha) and 17% (Yala). Similarly, at Badalgama average water balance error is underestimated 11%,

and seasonal water balance errors are underestimated 8% and 20% for Maha and Yala seasons respectively.

7. However spatial transferability and spatiotemporal transferability cannot be performed with good confidence (overall MRAE for spatial transferability: 0.7 for Giriulla and 1.06 for Badalgama; overall MRAE for spatiotemporal transferability: 0.70 for Giriulla and 1.59 for Badalgama), though both catchments have similar hydrological heterogeneity.

8. The capability of parameter transferability depend on application in water resources management, requirement of temporal resolution and catchment characteristics.

7.2 Recommendation

1. The recession method has been used in this study to estimate the base flow. However, it was not responded well especially in dry periods, which caused to increase the mass balance error. Therefore, it is recommended to improve the base flow simulation accuracy by considering the linear reservoir method.

2. This study could be improved with the application of Climate change factors in temporal transferability and spatiotemporal transferability.

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APPENDIX A – DATA AND DATA CHECKING AT GIRIULLA

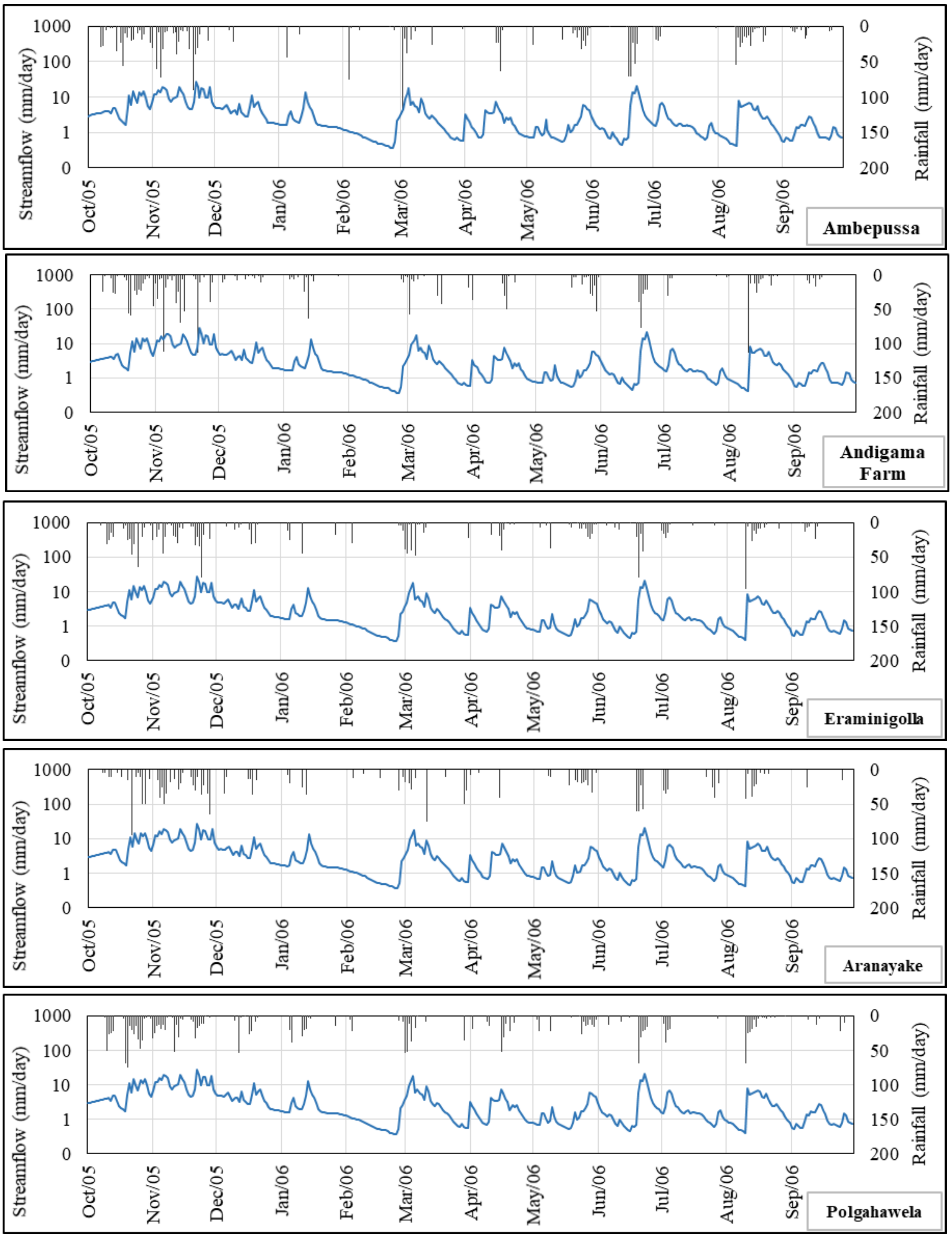


Figure A-1: Rainfall responses from each station in year 2005/2006

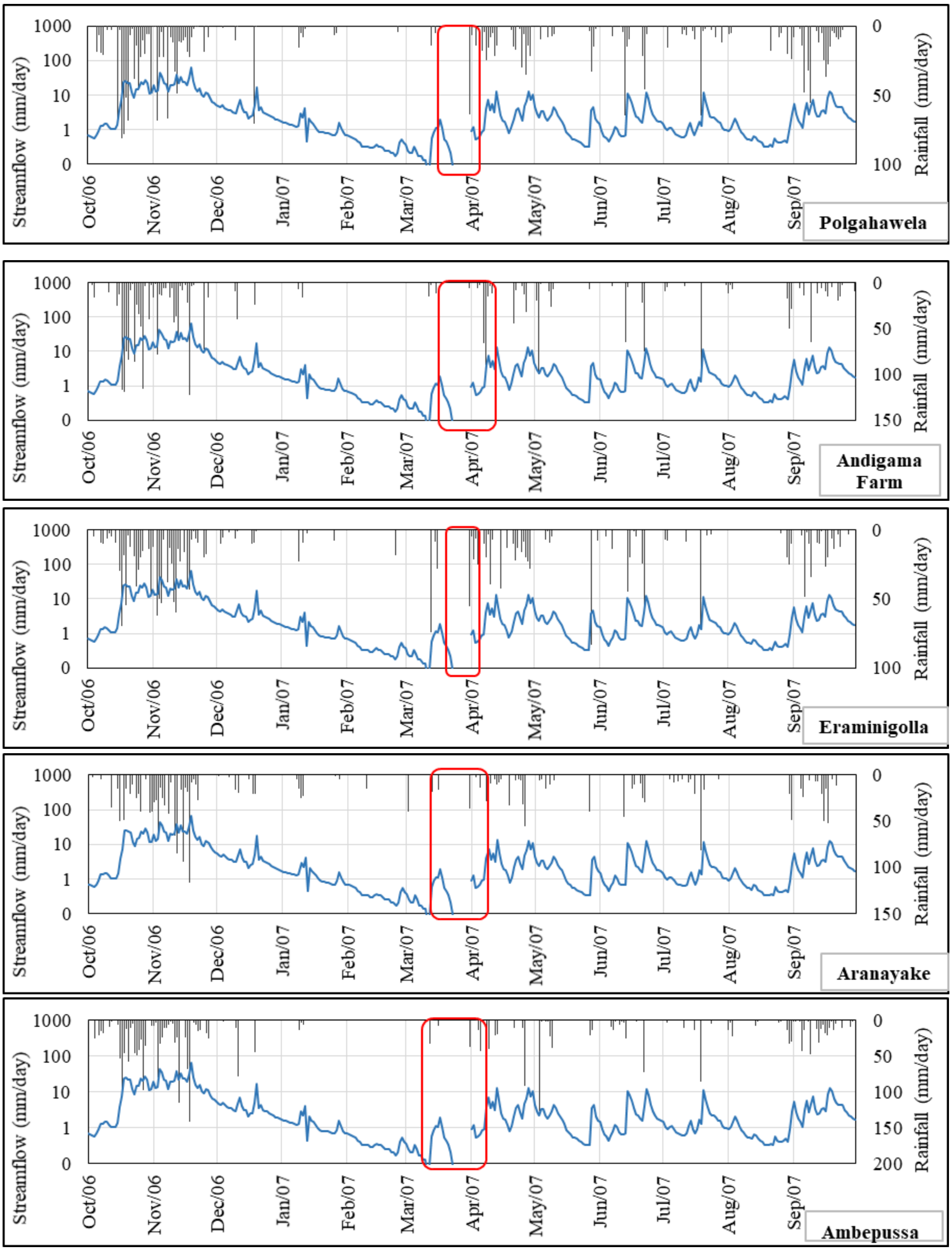


Figure A-2: Rainfall responses from each station in year 2006/2007

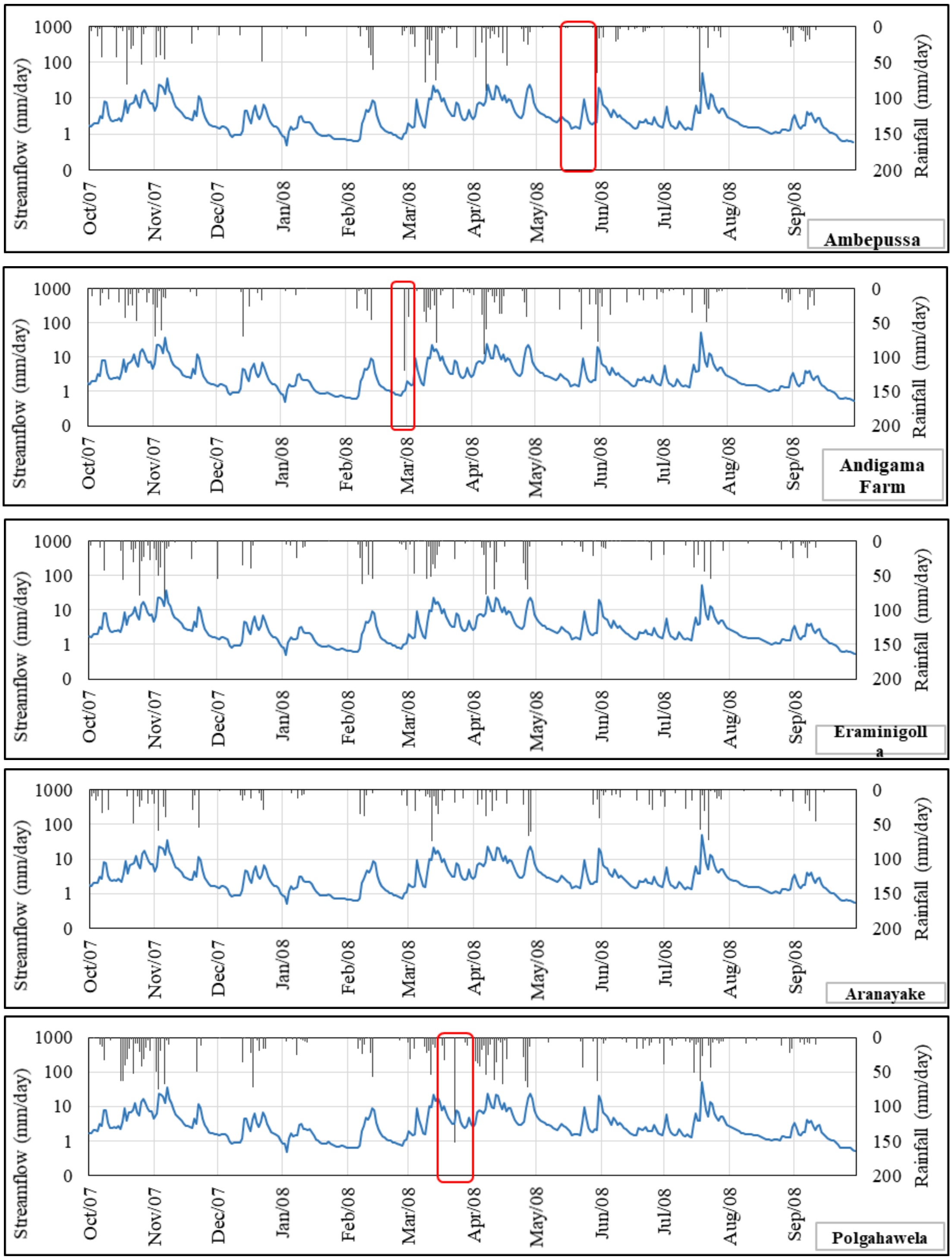


Figure A-3: Rainfall responses from each station in year 2007/2008

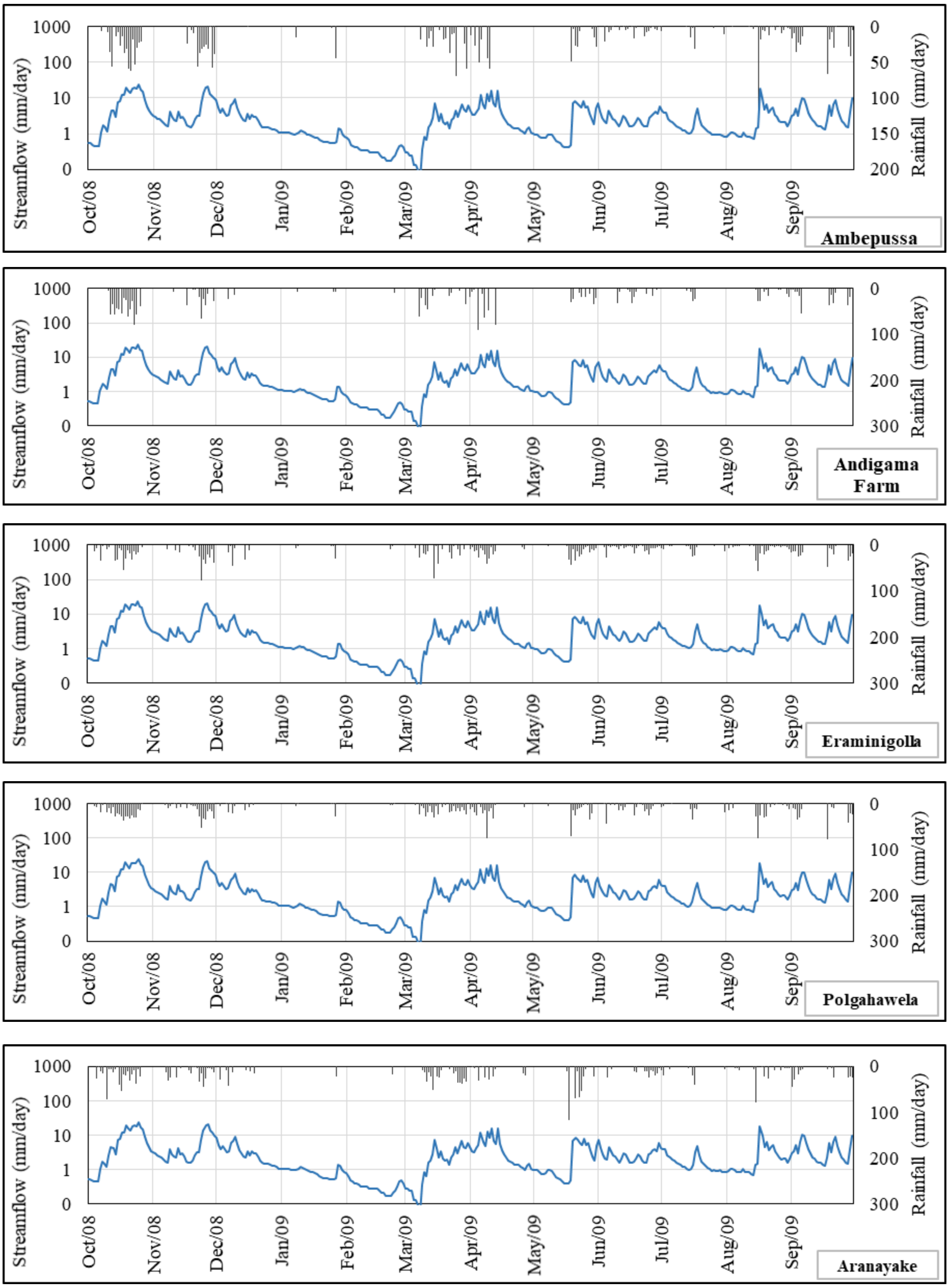


Figure A-4: Rainfall responses from each station in year 2008/2009

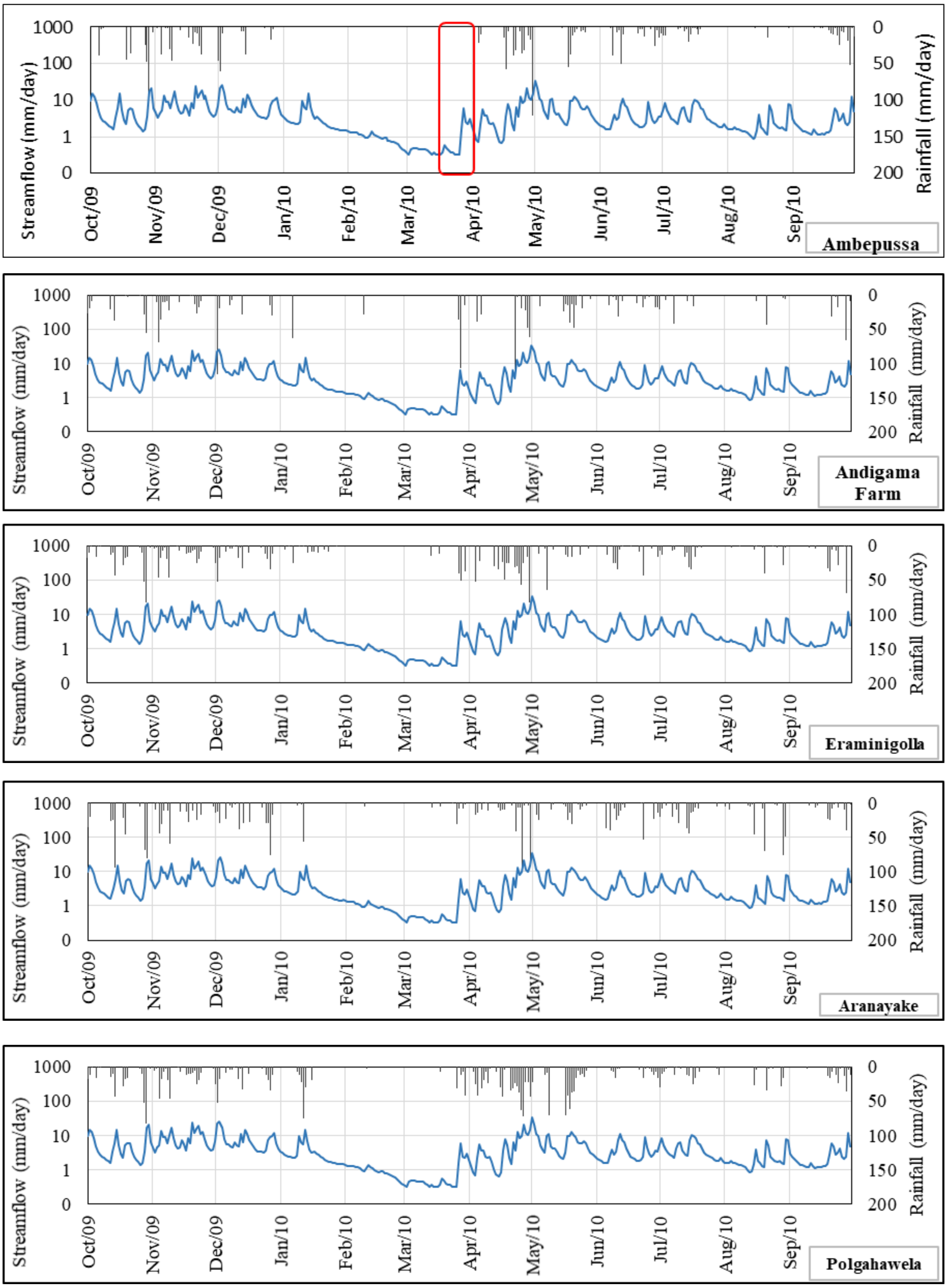


Figure A-5: Rainfall responses from each station in year 2009/2010

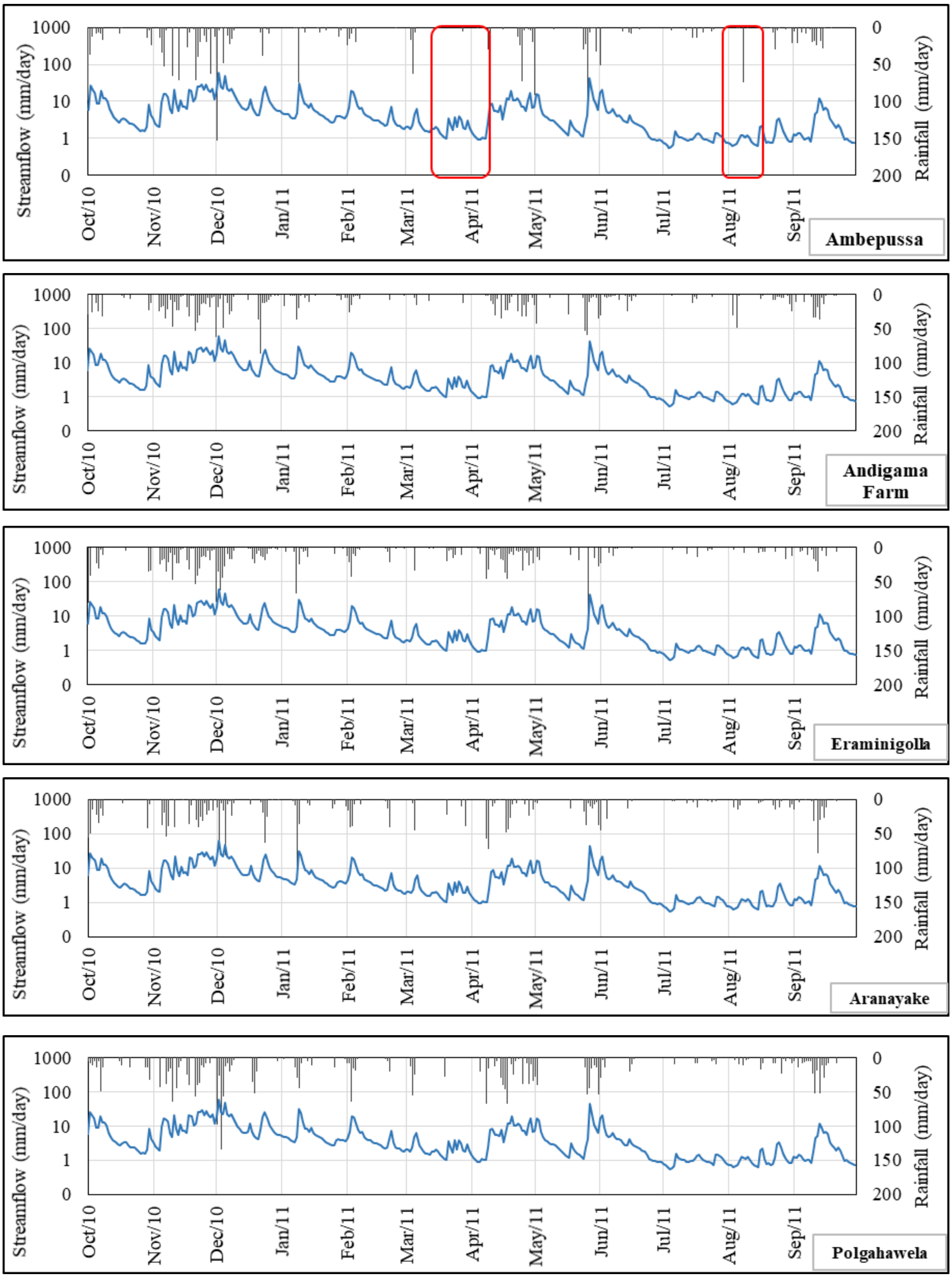


Figure A-6: Rainfall responses from each station in year 2010/2011

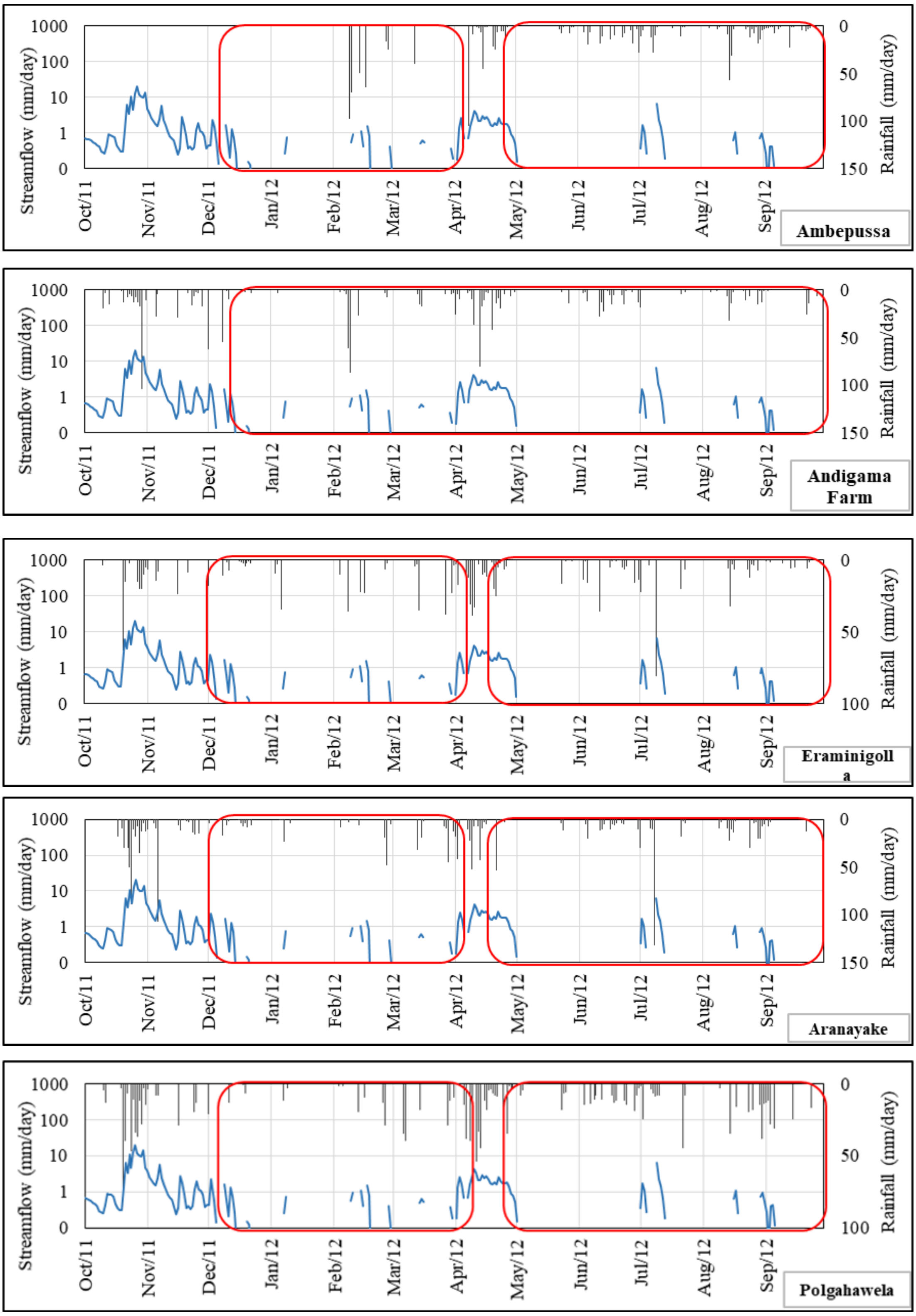


Figure A-7: Rainfall responses from each station in year 2011/2012

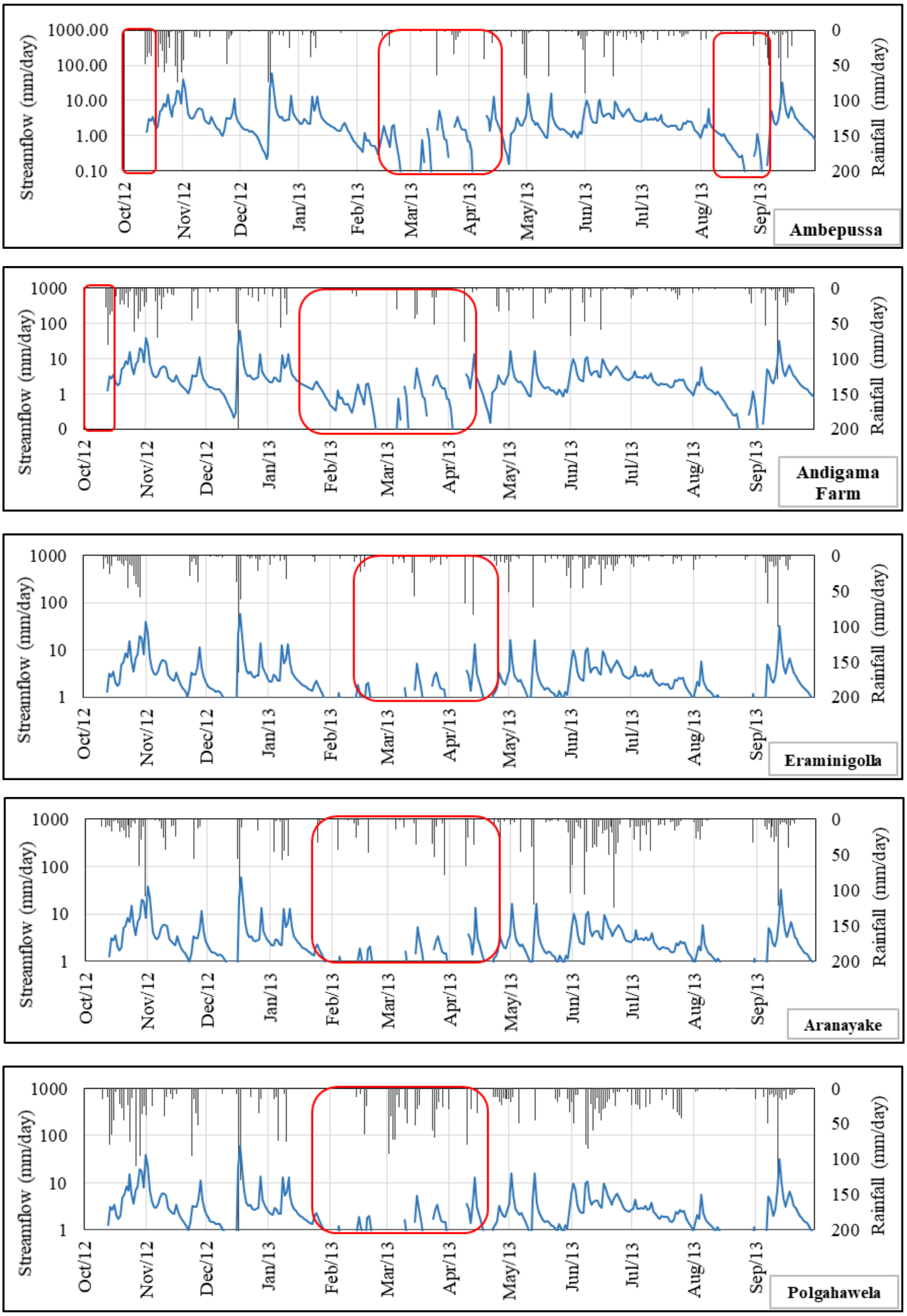


