ANALYSIS OF THE EFFECT OF LOSS AND BASEFLOW METHODS AND CATCHMENT SCALE ON PERFORMANCE OF HEC-HMS MODEL FOR KELANI RIVER BASIN, SRI LANKA

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Thesis submitted in partial fulfilment of the requirements for the degree of
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Supervised by
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June 2018

DECLARATION

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

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

Analysis of the Effect of Loss and Baseflow Methods and Catchment Scale on Performance of HEC-HMS Model for Kelani River Basin, Sri Lanka

ABSTRACT

Hydrological models have become an indispensable tool for efficient water resource management which requires proper estimation of runoff in basins and recognition of appropriate catchment scale. The HEC-HMS (Hydrologic Engineering Center's Hydraulic Modeling System) is a reliable and freely available model. Different loss and baseflow estimation methods available in HEC-HMS have their own pros and cons. Lumping of model parameters over a large area reduces the model performance. In order to find the best loss and baseflow methods for simulating rainfall runoff and to check the possibility of further improvement in model performance by moving toward distributed modeling, Glencorse watershed in Kelani river basin of Sri Lanka was selected as the project area.

Daily rainfall data from 2006/2007 to 2008/2009 and 2010/2011 to 2013/2014 for four rainfall stations in Glencorse watershed with daily stream flow data of Glencorse gauging station for the same duration were used for this study. Two different combinations of baseflow and loss methods for simulation of runoff were considered while Clark unit hydrograph method was used as transform model. In the First Option, the Deficit and Constant Method and Recession Method were used as loss and baseflow methods, respectively, while for the Second Option, the Soil Moisture Accounting (SMA) and Linear reservoir methods were used for continuous simulation. Glencorse watershed was divided into 3, 6, 9 and 16 sub divisions to assess the improvement in model performance by shifting toward distributed modelling. Manual calibration approach was used for with Mean Ratio of Absolute Error (MRAE) as the main objective function while another two statistical goodness of fit measures, Nash–Sutcliffe model efficiency coefficient (NASH) and percent error in volume were also checked as an additional observation.

Soil Moisture Accounting as loss model and linear reservoir model as baseflow model simulated runoff more efficiently as compared to the other combination. Evaluation showed value of MRAE and NASH for Option 1 were 0.38 and 0.67 for calibration and 0.40 and 0.42 for verification, respectively. Option 2 evaluation showed MRAE and NASH as 0.31 and 0.70 for calibration and 0.34 and 0.57during verification, respectively. Soil Moisture Accounting and Linear Reservoir method used for distributed model showed improvement in model performance up to 6 sub-divisions after which the model performance started declining. Selection of appropriate method among different methods available in HEC-HMS should be in accordance with overall objective of study as it plays an important role in accurate estimation of runoff. Moving toward distributed modelling improves model performance but high resolution data and machine power is required..

Keywords: hydrological modelling, water resource management, HEC-HMS software, loss and base flow methods

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1 INTRODUCTION

1.1 General

Water is an essential resource for the existence of life on planet. Water, once an abundant natural resource, is now becoming a more valuable resource owing to exponential increase in human population and manmade pollution mainly due to industrial wastes. Water management refers to the management of water under set policies and regulations by the use of certain tools. In order to replicate the hydrological response in a basin due to precipitation or for future forecasts, hydrological models have become an indispensable tool for efficient management of basin water. During the past few decades, demand for water has increased significantly and seasonal flow patterns are significantly varied due to climatic change. There is ample evidence to suggest that the climate of South Asia has already changed (Eriyagama and Smakhtin, 2010). Therefore, careful management of limited water resources has become even more important.

Nowadays, different hydrologic models are available like Snowmelt Runoff Model (SRM) (Rulin et al.2008), HEC-HMS (Rathod, Borse, & Manekar, 2015), Storm Water Management Model (SWMM) (Jiang, Chen, & Wang, 2015), NedborAfstromnings Model (NAM) (Hafezparast, 2013), etc., for water resources modelling in a basin. Hydrological models can be classified into different categories depending on their basic operational principles, usage and availability. In presence of availability of many different models, hydrological model HEC-HMS (Hydrological Engineering Cooperation-Hydraulic Modelling System) developed by U.S. Army Corps of Engineers was selected for this study due to its availability in public domain, peer reviewed applications and availability of sufficient literature for the project area. Graphical User Interface makes it popular among users (USACE 2000). The software is very adaptable as it includes a variety of model choice for each segment of the hydrological cycle. Through the years, it has been used for many diverse applications for achieving goals in flood damage reduction, environmental restoration, reservoir and system operation, water supply planning, among others (USACE, 2000).