Figure A-8: Rainfall responses from each station in year 2012/2013

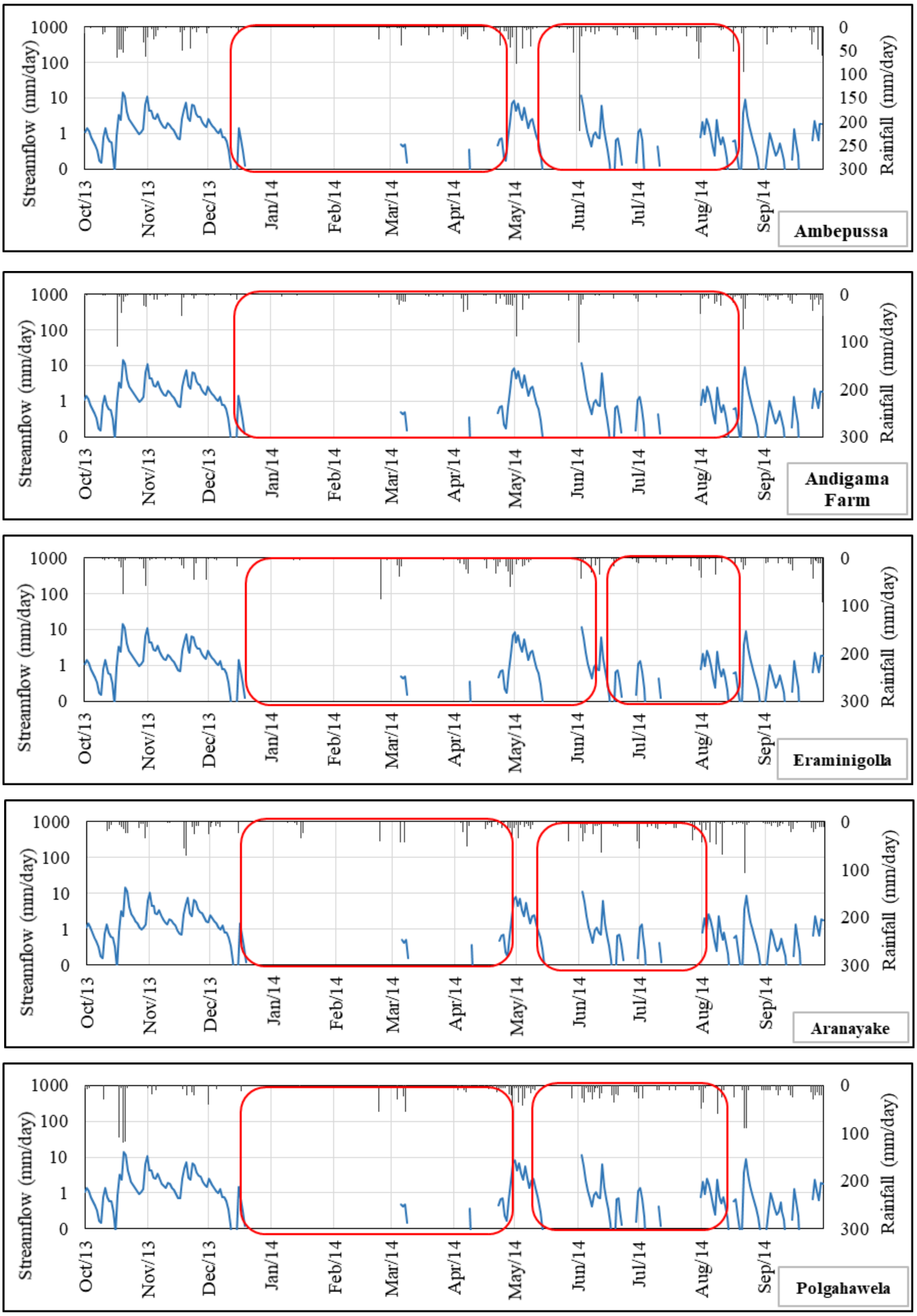


Figure A-9: Rainfall responses from each station in year 2013/2014

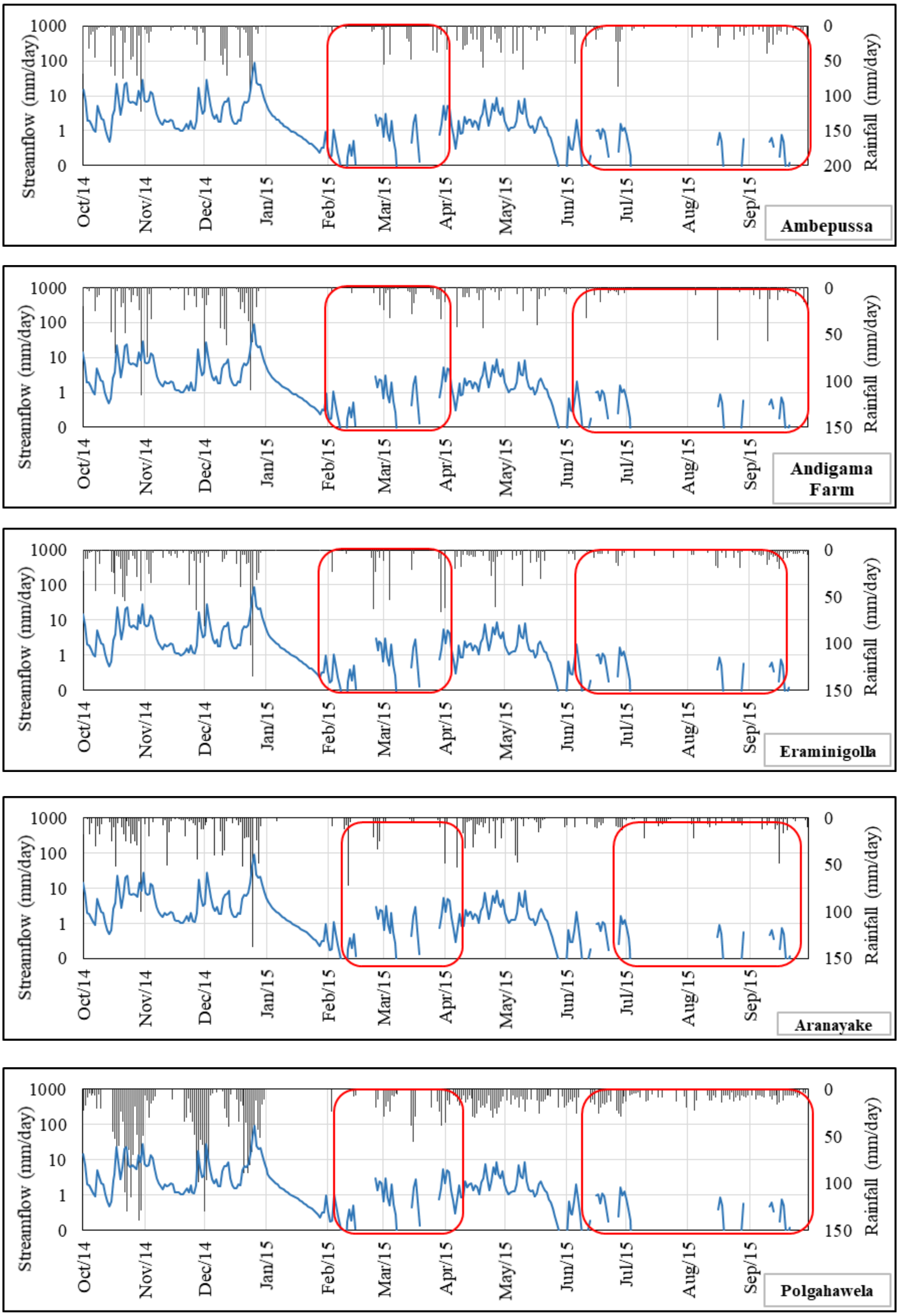


Figure A-10: Rainfall responses from each station in year 2014/2015

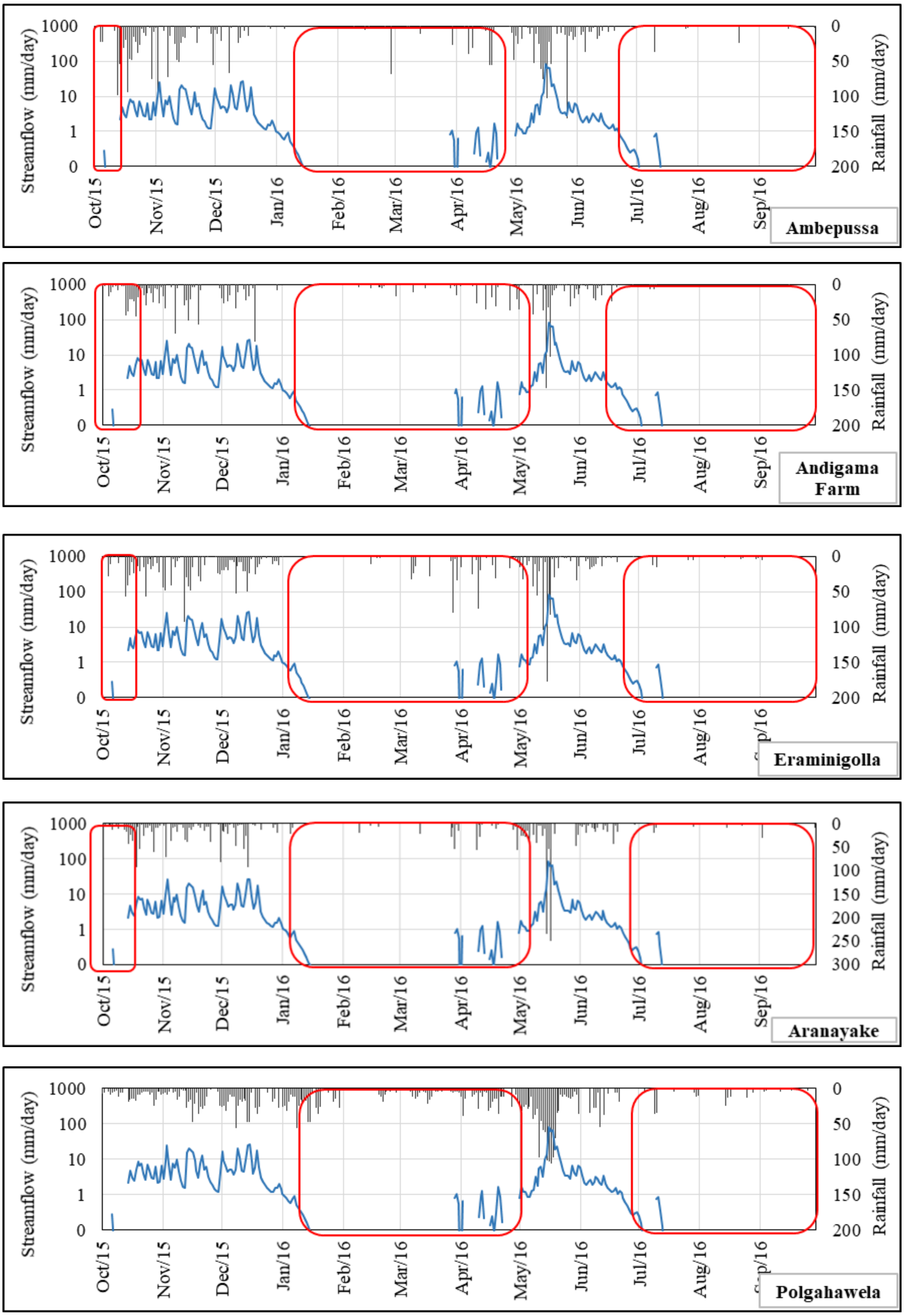


Figure A-11: Rainfall responses from each station in year 2015/2016

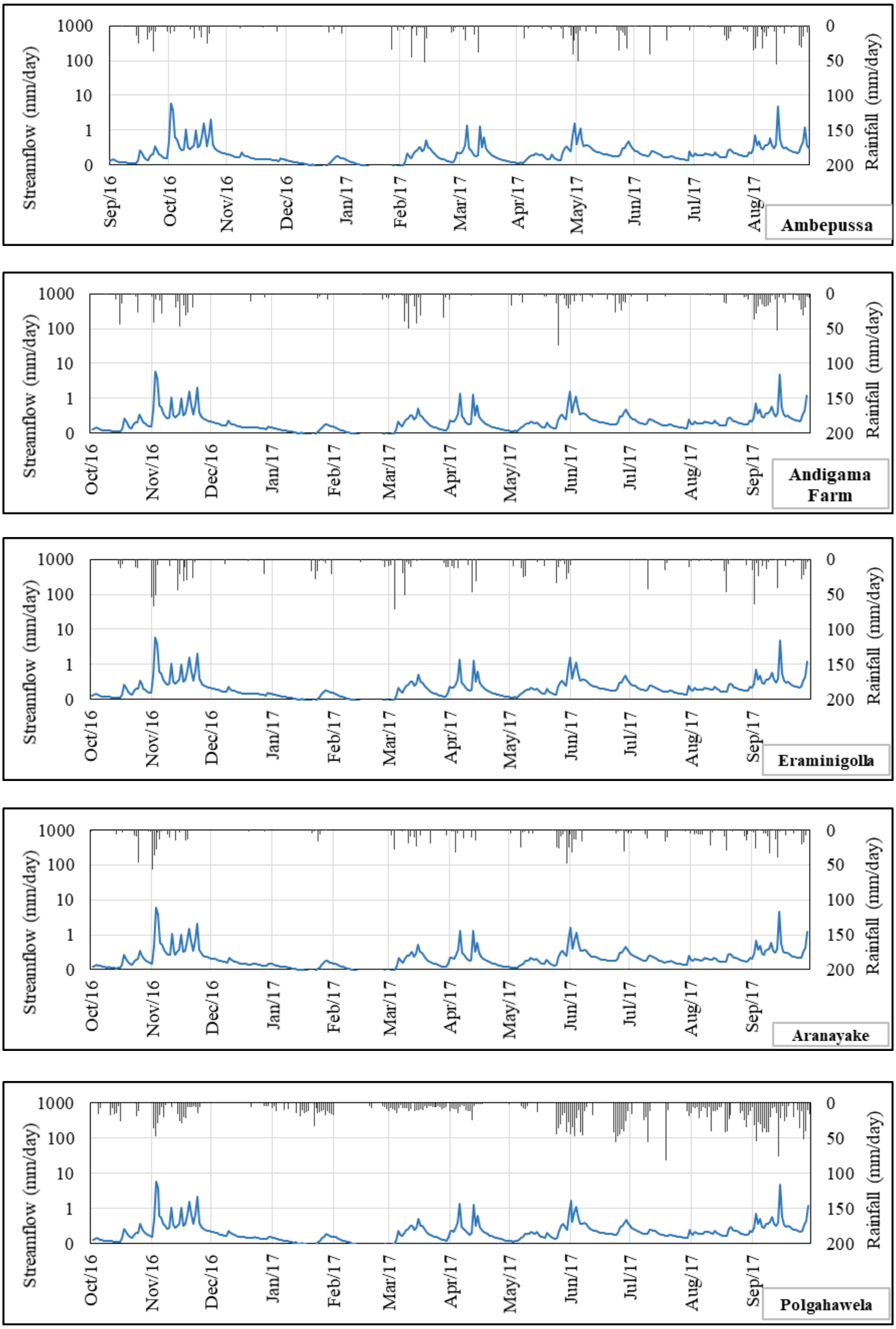


Figure A-12: Rainfall responses from each station in year 2016/2017

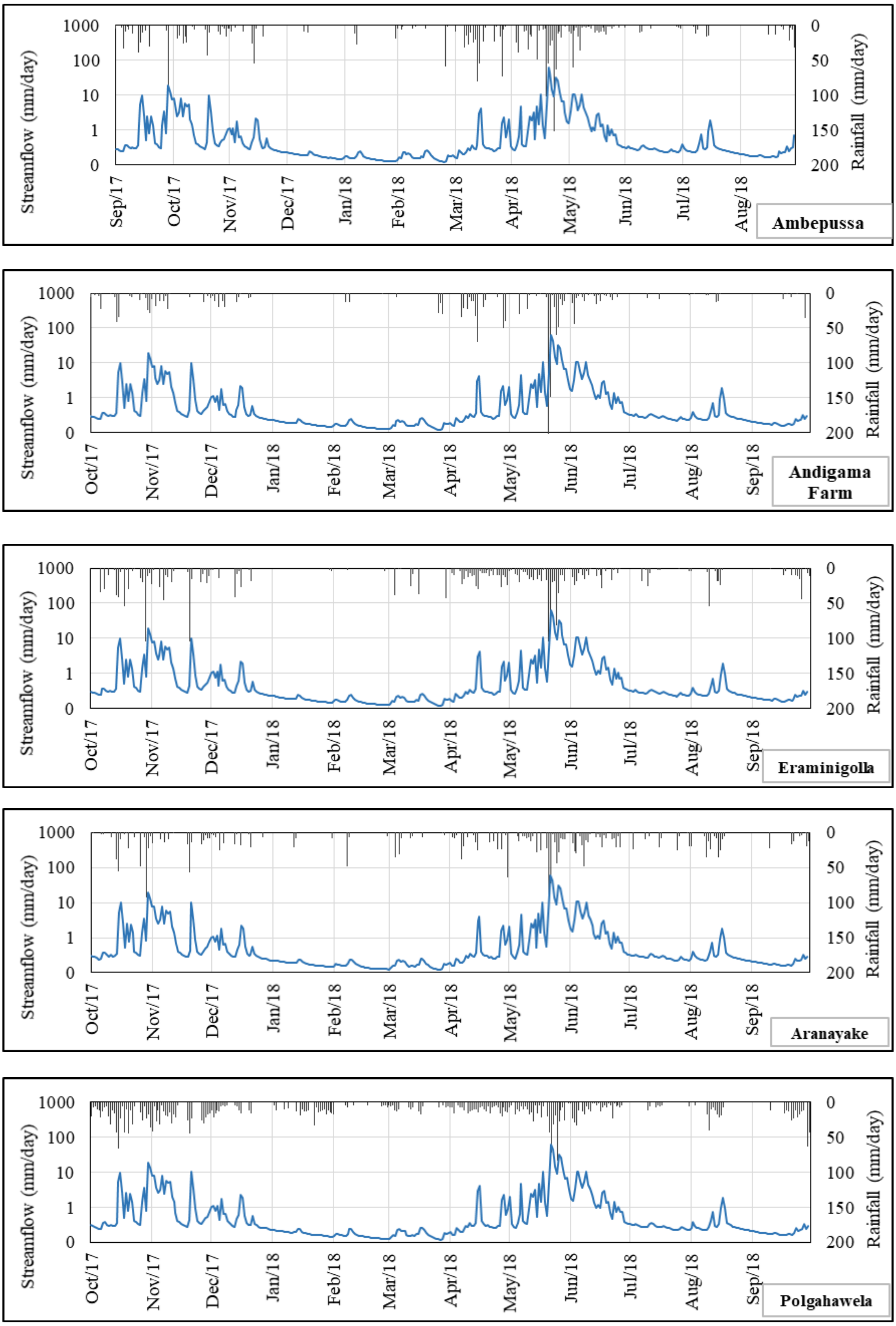


Figure A-13: Rainfall responses from each station in year 2017/2018

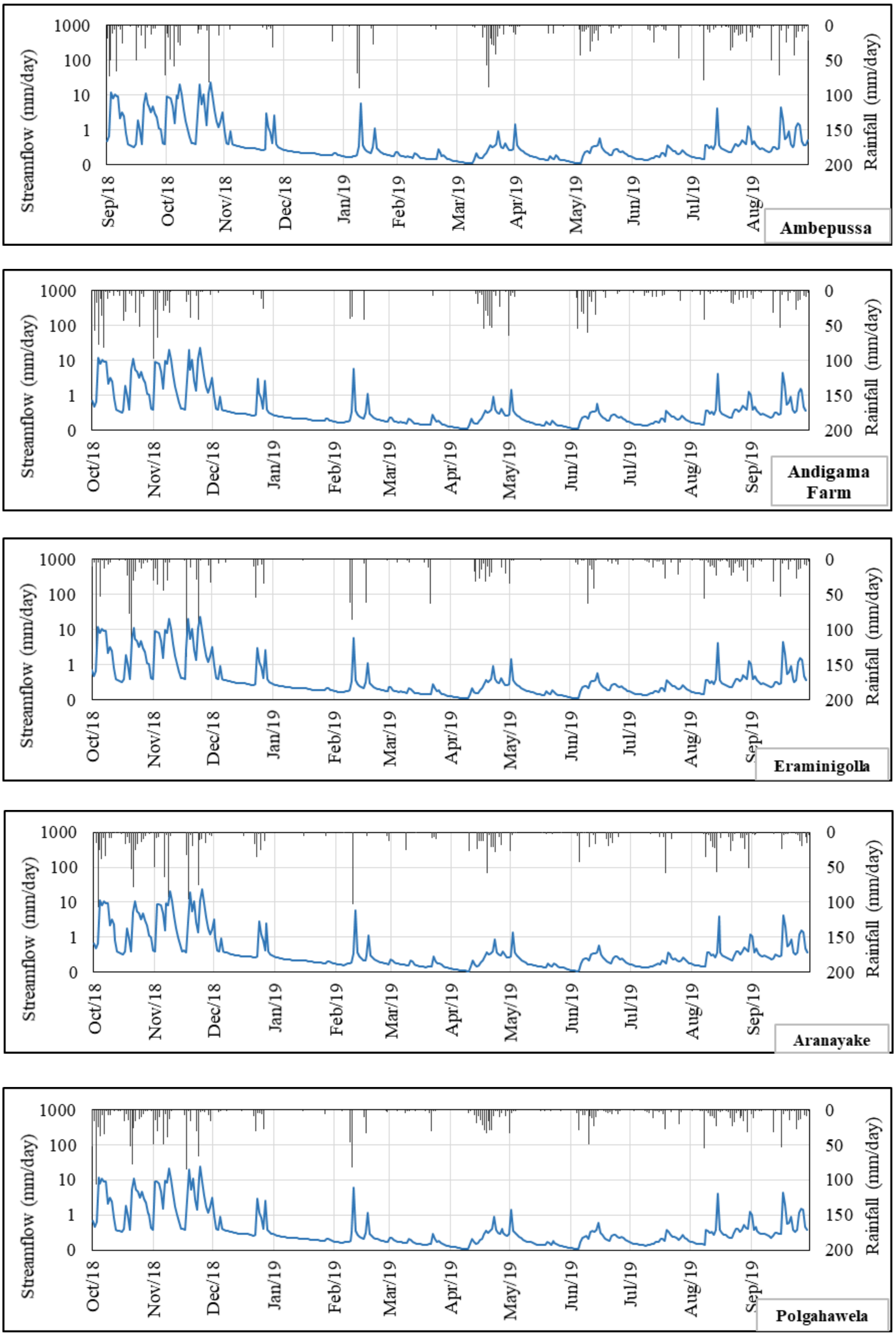


Figure A-14: Rainfall responses from each station in year 2018/2019

APPENDIX B – DATA CHECKING AT BADALGAMA

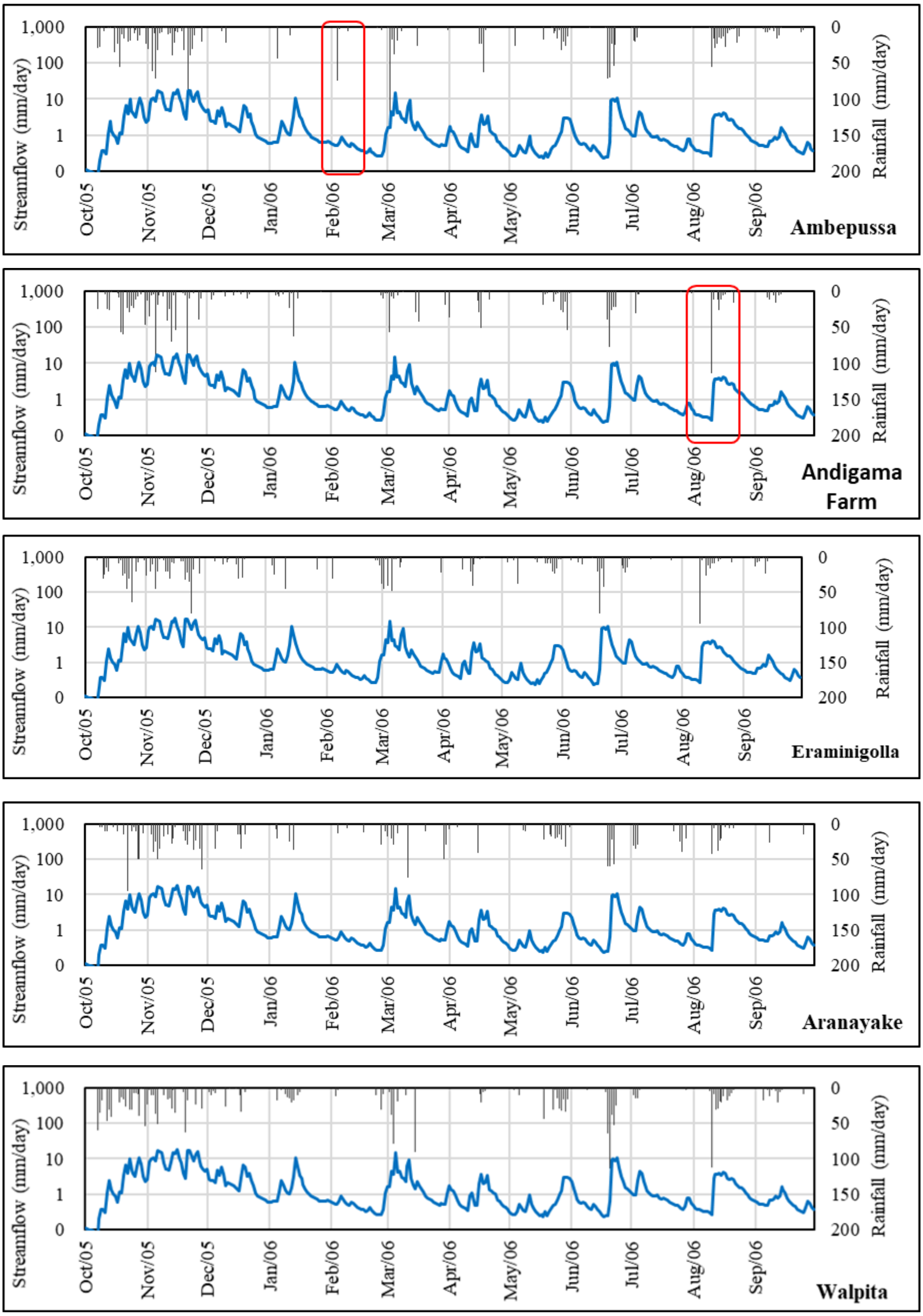


Figure B-1: Rainfall responses from each station in year 2005/2006

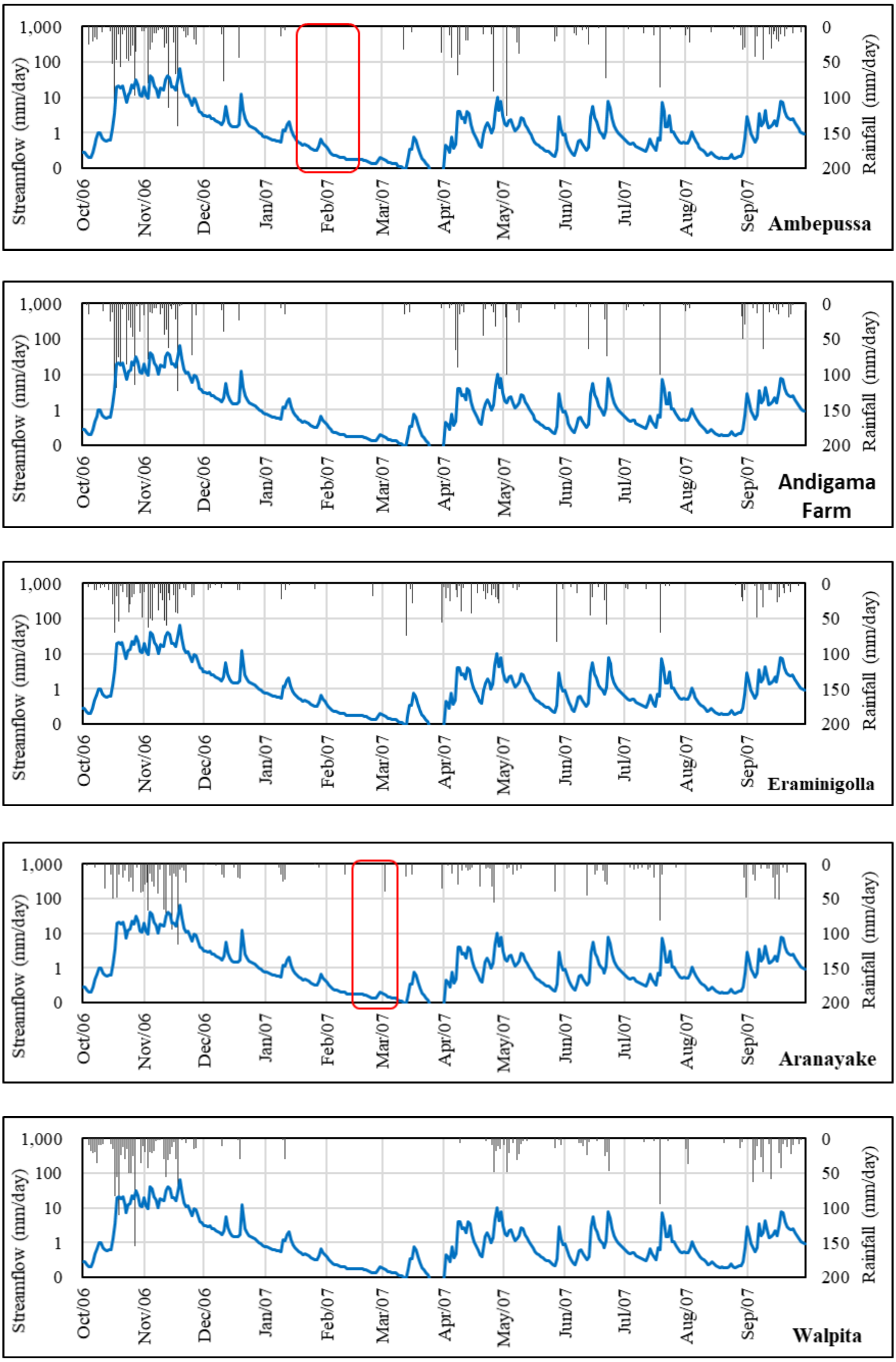


Figure B-2: Rainfall responses from each station in year 2006/200

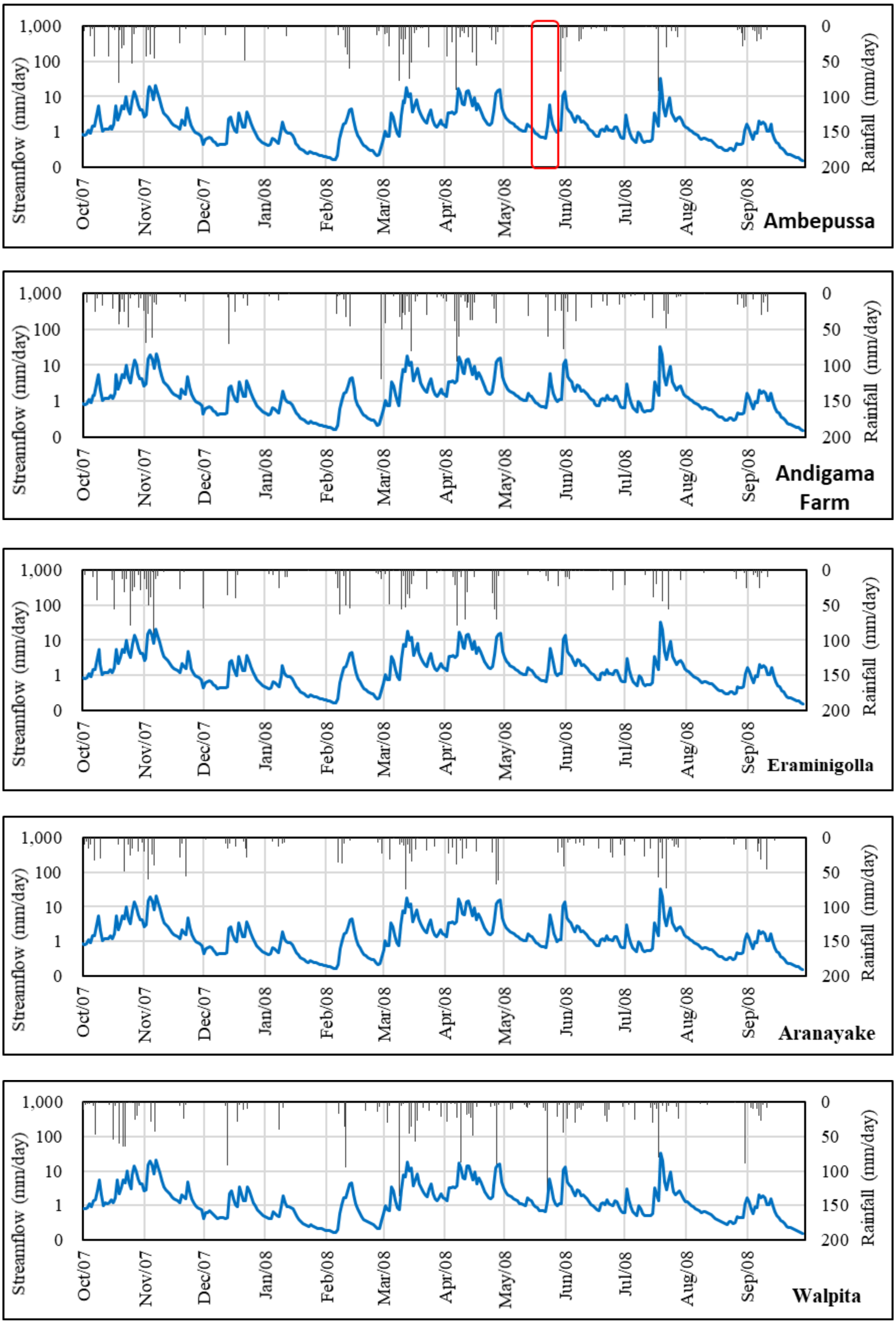


Figure B-3: Rainfall responses from each station in year 2007/2008

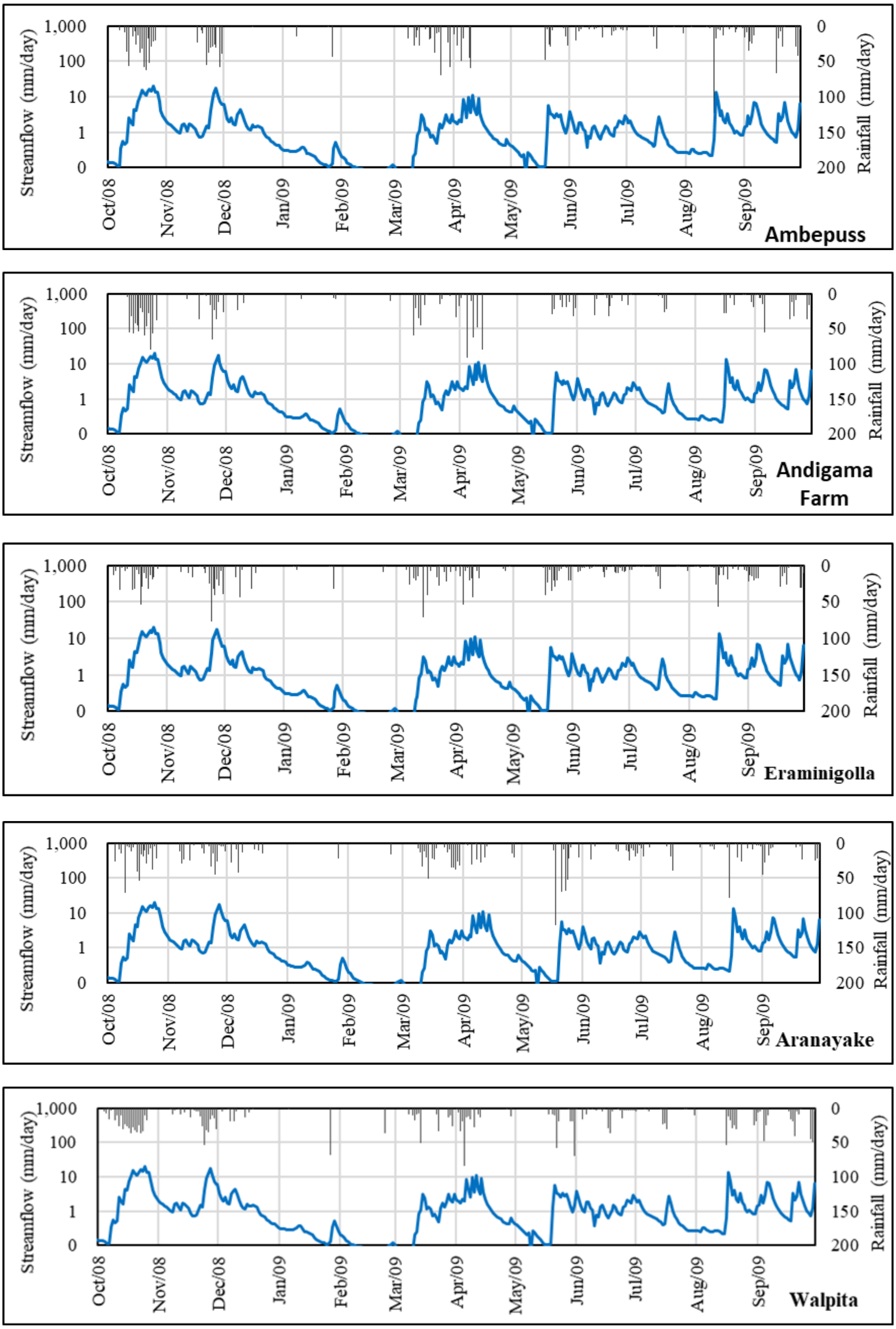


Figure B-4: Rainfall responses from each station in year 2008/2009

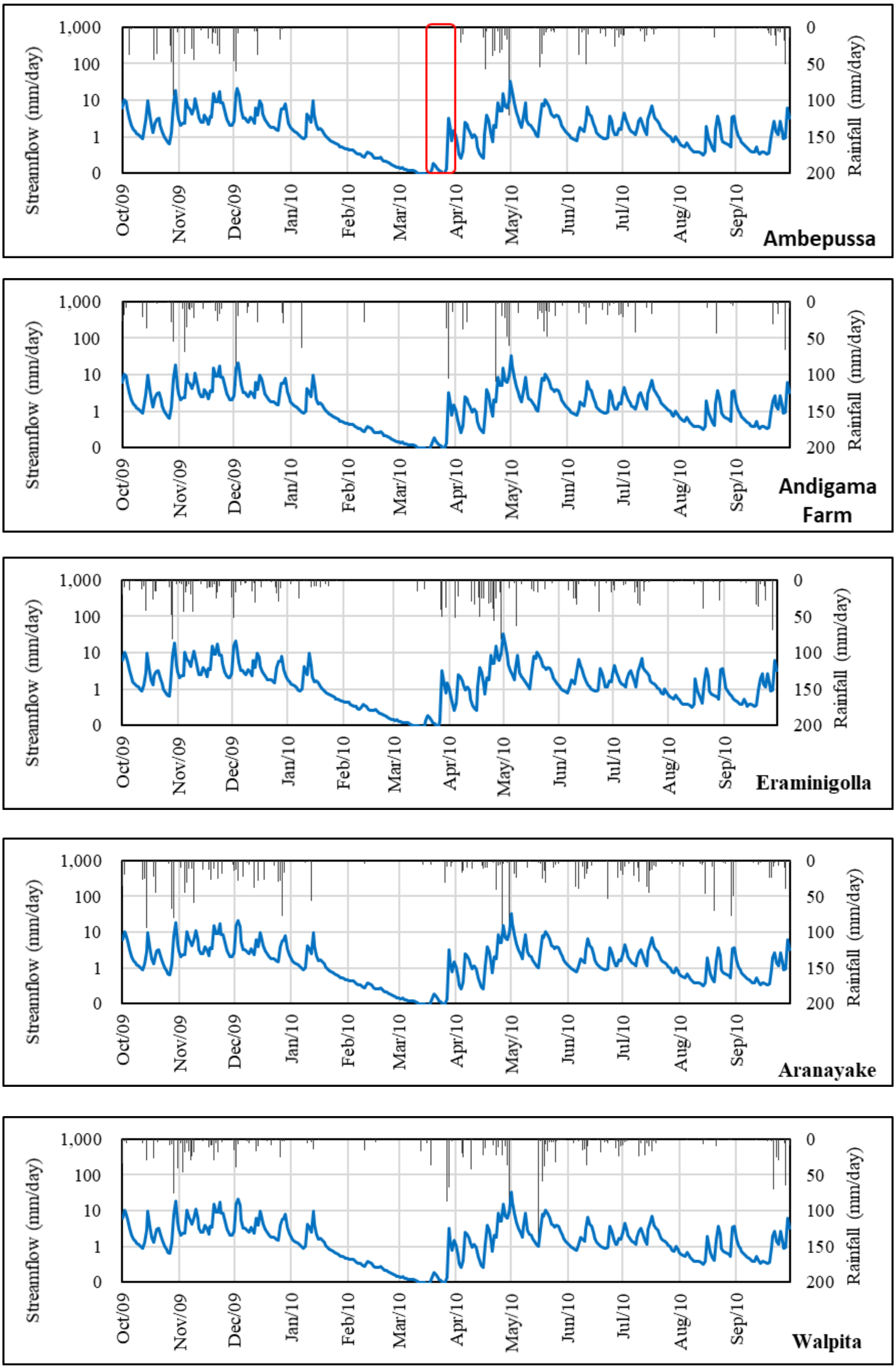


Figure B-5: Rainfall responses from each station in year 2009/2010

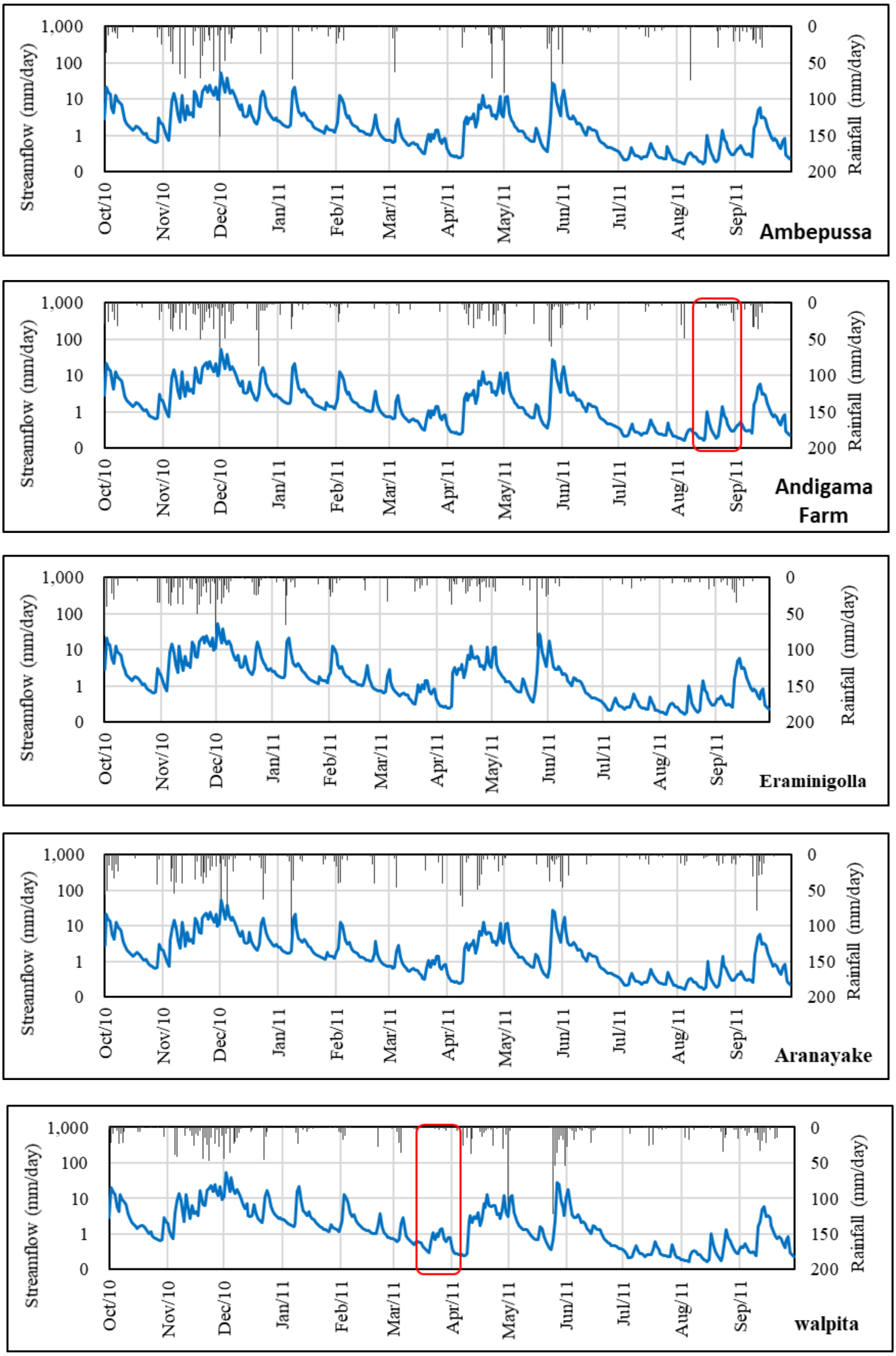


Figure B-6: Rainfall responses from each station in year 2010

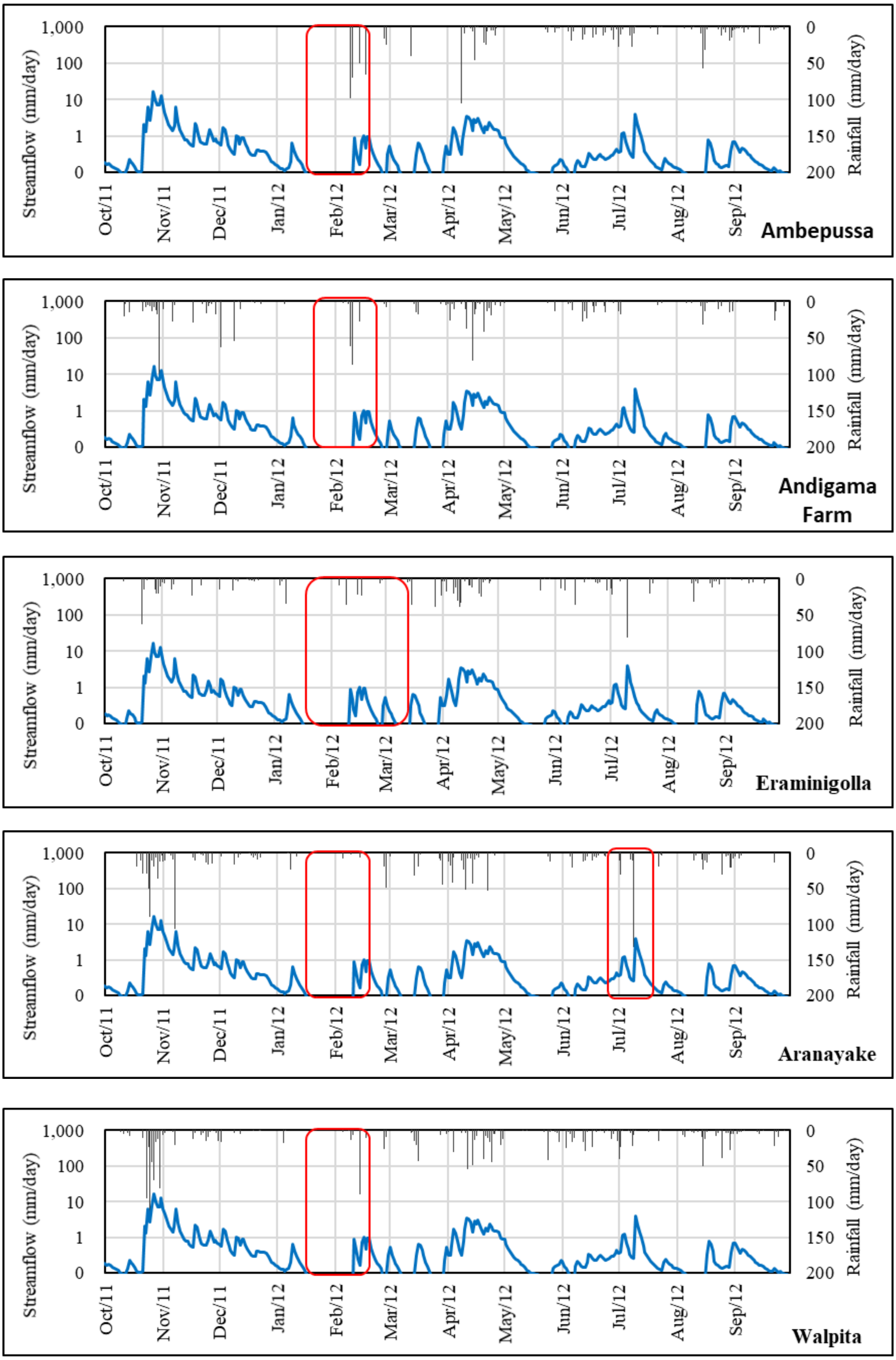


Figure B-7: Rainfall responses from each station in year 2011/2012

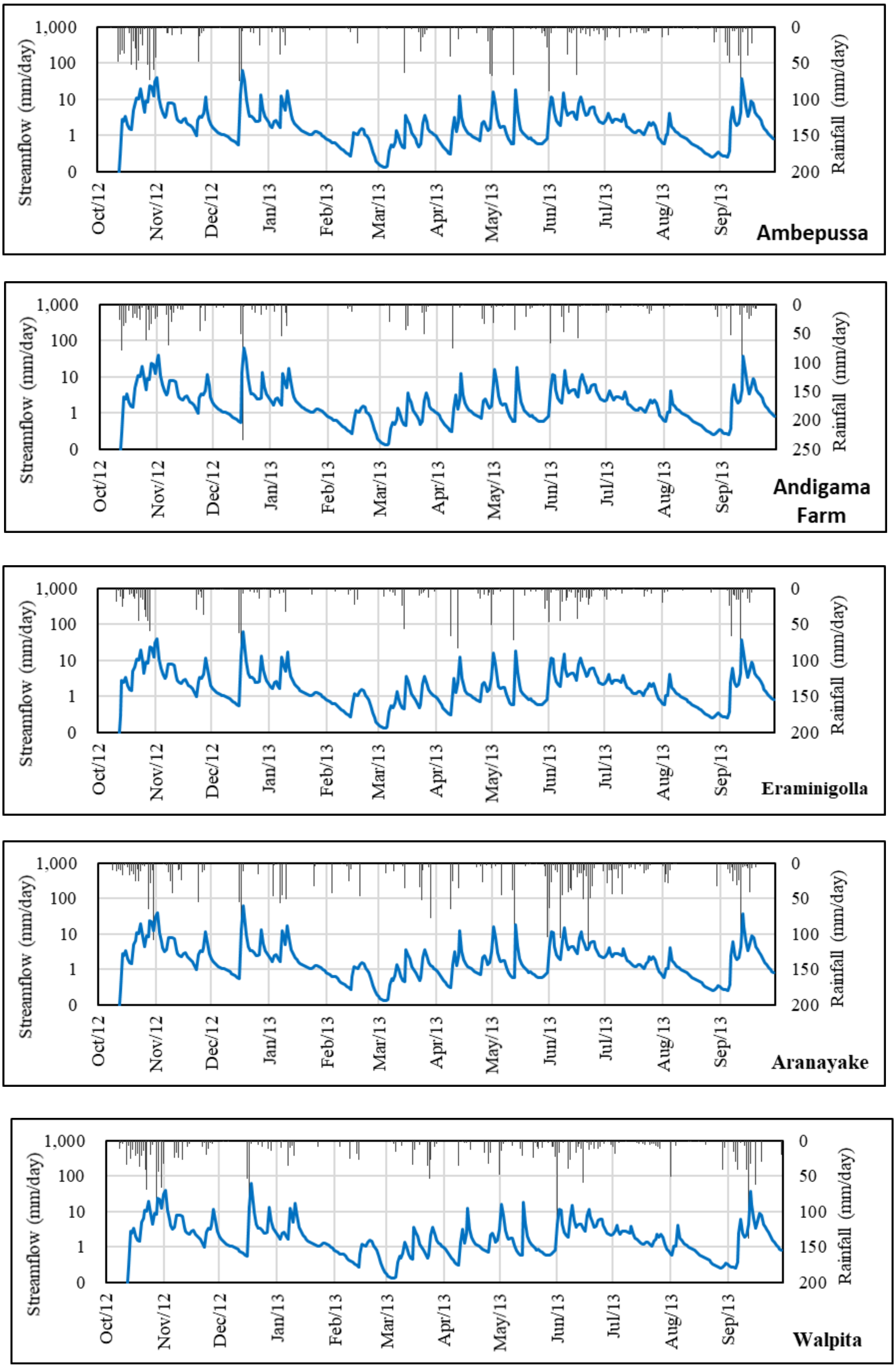


Figure B-8: Rainfall responses from each station in year 2012/2013

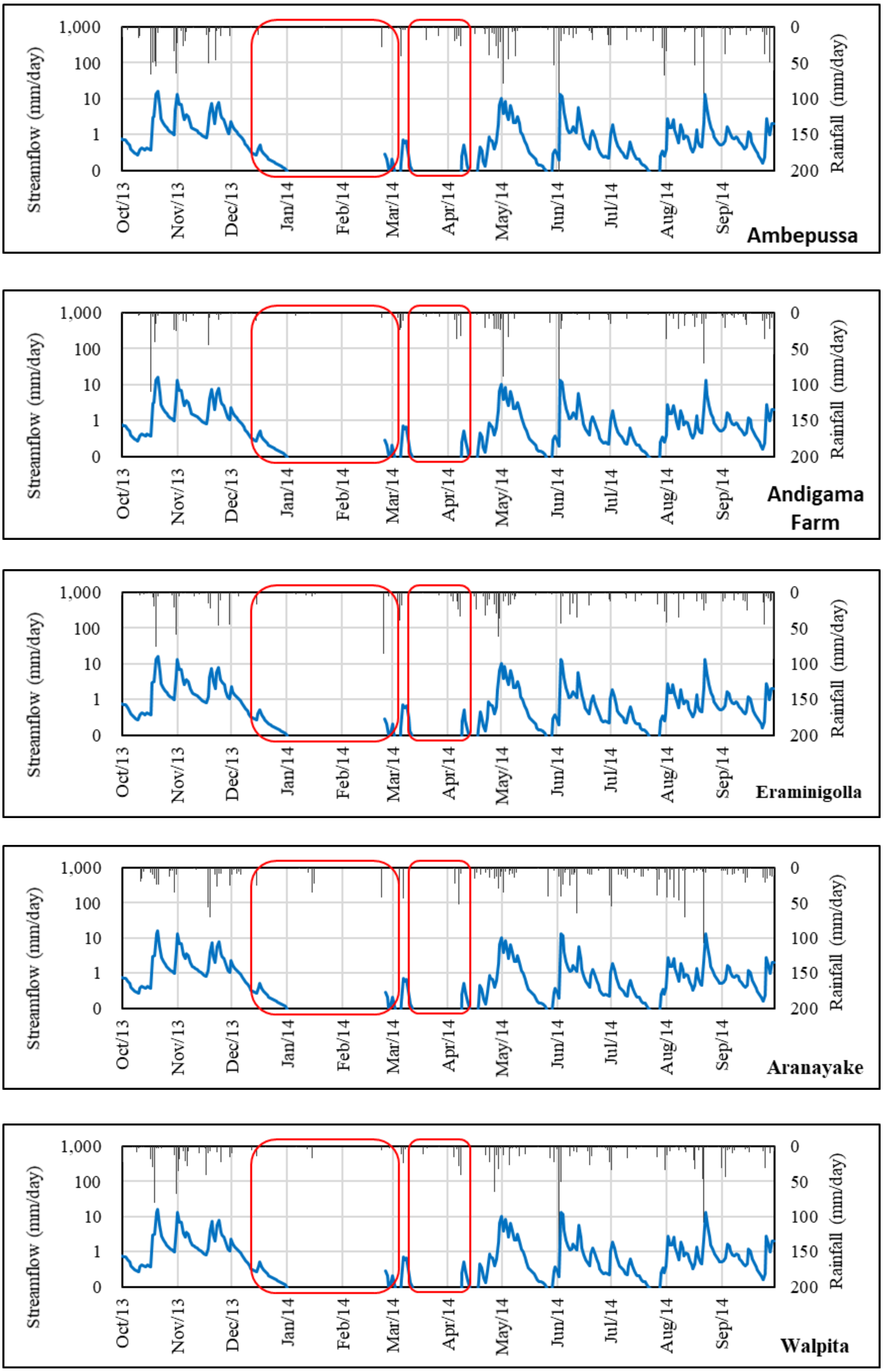


Figure B-9: Rainfall responses from each station in year 2013/2014

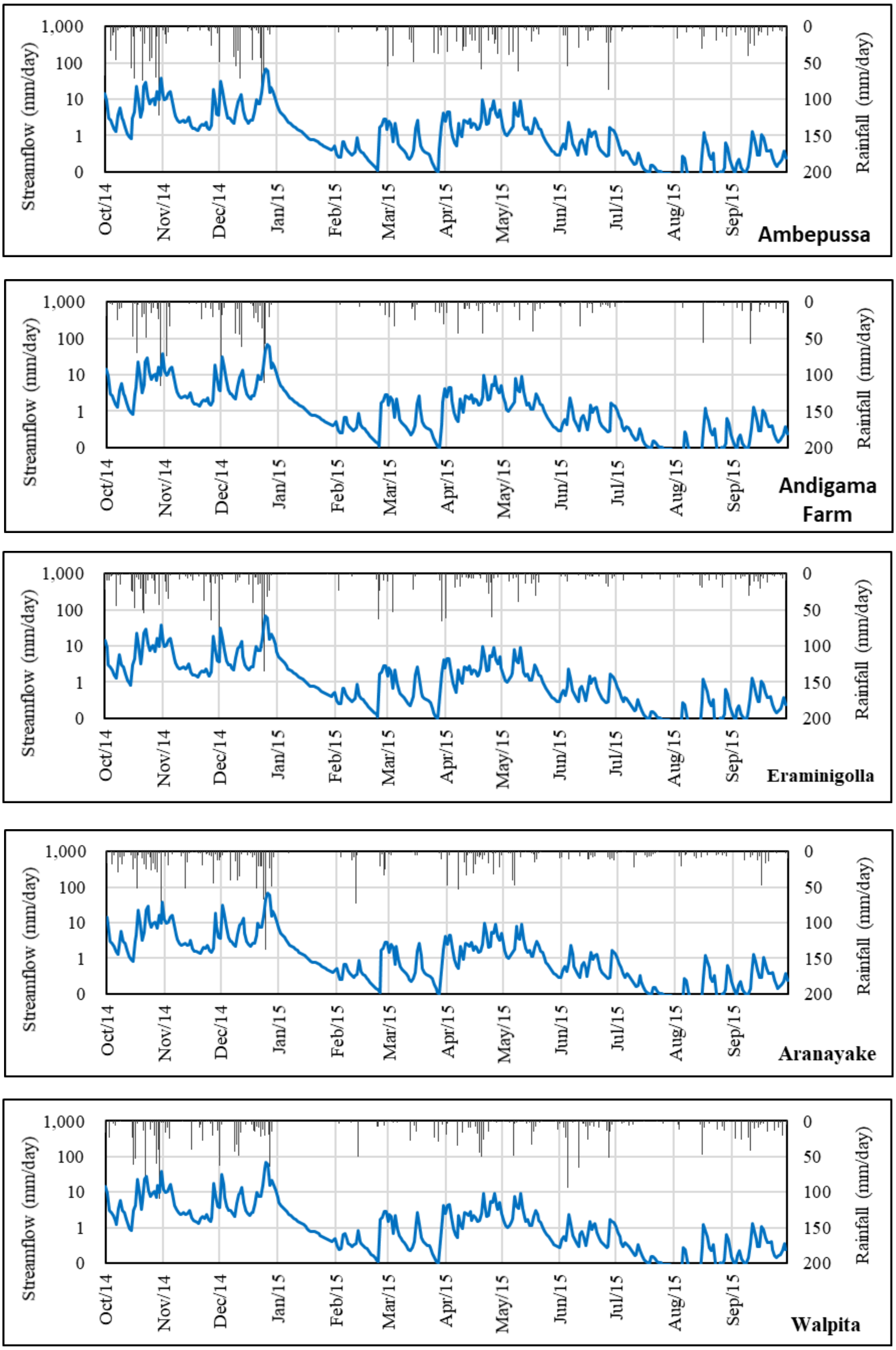


Figure B-10: Rainfall responses from each station in year 2014/2015

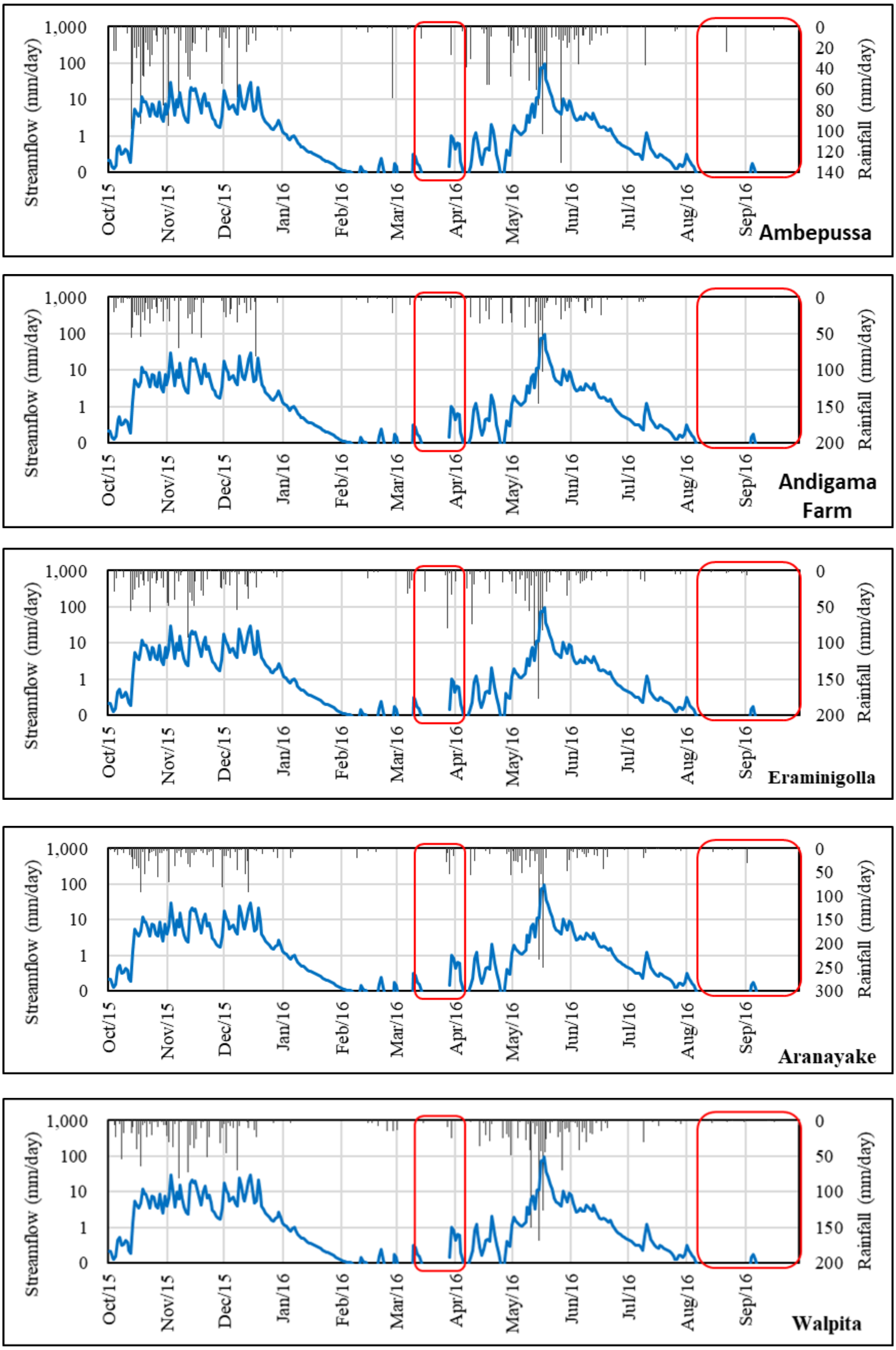


Figure B-11: Rainfall responses from each station in year 2015/2016

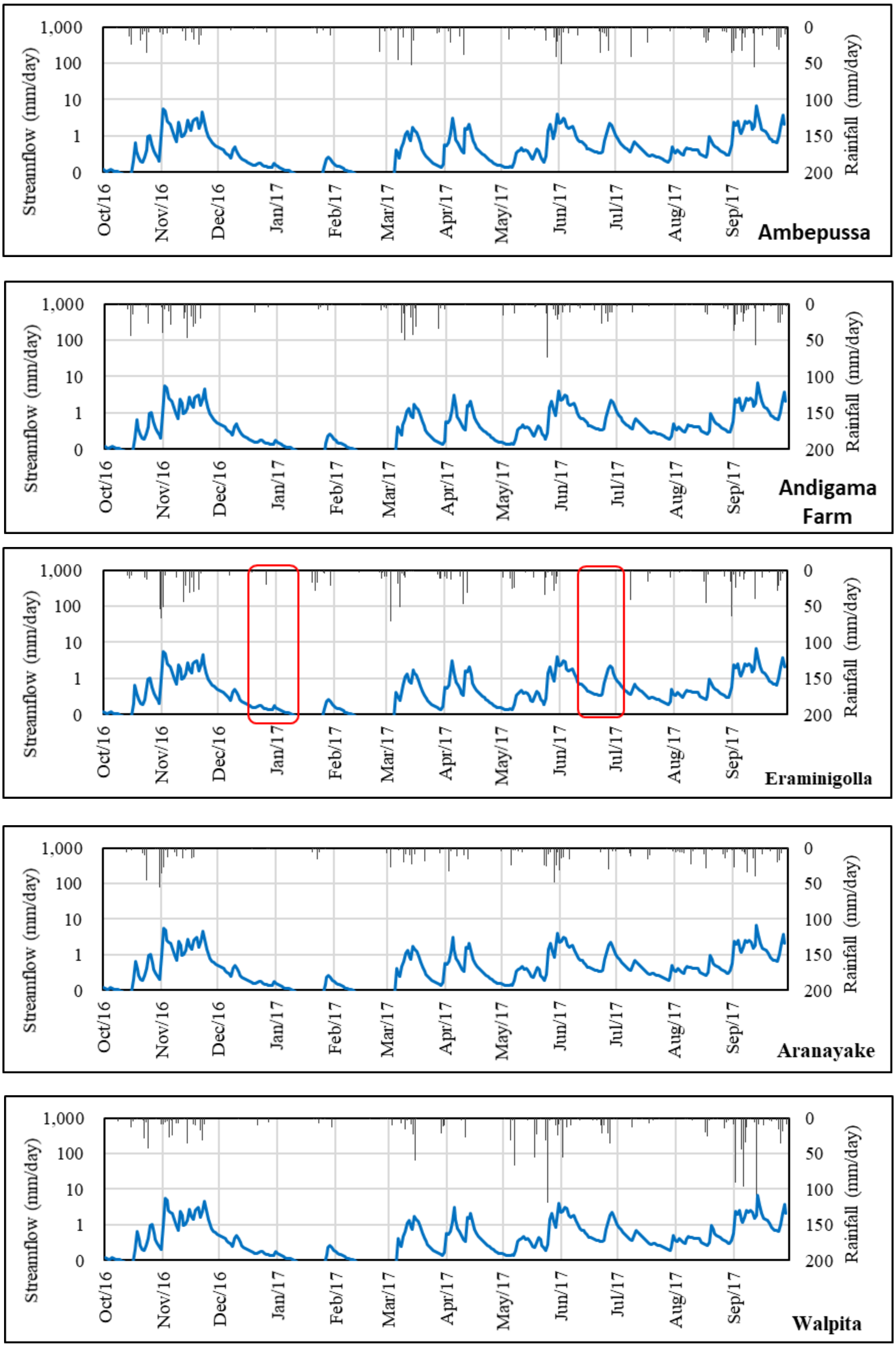


Figure B-12: Rainfall responses from each station in year 2016/2017

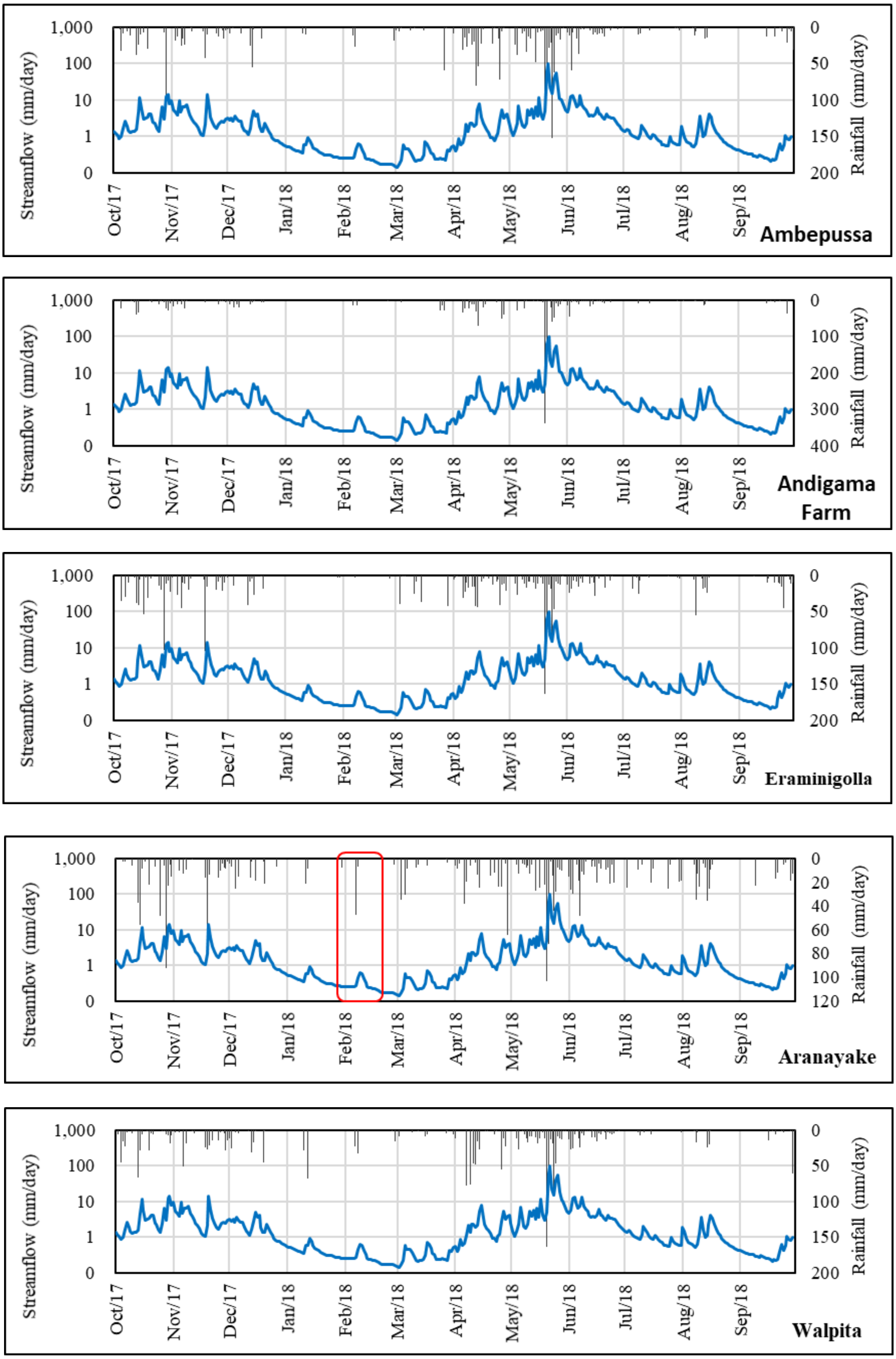