Several studies have been carried out using HEC-HMS model all over the world under different climate and soil conditions. Demonstration of potential HEC-HMS applications in disaster management, flood control and water management was shown by De Silva, Weerakoon and Herath (2014) by using HEC-HMS model for both event based and continuous modelling in Kelani river basin, Sri Lanka. Development of HEC-HMS model was carried out for both event based and continuous modelling for Monalack watershed in west Michigan (Chu & Steinman, 2009). It has also been widely used for flood forecasting and early warnings in different regions of the world (Rathod, Borse, & Manekar, 2015). Model was found to be accurate in predicting watershed response in event and continuous based simulation as well as for watershed management (Gibson , Pak, & Fleming, 2010).

The HEC-HMS offers various methods for simulation of rainfall losses, with transformation into surface runoff and baseflow. Among nine different methods available for simulating precipitation losses, only two can be used for continuous simulation while all other methods are designed for event based simulation. Same is the case with baseflow methods. Some can be used only in combination with particular loss models. Continuous hydrological modeling demonstrates the hydrological processes and phenomena over a long duration of time that includes both wet and dry conditions, therefore importance of selecting methods increases particularly in case of continuous simulation. Each method has its own pros and cons. Selection of a particular method depends upon the objective(s) to be achieved. Accurate prediction of runoff for optimum water resource management is dependent on the method selected for simulating direct runoff and baseflow. Comparison of different loss methods available in HEC-HMS with regard to different objective functions and their ranking from high to low preference was carried out by Sardoii, Rostami, Sigaroudi and Taheri (2012) in Amirkabir dam watershed, Iran. Green Ampt method was ranked as the most appropriate loss method for event based simulation according to the study. Similarly, a study carried out by Razmkhah (2016) in order to compare different loss methods ranked Soil Moisture Accounting (SMA) as the best method for event based runoff modelling. Selection of appropriate method plays an important role in effective watershed management.

Lumping of the parameters over a large area results in a decrease in model performance. Distributed hydrological modelling is found out to be more accurate as runoff is a function of both temporal and spatial variability unlike in lumped models where runoff is regarded as a function of only time which does not depict the actual situation. Distributed models require extensive data as compared to lumped models which makes it less popular among water resource managers.

Study carried out for investigating the scale effect by an application of distributed model, Topography based hydrological Model (TOPMODEL) in North Carolina, USA showed existence of Representative Elementary Area (REA) in the context of runoff generation and it is described that variability of soil and rainfall in an area plays a secondary role in runoff generation whereas it is strongly influenced by size and shape of sub catchment (Wood, Sivapalan, Beven and Band, 1988). Investigation of catchment scale by using Kinematic Runoff and Erosion Model (KINEROS) revealed that runoff per unit area decreases with the increase in sub catchment area (Bisri, Limantara, Prasetyorini, & Chasanawati, 2017). Event based rainfall runoff model developed by Nandalal and Ratnayake (2016) using HEC-HMS in Kalu ganga basin, Sri Lanka showed no effect of sub divisions of catchment on model performance for flood prediction due to rainfall. Semi distributed model developed by HEC-HMS in conjunction with Geospatial hydrologic modeling extension for Tapi watershed simulated peak runoff and total runoff better than lumped one (Himesh, Rao and Mahajan, 2000). Investigation of effect of sub catchment on model performance revealed that modelling performance can be increased up to a certain number of sub divisions as compared to the corresponding lumped after which there is no improvement in model performance (Kanchanamala, Herath and Nandalal, 2016). Thus, proper recognition of catchment scale in order to improve model performance is of extreme importance.