Figure B-13: Rainfall responses from each station in year 2017/2018

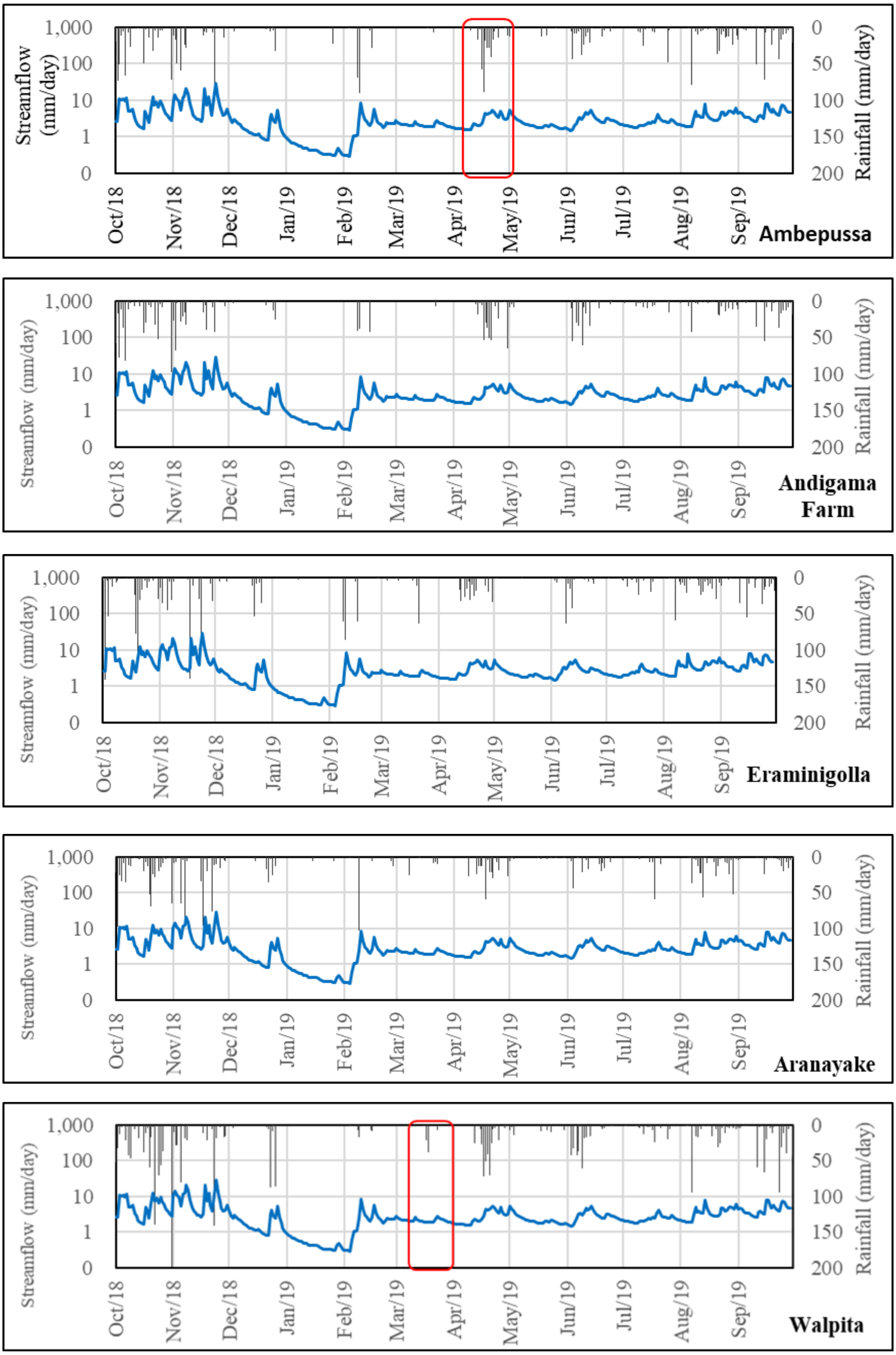


Figure B-14: Rainfall responses from each station in year 2018/2019

APPENDIX C – OBSERVED STREAMFLOW COMPARISON

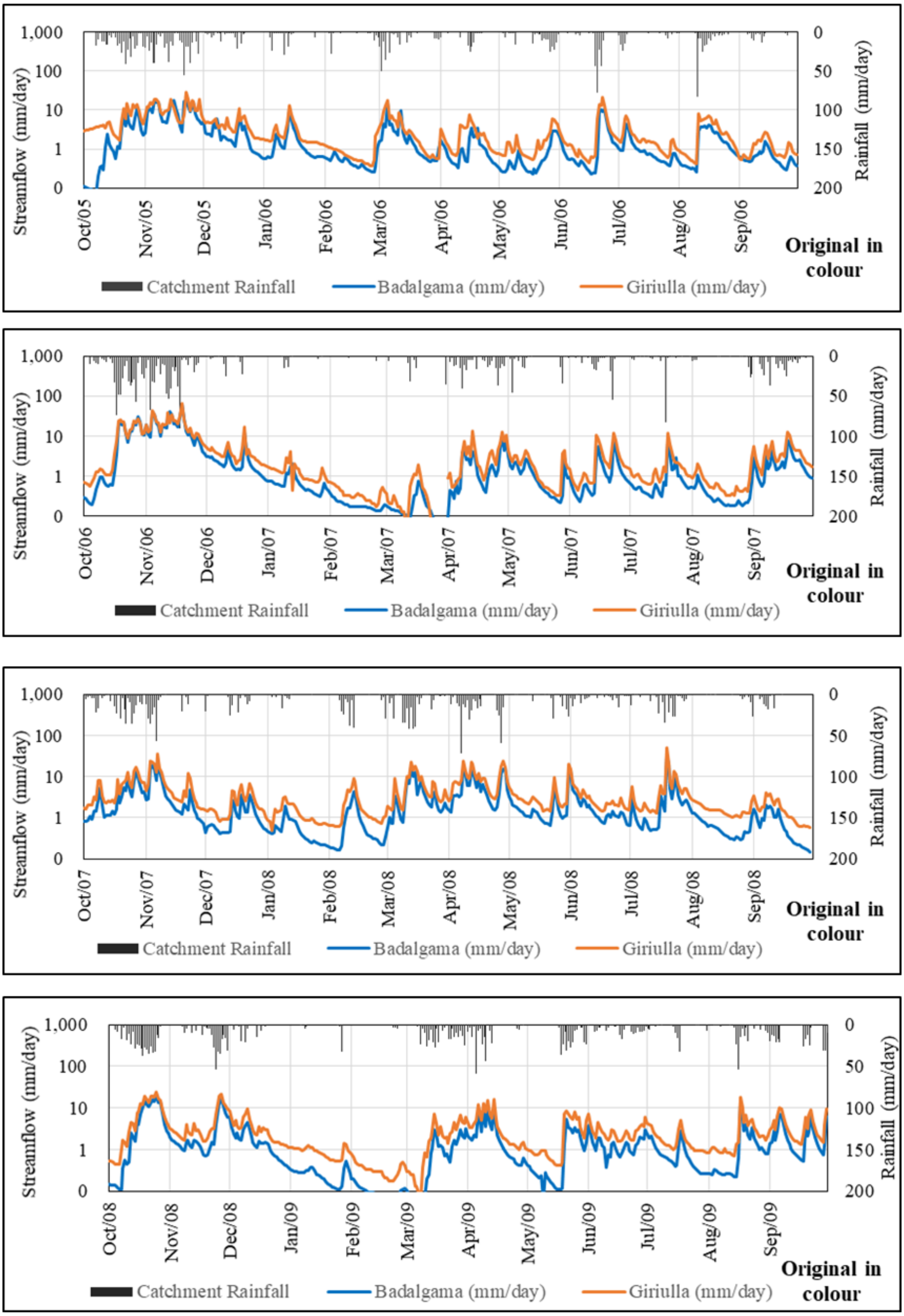


Figure C-1: Comparison of streamflow from 2005/2006 to 2008/2009

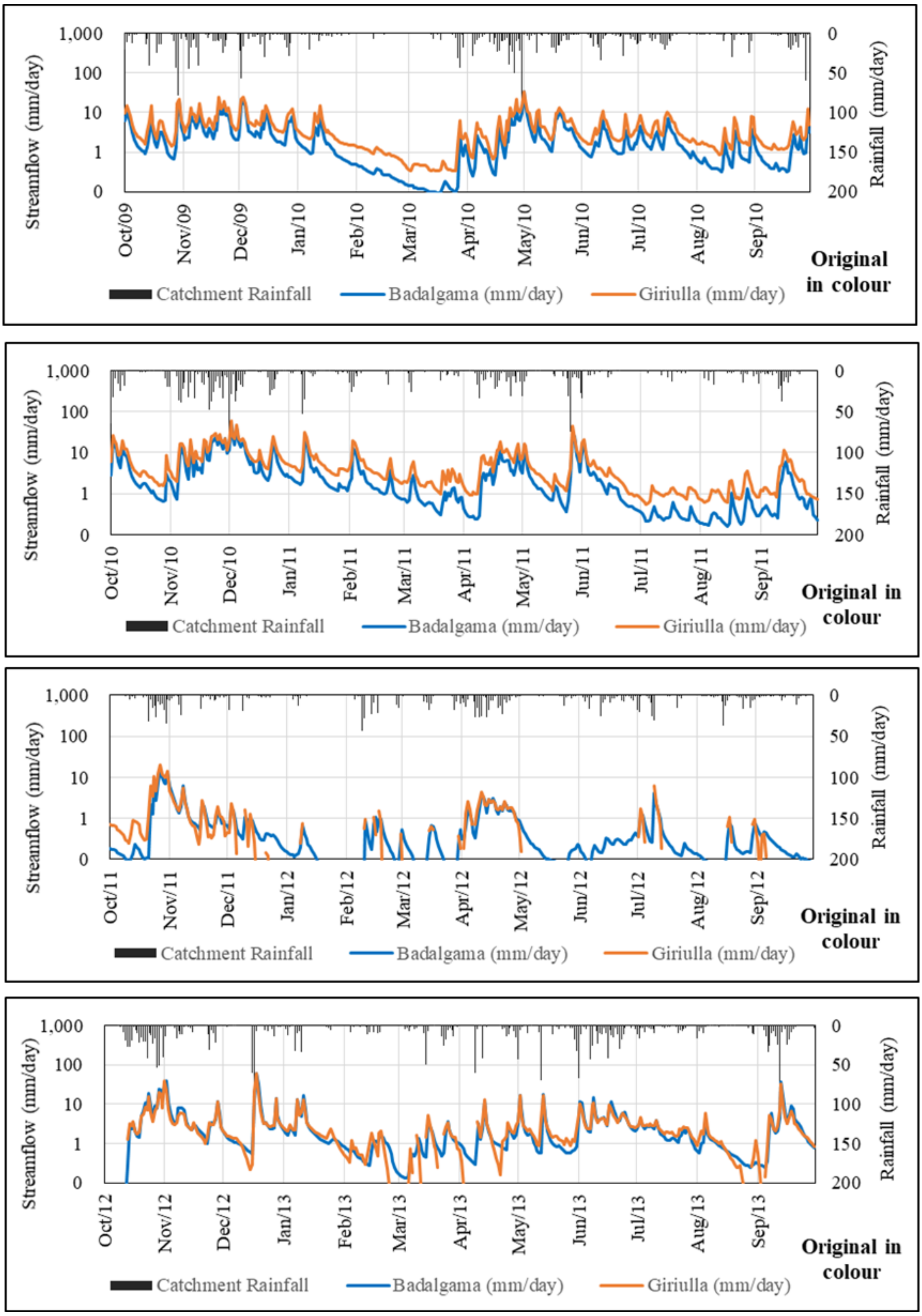


Figure C- 2: Comparison of streamflow from 2009/2010 to 2012/2013

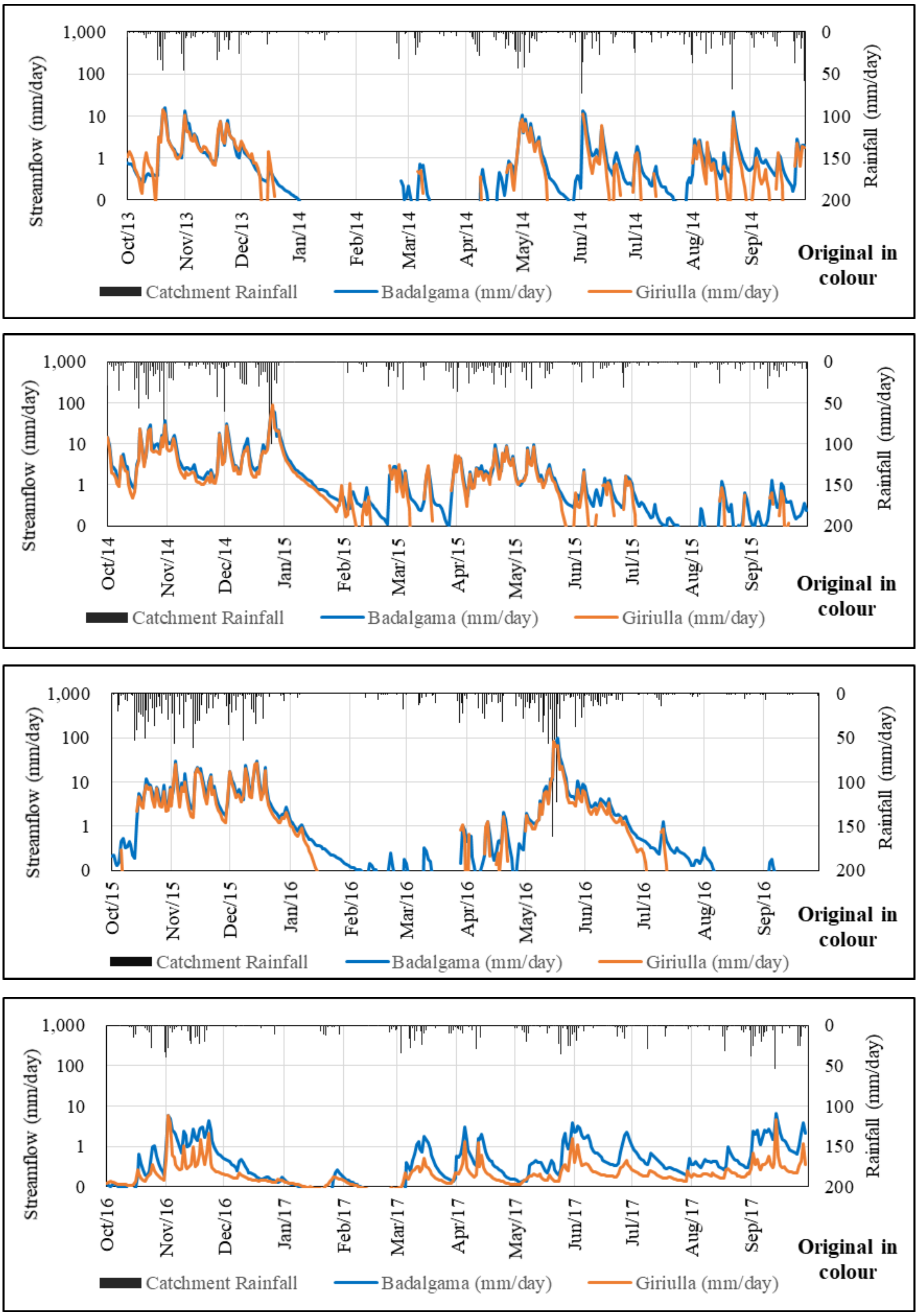


Figure C-3: Comparison of streamflow from 2013/2014 to 2016/2017

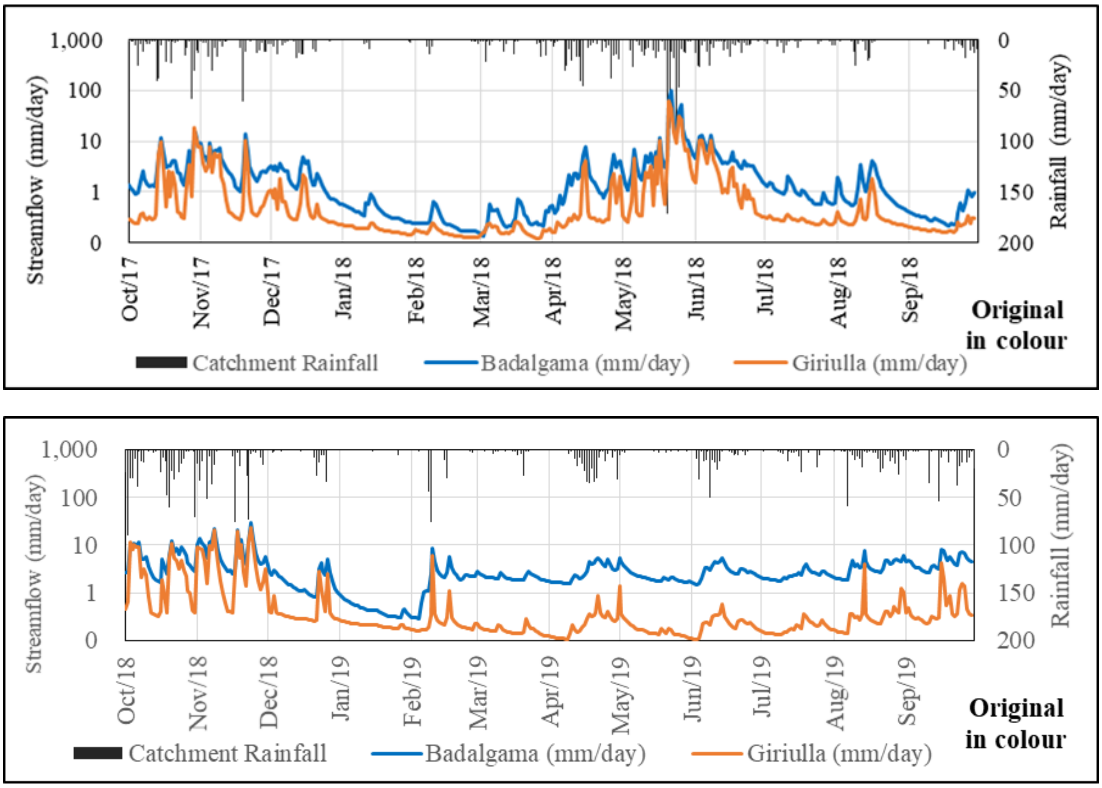


Figure C-4: Comparison of streamflow from 2017/2018 to 2018/2019

APPENDIX D – CALIBRATION AND VALIDATION RESULTS IN NORMAL PLOT

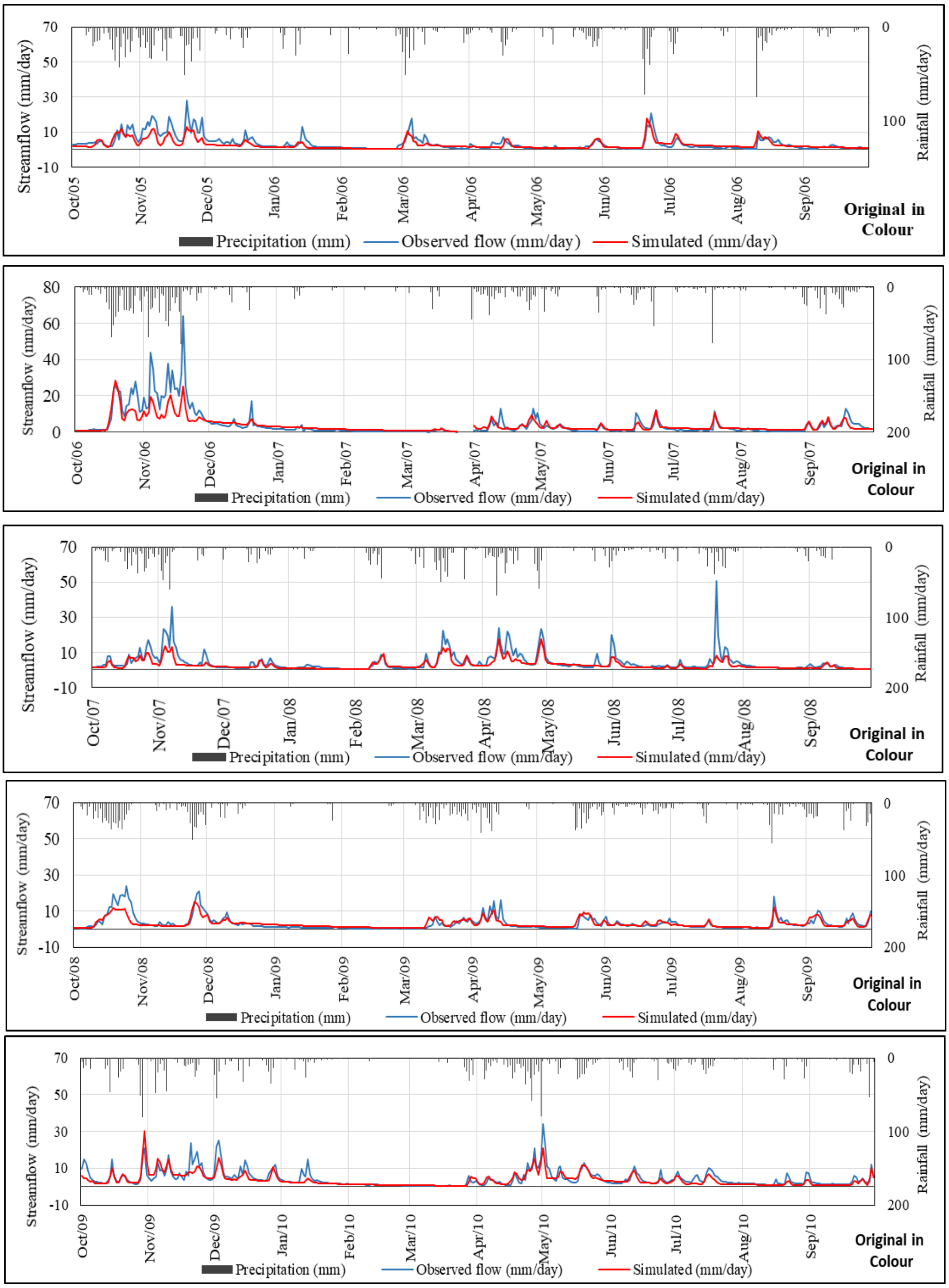


Figure D-1: Normal plot of Streamflow hydrographs at Giriulla – calibration

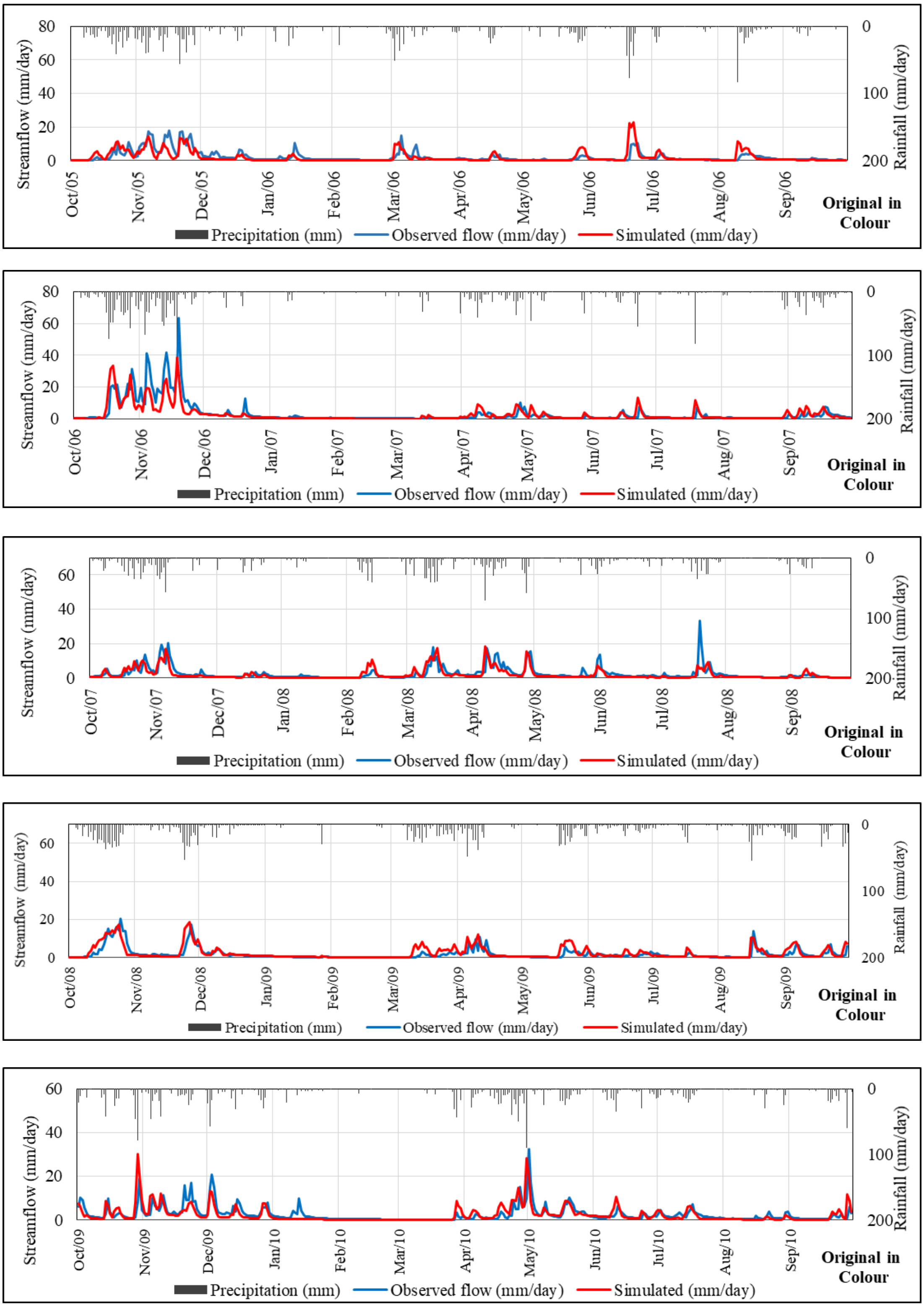


Figure D-2: Normal plot of Streamflow hydrographs at Badalgama – calibration

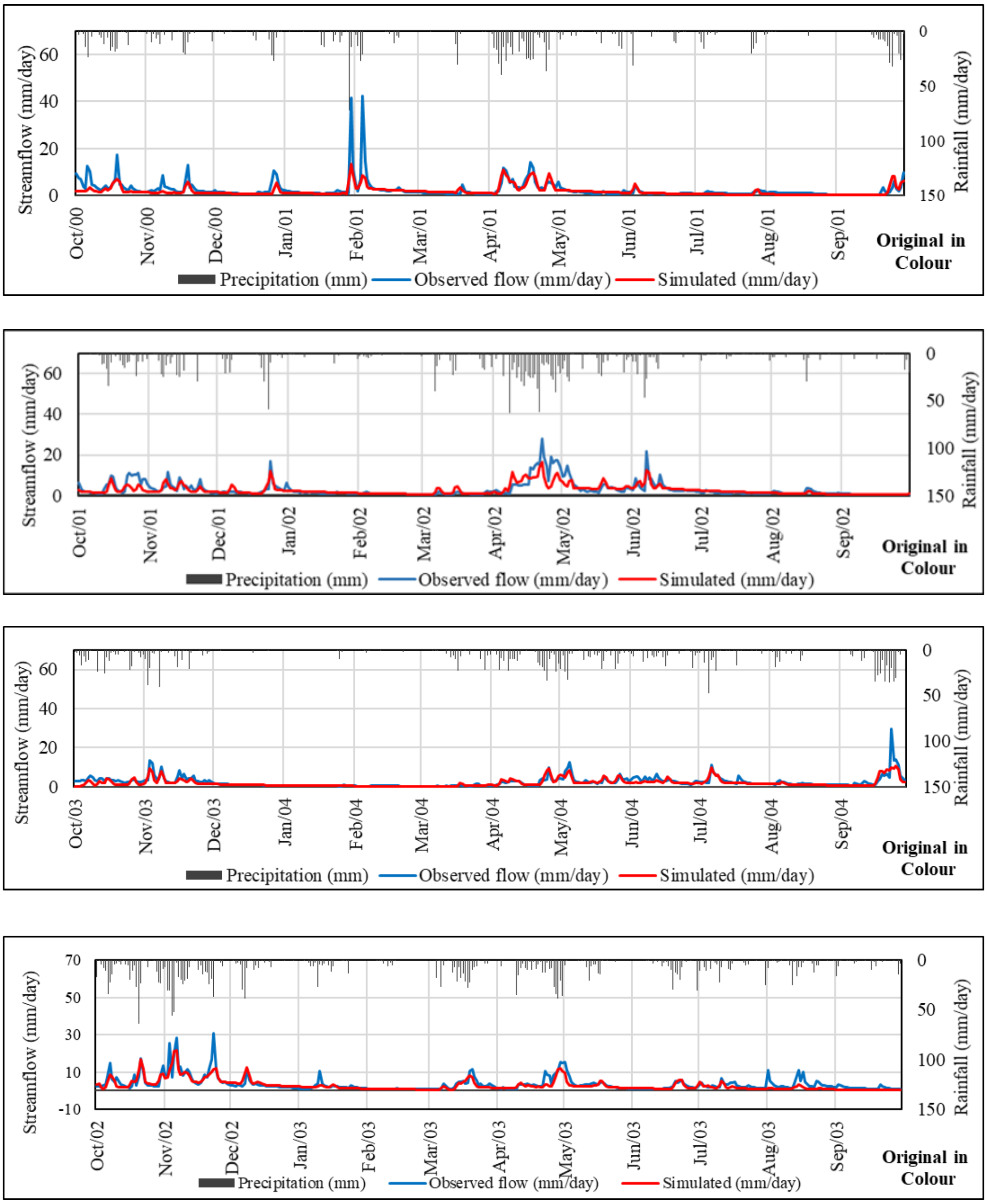


Figure D-3: Normal plot of Streamflow hydrographs at Giriulla – Validation

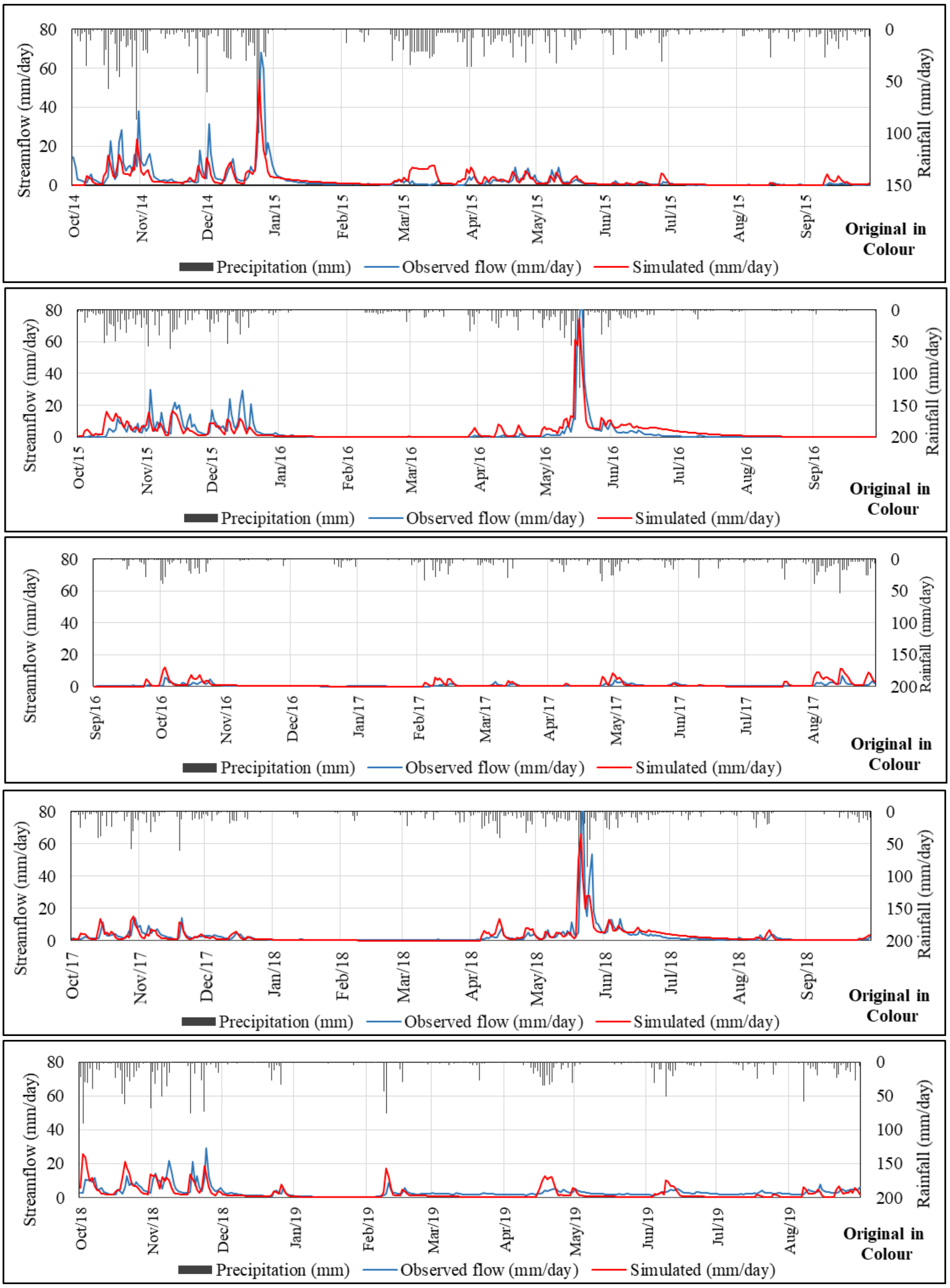


Figure D-4: Normal plot of Streamflow hydrographs at Badalgama – Validation

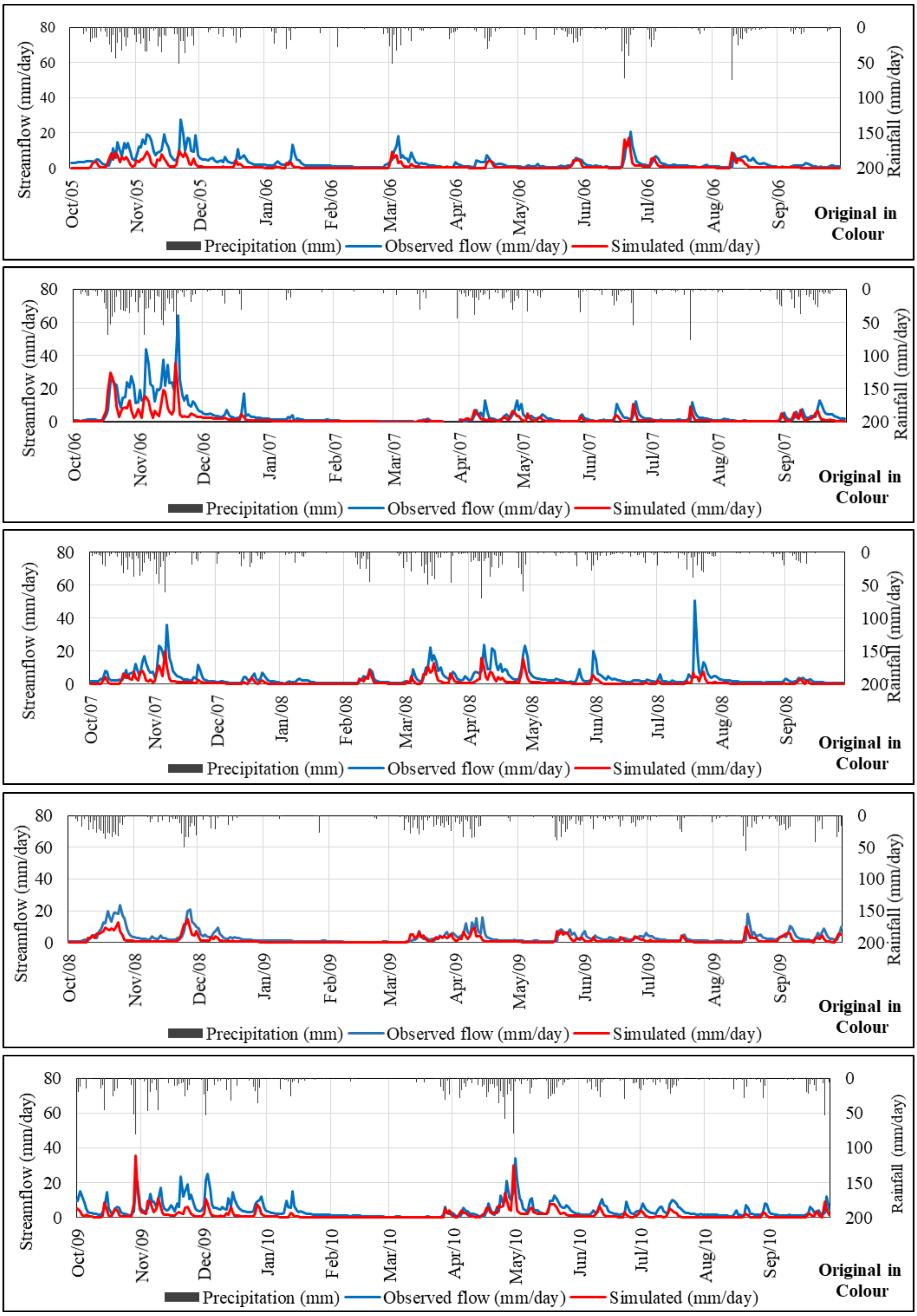
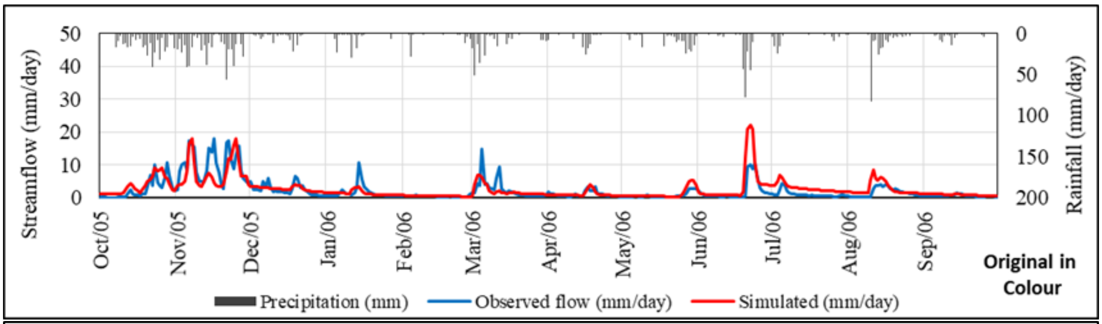
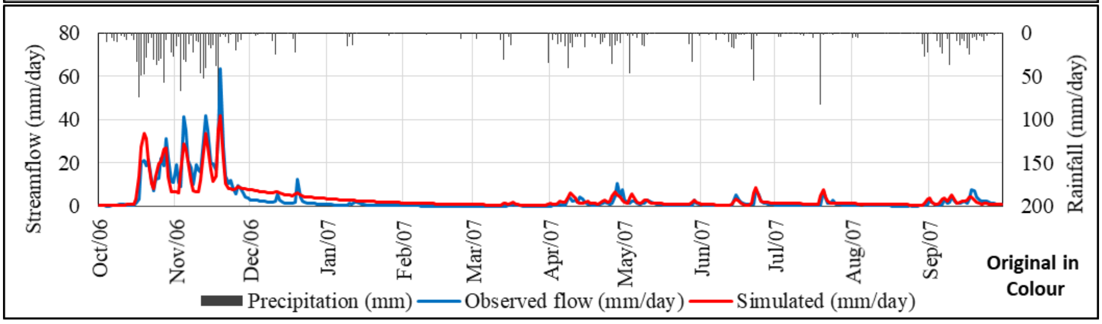
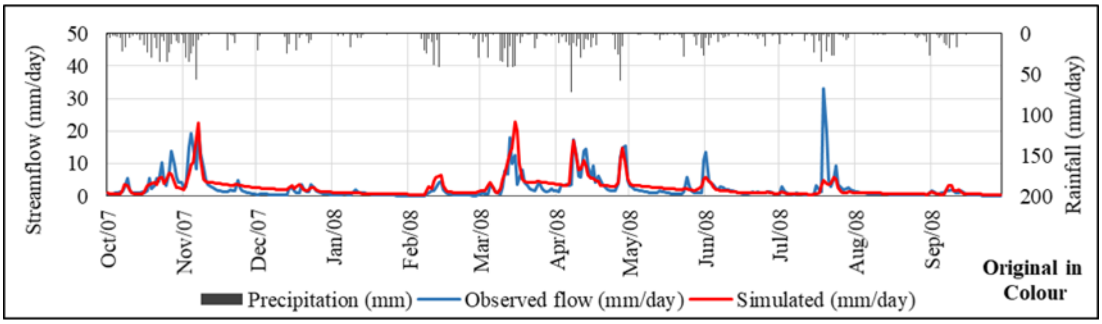
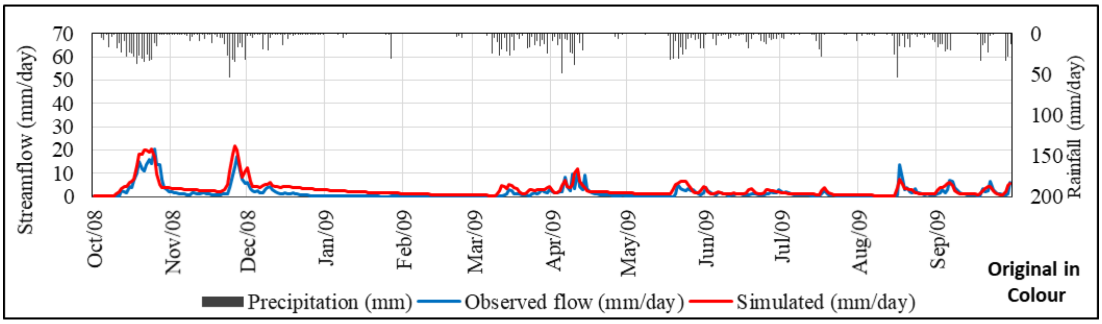


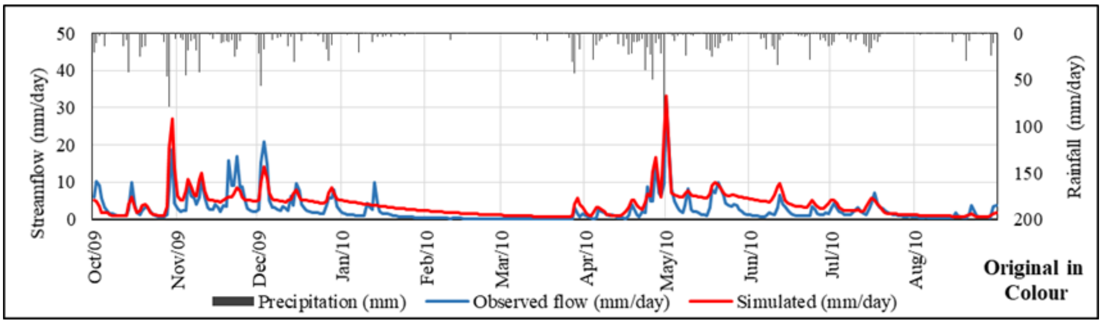
Figure D- 5: Normal plot of Streamflow hydrographs at Giriulla – Transferability

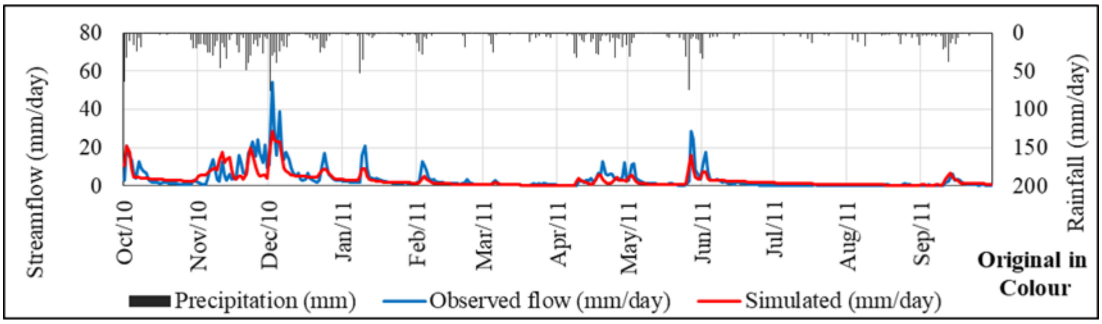

Streamflow (mm/day)
Rainfall (mm/day)
Oct/05 Nov/05 Dec/05 Jan/06 Feb/06 Mar/06 Apr/06 May/06 Jun/06 Jul/06 Aug/06 Sep/06
Precipitation (mm)
Observed flow (mm/day)
Simulated (mm/day)
Original in Colour

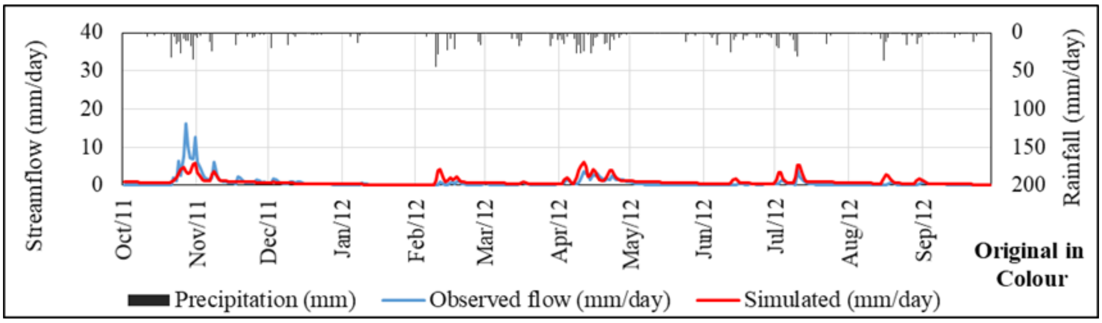

Streamflow (mm/day)
Rainfall (mm/day)
Oct/06 Nov/06 Dec/06 Jan/07 Feb/07 Mar/07 Apr/07 May/07 Jun/07 Jul/07 Aug/07 Sep/07
Precipitation (mm)
Observed flow (mm/day)
Simulated (mm/day)
Original in Colour

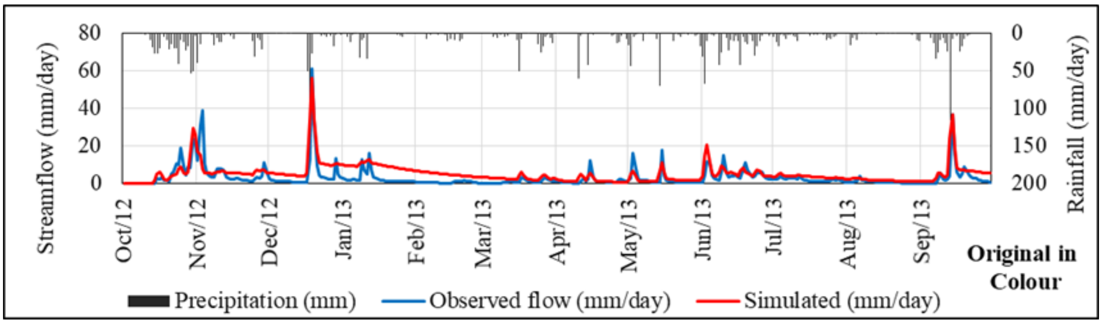

Streamflow (mm/day)
Rainfall (mm/day)