Project area, Kelani river basin, is the fourth largest river basin of Sri Lanka. It is one of the most important rivers in the country as it supplies 80% of water to Colombo city. Multiple water demands exist in this river basin. Kelani river basin can be divided into three peneplains. The river originates from central part of the country with a steeper slope. The slope becomes mild as it moves downstream. The river density is less at upstream locations of river basin which increases in downstream. Thus, the river passes through an area having different physical properties. Therefore, this study will aim to investigate on possibility of improvement of model performance by shifting toward distributed modelling approach and identification of most appropriate loss and baseflow methods among various methods available in HEC-HMS by considering Kelani river basin up to Glencorse.

1.2 Problem Statement

Improper runoff estimation in basins and lumping of the model parameters over a large area result in decrease of model performance in rainfall runoff models leading to problems in optimum management of water resources. Different methods are available for runoff estimation in HEC-HMS model for continuous simulation with each method having its own advantages and disadvantages. Therefore, selection of suitable method plays an important role in accurate estimation of runoff.

1.3 Overall Objective

The overall objective of the study is the comparison of two different loss and baseflow methods available for continuous simulation in HEC-HMS model and investigate the effect of catchment scale on model performance. Therefore, purpose of this study is to compare the different baseflow and loss methods and identify the improvements that can be achieved by moving toward distributed modelling.

1.4 Specific Objectives

1. Development of HEC-HMS lumped model for two different loss and baseflow methods.

2. To perform sensitivity analysis to identify the sensitive parameters and their response on model performance.
3. Calibration and validation of lumped model for two Options.
4. Selection of loss and baseflow method based on the model performance.
5. Analysis of the catchment scale effect on the performance of the model.
6. Deriving recommendations for efficient use of HEC-HMS.

1.5 Scope and Limitations of the Study

- To study and explore the working and function of HEC-HMS which is one of the most widely used software in hydrological modeling.
- To find the best method for simulating precipitation loss and baseflow among methods available in HEC-HMS for continuous simulation for accurate estimation of runoff.
- To investigate the effect of catchment scale on model performance for efficient water resource management.
- Model was calibrated by manual approach which is feasible for lumped models but for distributed models where number of parameters increase exponentially, the manual calibration is no longer feasible.
- In case of distributed modelling, only sensitive parameters were changed during calibration procedure while less sensitive parameters were kept constant for sub divisions due to unavailability of fine resolution data and efficient computing systems.
- Baseflow parameters were solely determined from calibration approach for modelling purpose.
- Field inspections of project area were not carried out during the course of study due to time limitation.

2 LITERATURE REVIEW

2.1 General

Detailed and systematic literature review was conducted during the initial phase of this study focusing mainly on State of art hydrologic and HEC-HMS modelling, Different loss and baseflow methods available in HEC-HMS, Objective function selection and Impact of catchment scale on model performance while also covering topics like Classification of hydrological models, Calibration and validation techniques and sensitivity analysis. Literature summary regarding HEC-HMS applications in Sri Lanka is given in Table 2-1.

2.2 Hydrological Modelling

Hydrological models are useful tools for water resources assessment, understanding of hydrological processes and prediction of the impact of changes in land use and climate.

Continuing innovations in data acquisition and computing technologies, and increasing modeling requirements have resulted in models that represent water related processes with more detail in space and time (Felipe & Baquero, 2007).

2.3 Hydrological Model Classifications

Hydrological models can be classified as empirical, conceptual or fully physical based. Empirical models contain no physical transformation function to relate input to output as such models usually build a relationship between input and output based on hydro-meteorological data (Sarkar and Kumar, 2012). In his study, Ondieki (1997) evaluated the water resource potential of non-perennial streams by investigating four catchments located in semi humid to semiarid regions, concluding that there exist some relationship of rainfall with runoff as well as suspended sediment load. But Costa, Botta and Cardille (2003) in their study concluded that rainfall alone cannot explain the variation of runoff efficiently which is due to antecedent moisture content, rainfall intensity, and physical characteristics of catchment such as geology, slope, soil, land use and land cover conditions.