Oct/07 Nov/07 Dec/07 Jan/08 Feb/08 Mar/08 Apr/08 May/08 Jun/08 Jul/08 Aug/08 Sep/08
Precipitation (mm)
Observed flow (mm/day)
Simulated (mm/day)
Original in Colour

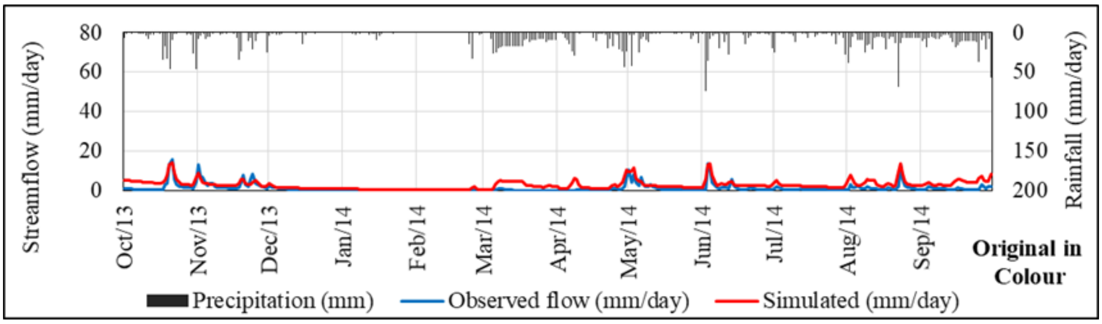

Streamflow (mm/day)
Rainfall (mm/day)
Oct/08 Nov/08 Dec/08 Jan/09 Feb/09 Mar/09 Apr/09 May/09 Jun/09 Jul/09 Aug/09 Sep/09
Precipitation (mm)
Observed flow (mm/day)
Simulated (mm/day)
Original in Colour

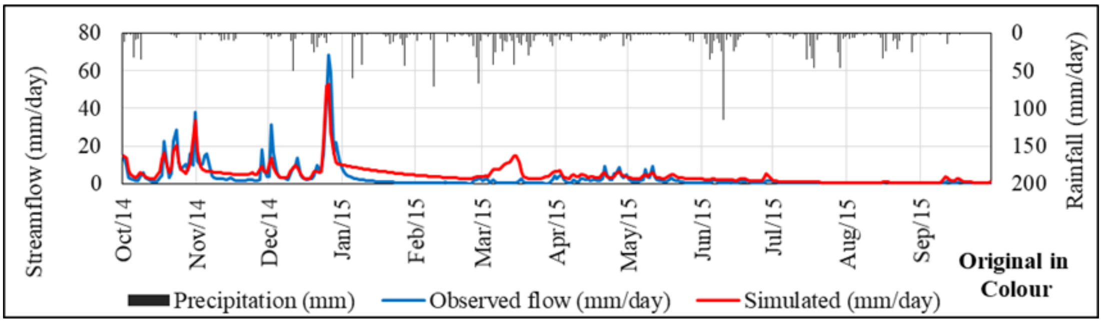

Streamflow (mm/day)
Rainfall (mm/day)
Oct/09 Nov/09 Dec/09 Jan/10 Feb/10 Mar/10 Apr/10 May/10 Jun/10 Jul/10 Aug/10
Precipitation (mm)
Observed flow (mm/day)
Simulated (mm/day)
Original in Colour


Streamflow (mm/day)
Rainfall (mm/day)
Oct/10 Nov/10 Dec/10 Jan/11 Feb/11 Mar/11 Apr/11 May/11 Jun/11 Jul/11 Aug/11 Sep/11
Precipitation (mm)
Observed flow (mm/day)
Simulated (mm/day)
Original in Colour


Streamflow (mm/day)
Rainfall (mm/day)
Oct/11 Nov/11 Dec/11 Jan/12 Feb/12 Mar/12 Apr/12 May/12 Jun/12 Jul/12 Aug/12 Sep/12
Precipitation (mm)
Observed flow (mm/day)
Simulated (mm/day)
Original in Colour


Streamflow (mm/day)
Rainfall (mm/day)
Oct/12 Nov/12 Dec/12 Jan/13 Feb/13 Mar/13 Apr/13 May/13 Jun/13 Jul/13 Aug/13 Sep/13
Precipitation (mm)
Observed flow (mm/day)
Simulated (mm/day)
Original in Colour


Streamflow (mm/day)
Rainfall (mm/day)
Oct/13 Nov/13 Dec/13 Jan/14 Feb/14 Mar/14 Apr/14 May/14 Jun/14 Jul/14 Aug/14 Sep/14
Precipitation (mm)
Observed flow (mm/day)
Simulated (mm/day)
Original in Colour


Streamflow (mm/day)
Rainfall (mm/day)
Oct/14 Nov/14 Dec/14 Jan/15 Feb/15 Mar/15 Apr/15 May/15 Jun/15 Jul/15 Aug/15 Sep/15
Precipitation (mm)
Observed flow (mm/day)
Simulated (mm/day)
Original in Colour

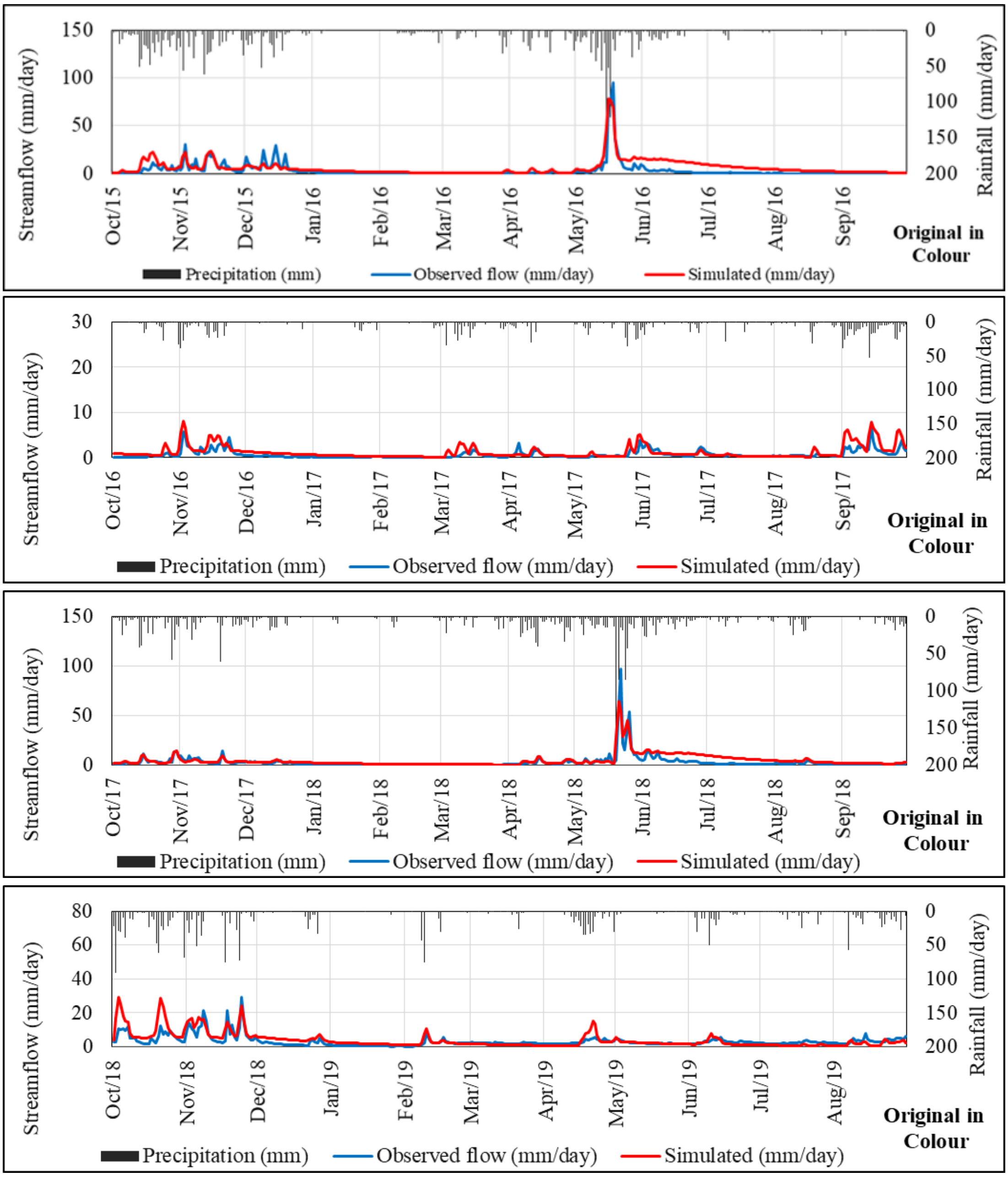
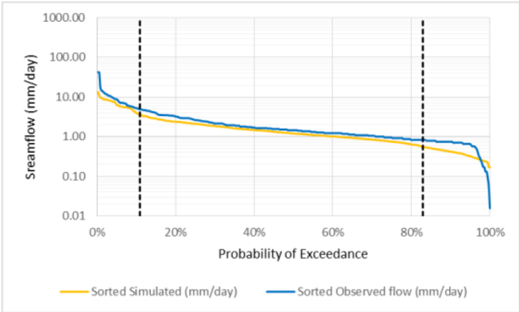
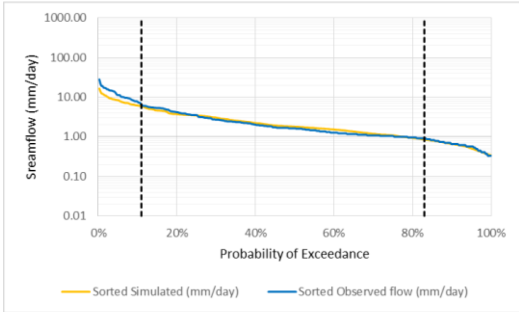


Figure D-6: Normal plot of stream flow hydrographs at Badalgama – Transferability

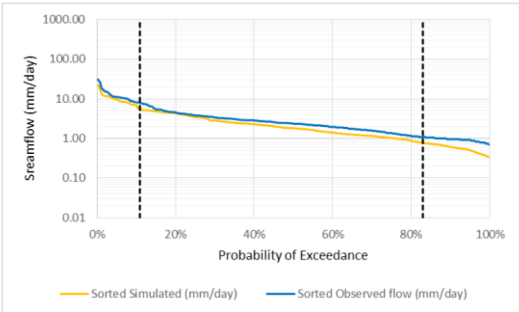
APPENDIX E: ANNUAL TRANSFERABILITY PERFORMANCE



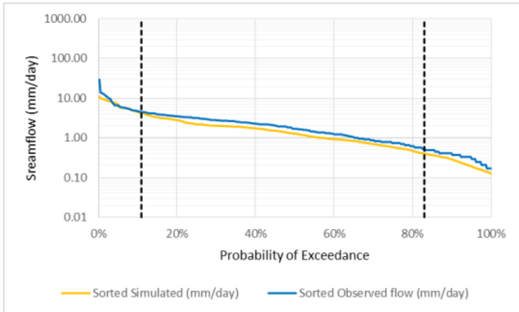
2000/2001



2001/2002

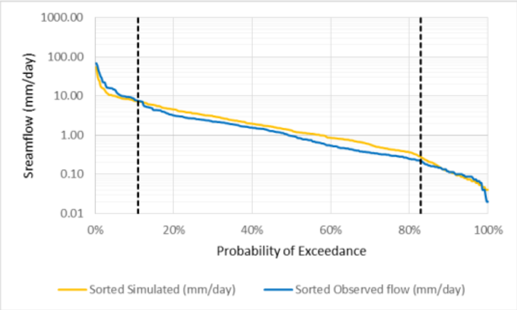


2002/2003

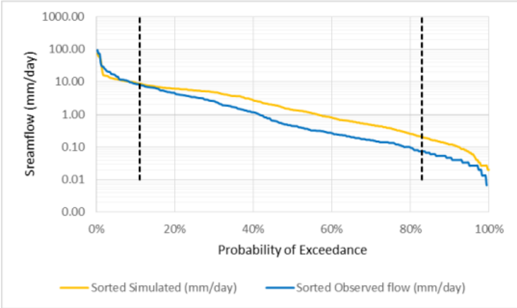


2003/2004

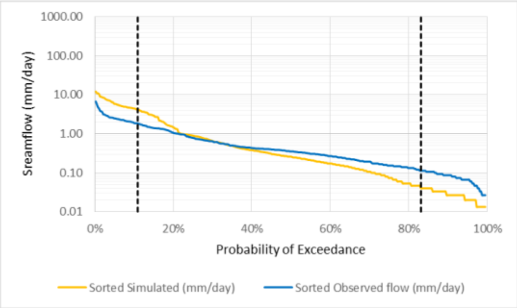
Figure E-1: Flow Duration Curve in Annual Scale for temporal Transferability at Giriulla



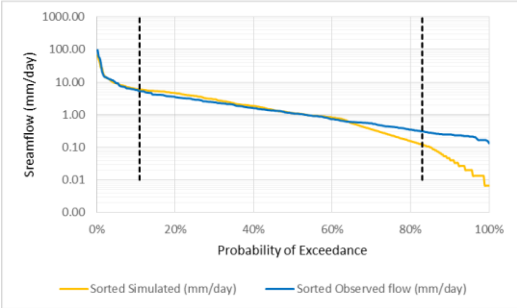
2014/2015



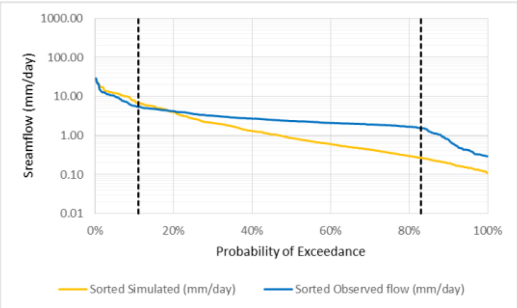
2015/2016



2016/2017

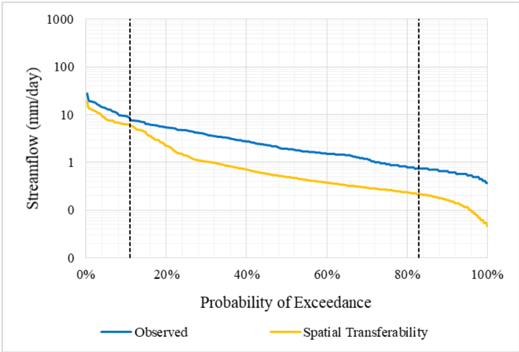


2017/2018

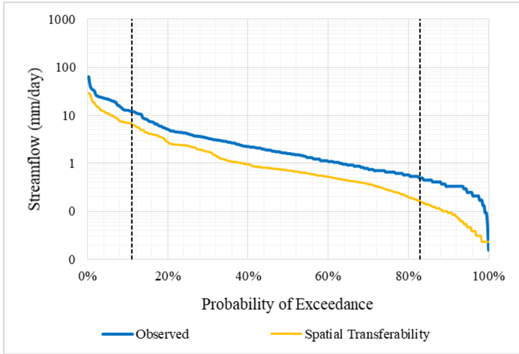


2018/2019

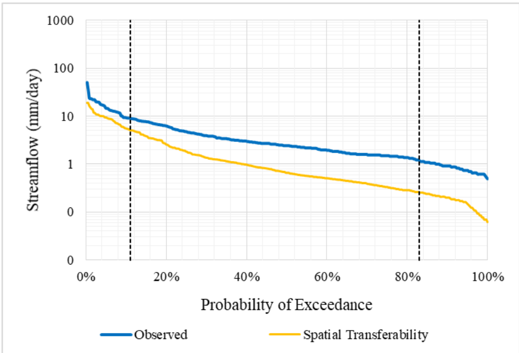
Figure E-2: Flow Duration Curve in Annual Scale for Temporal Transferability at Badalgama



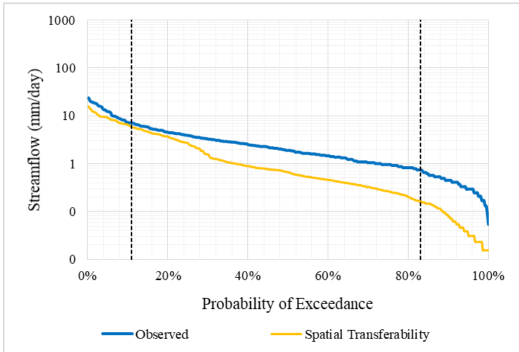
2005/2006



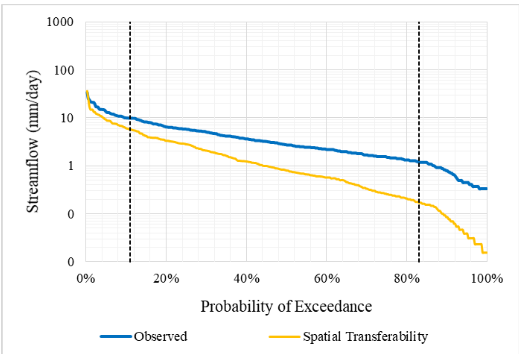
2006/2007



2007/2008

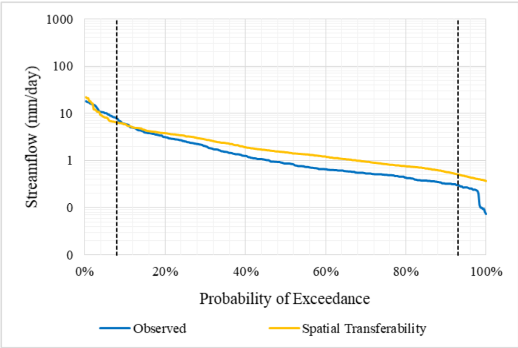


2008/2009

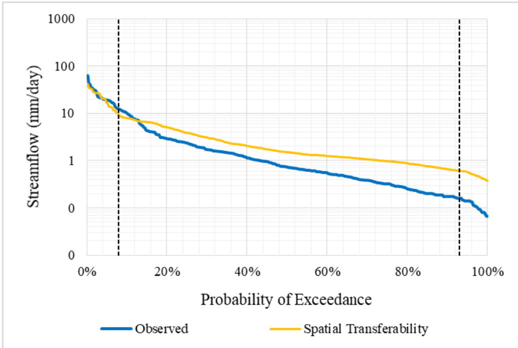


2009/2010

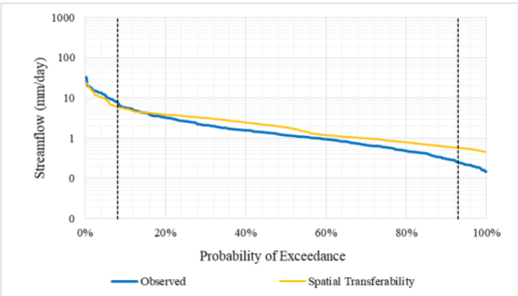
Figure E-3: Flow Duration Curve in Annual Scale for Spatial Transferability at Giriulla



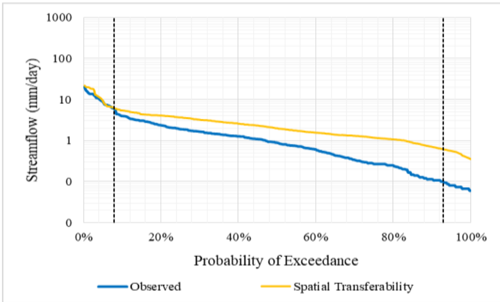
2005/2006



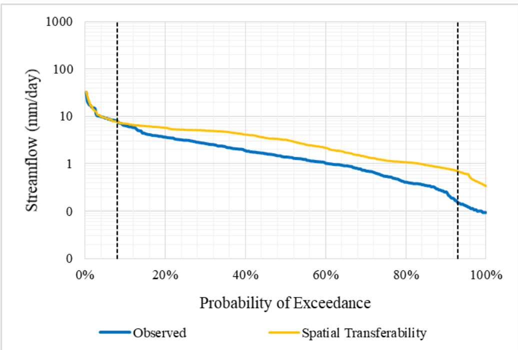
2006/2007



2007/2008



2008/2009



2009/2010

Figure E-4: Flow Duration Curve in Annual Scale for Spatial Transferability at Badalgama

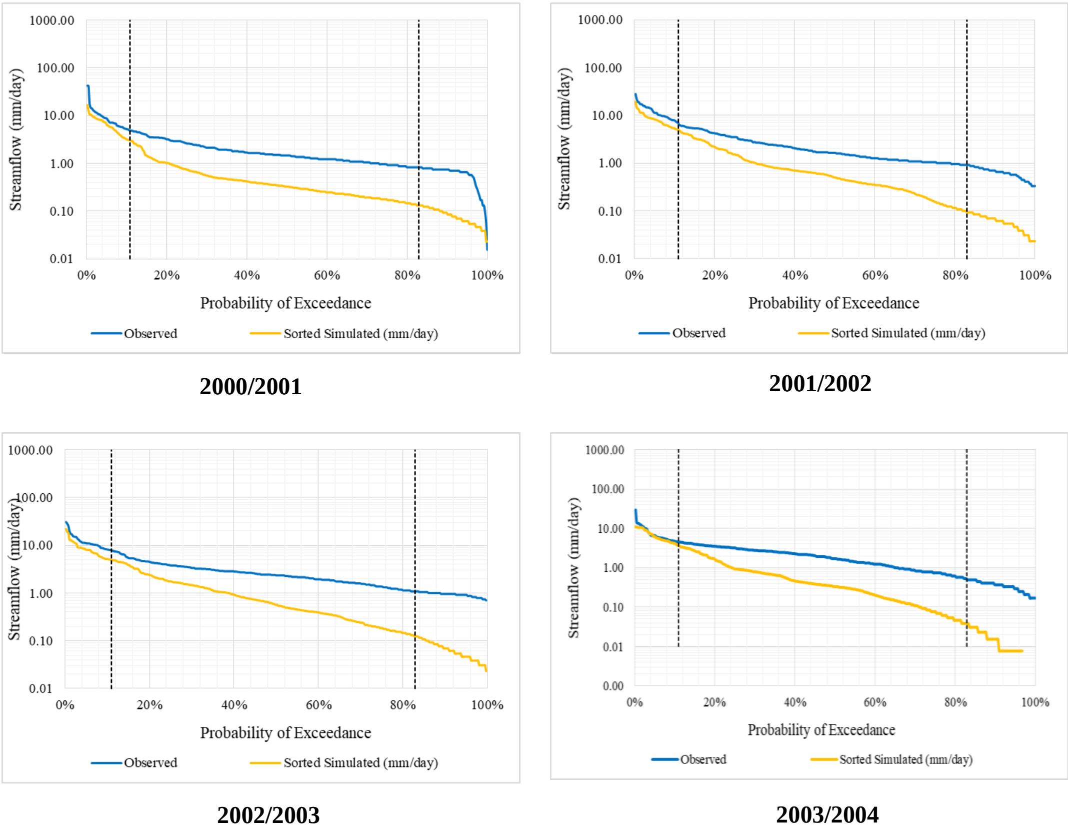
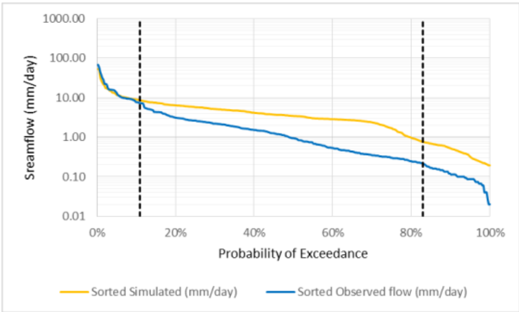
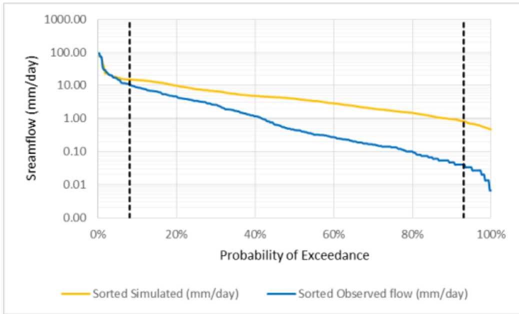


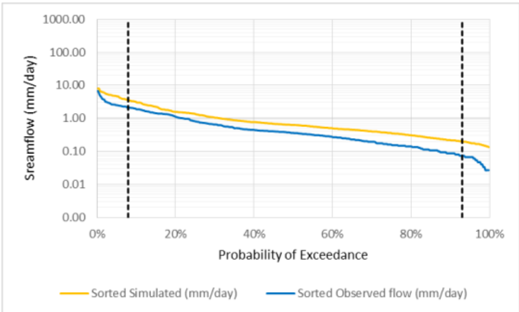
Figure E-5: Flow Duration Curve in Annual Scale for Spatiotemporal transferability at Giriulla



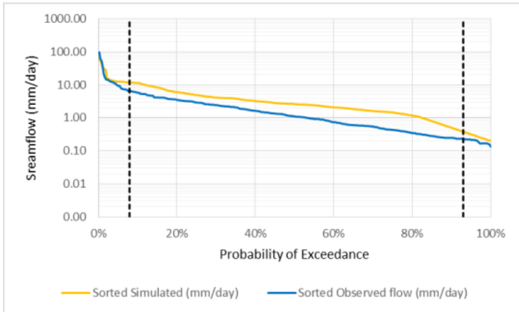
2014/2015



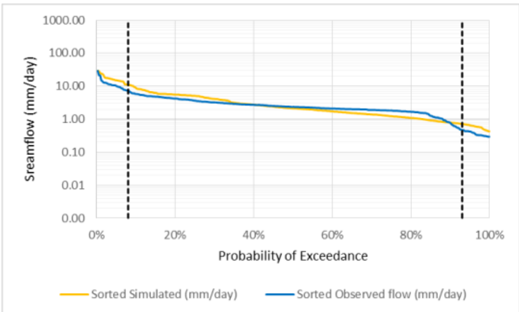
2015/2016



2016/2017



2017/2018



2018/2019

Figure E-6: Flow Duration Curve in Annual Scale for Spatiotemporal transferability at Badalgama