Conceptual models as defined by Pechlivanidis, Jackson, McIntyre and Wheater (2011) are based on two criteria; i.e. the structure of model is specified prior to any modeling being undertaken and not all model parameters have a direct physical interpretation and have to be estimated through calibration against observed data. Study carried out on soil moisture dynamics by Parajka et al. (2006) revealed it has significant impact on hydrological processes by utilizing the scatter meter data in a conceptual semi distributed model. Lumped conceptual model to predict the runoff and also to test the calibration procedure was developed by Valent, Szolgay and Riverso (2012) which suggested that model has some uncertainties regarding conceptualization of complex runoff generation process and the quality of input data.

Physics based model may be defined by parameters which are wholly measurable by using basic mathematical equations such as Green –Ampt equations, St. Venant equations, etc. Physically based models are able to explicitly represent spatial variability of important land surface characteristics such as slope, aspect, vegetation as well as climatic parameters including temperature, precipitation and ET distribution (Akbari and Singh, 2012).

Models can be categorized as lumped, semi distributed or distributed when the spatial description of processes are considered (Krysanova, Bronstert and MüLler-Wohlfeil, 1999). The lumped modeling approach considers a watershed as single unit for computation purposes where the watershed parameters and variables are averaged over this unit (Cheng, 2010). An important shortcoming of simple lumped parameter models is that their parameters are not directly related to the physical characteristics of the catchment. In general, their applicability is limited to gauged watersheds where the expected conditions are within the historic data used for calibration and where no significant change in catchment conditions has occurred (Reed et al., 2004). The semi distributed models partition the whole catchment into sub-basins or HRUs (Daofeng, Ying, Changming and Fanghua, 2004). Distributed models attempt to simulate both the spatial heterogeneity and the physical processes occurring within a watershed (Bobba, Singh and Bengtsson, 2000). Compared to lumped models, semi-distributed and distributed models better account for the spatial variability of hydrologic processes, input, boundary conditions and watershed characteristics (Elfert & Bormann, 2010).

Rainfall runoff models can be classified as event based models or continuous simulation models. Event hydrological modeling reveals the response of basin to an individual rainfall event while continuous hydrological modeling demonstrates the hydrological processes and phenomena over a long duration of time that includes both wet and dry conditions. Therefore, fine-scale event hydrological modeling is helpful for understanding detailed hydrological processes and identifying the relevant parameters that will be helpful for coarse scale-continuous modeling, especially when there is scarcity of data.

2.4 HEC-HMS Model

HEC-HMS developed by U.S. Army Corps of Engineers is capable of simulating the complete hydrological processes of dendritic watershed system. Its availability in public domain, peer reviewed and availability of sufficient literature for project area. Graphical User Interface makes it popular among users. The software is very adaptable as it includes a variety of model choice for each hydrological cycle segment. Through the years it has been used for many diverse applications for achieving goals in flood damage reduction, environmental restoration, reservoir and system operation, water supply planning, among others (USACE, 2000).

Several studies have been carried out using HEC-HMS model all over the world under different climate and soil conditions for achieving different objectives. Development of HEC-HMS model for both event based and continuous modelling for Mona lack watershed in west Michigan was carried out by (Chu and Steinman, 2009). Demonstration of potential HEC-HMS applications in disaster management, flood control and water management was shown by De Silva, Weerakoon and Herath (2014) by developing HEC-HMS model for both event and continuous modelling in Kelani river basin in Sri Lanka. It has also been widely used for flood forecasting and early warnings in different regions of world by (Rathod et al., 2015b). Calibration and validation of lumped and distributed HEC-HMS model was carried out by Roy, Begam, Ghosh and Jana (2013) for Subamarekha river basin, India. Two distributed model for different number of sub divisions were successfully calibrated and validated for Kalu ganga basin,Sri Lanka

(Nandalal & Ratnayake, 2016). Model was found to be accurate in predicting watershed response in event and continuous based simulation as well as for watershed management.

2.4.1 HEC-HMS Model Structure

Runoff volume is computed in HEC-HMS by subtracting from precipitation, the amount of water that is intercepted, infiltrated, stored, evaporated or transpired (USACE, 2000). HEC-HMS consists of three basic components required for running of any project. These are (1) Basin model (2) Precipitation model (3) Control specification. Basin model is used for converting atmospheric condition into streamflow at specific location in the watershed. Precipitation model is used to input required meteorological data into software. Control specification is used for specifying starting and ending period of simulation with time interval to be used for simulation. Main component of basin model includes loss model, transform model, baseflow model and routing model.

HEC-HMS offers different method for simulation of each cycle of segments. Pros and cons of each methods are given in (USACE, 2000).

2.4.2 Precipitation Loss Model

Among nine different methods available in HEC-HMS for simulation of precipitation loss only two methods i.e. Deficit and Constant method and Soil Moisture Accounting method can be used for continuous simulation (Cunderlik & Simonovic, 2004). Deficit and Constant loss methods is similar to Initial/Constant uniform method in which a total loss volume and initial loss volume are used to specify an initial value. Four parameters i.e. Initial Deficit, constant loss rate, maximum deficit and impervious area are required for simulating precipitation loss.

Initial deficit indicates the amount of water required for saturation of soil layer to the maximum storage (USACE, 2000). Maximum storage represents the maximum amount of water that can be stored in soil layer specified as depth. This parameter has no typical values but it is similar to maximum potential retention defined by SCS curve number which can be calculated by using equation given by SCS (Chow, Maidment and Mays, 1988). Constant rate specifies the percolation rate when soil is fully saturated. Initial loss can recover after a long period of no rainfall in this method which make it different from Initial and Constant loss model.

Soil Moisture Accounting method capable of simulating dynamic movement of water in and above the soil by using five layers i.e. canopy interception, surface depression storage, soil, upper groundwater and lower ground water unlike other methods like SCS curve number based model which focus only on the surface processes but ignore soil profile are rarely applied due to challenges of parameter estimation and calibration (Tramblay et al., 2010). Initial conditions for these five layers must be specified as the percentage of water in the respective storage layer prior to simulation. Maximum infiltration rate represents maximum rate of water that can be enter from surface storage into soil layer. Saturation hydraulic conductivity of soil can be taken as initial estimate. Impervious area represents the area with no infiltration. Soil storage represents the total storage of water that can be stored in upper layer of soil that can be removed by both evapotranspiration and percolation to lower layers while tension storage represents the water held in the pores of soil which will lose water through evaporation only. Percolation rate specify water entry rate from soil to groundwater layer. Typical value of percolation rate of soils can be found in literature. Ground water storage and percolation rate are similar to soil layer while ground water coefficient represents maximum retention time in ground water layer (USACE, 2000). Study carried out by Singh and Jain (2015) ranked soil storage and soil percolation as most sensitive parameter of this method.

Comparison of different loss method available in HEC-HMS with regard to different objective function and their ranking from high to low preference was carried out by Sardoii, Rostami, Sigaroudi and Taheri (2012) in Amirkabir dam watershed, Iran. Green Ampt method was classified as the most appropriate loss method for event based simulation according to the study. Similarly a study carried out by Razmkhah (2016) in order to compare different loss method ranked Soil Moisture Accounting as the best method for event based runoff modelling. Selection of appropriate loss method plays an important role in accurate estimation of runoff.

2.4.3 Transform Model

Seven transform models are available for transformation of precipitation excess to runoff. Comparative study for different available transform methods in HEC-HMS for Attanagalu Oya basin, Sri Lanka carried out by Halwatura and Najim (2013) showed Snyder unit hydrograph simulate stream flow more efficiently than Clark unit hydrograph. Study carried out in project area by Weerakoon, De Silva and Herath (2014) selected Clark unit hydrograph as transformation method to take into account small storage unit at upstream of catchment. Two critical processes of translation of excessive rainfall and attenuation due to storage like reservoirs in the sub basins are directly represented by Clark unit hydrograph method. Two parameters required for this method are Storage coefficient and Time of concentration.

2.4.4 Baseflow Model

Four method available for simulating baseflow in HEC-HMS are Recession method, Bounded recession method and constant monthly method each one having their own advantages and dis advantages.

Recession method although it is designed primarily for event based simulation it has ability to reset after each storm event and consequently can be used for continuous simulation (USACE, 2000). Three parameters required for this method are initial discharge, recession constant and ratio to peak. Initial flow specifies the discharge prior to simulation interval. Recession constant represents baseflow decay while ratio to peak represents threshold flow below which baseflow occurs in accordance to recession constant

Linear reservoir model can only be used for simulating bae flow in conjunction with soil moisture accounting loss method. It simulates the storage and movement of sub surface flow as storage and movement of water through reservoirs. Mathematically it is similar to manner in which Clark unit hydrograph represents runoff of watershed (USACE, 2000). Linear reservoir model can be used for efficient simulation of baseflow of undisturbed catchment as baseflow falls rapidly to a lower level for disturbed catchment about 40 % faster than un disturbed catchment (Buytaert, De Bièvre, Wyseure and Deckers, 2004).

Three parameters required for this method are Initial discharge, Groundwater coefficient and number of reservoirs.

2.5 Objective Function

The objective function is used to evaluate the hydrological model simulation result. In contrast with manual calibration the automatic calibration adopts the visual inspection of similarities and differences between the model simulations and observations. Therefore, hydrologists proposed many statistical measures as efficiency criteria to confirm the goodness -of -fit of hydrologic model in the automatic calibration program in last decade. Most objective functions used for calibration of hydrological models contain a summation of the error term, i.e. the difference between the simulated and observed variable The selection of objective function depends on the modeling objectives such as modeling for flood control, water resource planning and management. The selection of objective function has differed from researcher to researcher even for same objective.

Objective function can be generally classified into two types: distance based objective function (also called absolute measure) and weak form-based objective function. The distance based objective function which is mostly used in the model calibration such as mean squared error and mean absolute error is defined as distance between model prediction and observed data Green and Stephenson (1986) whereas weak form based objective function such as the coefficient of determination and the volume/cumulative error is used to estimate the statistical properties of model residual between the model prediction and observed data (Guinot, Cappelaere, Delenne and Ruelland, 2011). For the comparison of performance of different hydrological model, the normalization of distance based objective functions are proposed e.g. the Nash-Sutcliffe efficiency defined by Nash and Sutcliffe (1970) that is the normalization of MSE.

Procedure was outlined by Diskin and Simon (1977) in their study for the selection of objective function by considering a number of objective applications and comparing with reference to one or more engineering application. They concluded that model should be calibrated using objective function that is best capable of generating the type of data that interests him.

After comparison of many objective functions Green and Stephenson (1986) concluded that objective function ultimately chosen should depend on the objective of the modeling exercise, because different objective functions are in favor of different hydrographic components by giving example that if modeler is interested only in peak flows then there is little point in investigation of low flows or hydrograph shape. Objective function recommended by this study are listed below

1. Percent Error in Peak (PEP)
2. Percent Error in Volume (PEV)
3. Sum of Squared Residuals (SSR)
4. Sum of Absolute Residuals (SAR)
5. Nash-Sutcliff Efficiency (NASH)

Different objective functions listed above are used by different researchers in order to achieve different objectives. One of the most widely used objective function is Nash-Sutcliff efficiency in which difference between observed and simulated value are calculated as squared value resulting in strong overestimation of larger value in time series whereas lower values are neglected (Legates and McCabe, 1999). Nash Sutcliff is not sensitive to low flow periods and some times over estimation of model performance in high flow could occur (Krause, Boyle and Bäse, 2005).

Percent Error in Volume only take into account percent difference between simulated and observed volume neglecting magnitude and timing of the peak flow.

Mean Ratio of Absolute Error which is defined as difference between simulated and observed flow with respect to that particular observation was used for assessing model performance in a research carried out by (Perera & Wijesekera, 2016). In presence of contrasting data in observed data set it gives better representation as it compares the error with respect to each observed flow.

HEC-HMS model was calibrated for Subarnarekha river basin in eastern India by Roy et al., (2013) selecting Nash-Sutcliffe, percentage error in peak and net difference of observed and simulated time to peak as objective functions

The latest version of HEC-HMS model includes optimization manager through which automatic calibration can be done. Five objective functions are available in optimization manager USACE (2000) i.e. Peak-weighted root mean square error, Sum of squared residuals, Sum of absolute residuals, Percent error in peak flow and Percent error in volume.

2.6 Calibration and Validation of Model

Calibration uses observed hydrological data in a systematic search for parameters that yield the best fit of the computed result to observed result (USACE, 2000). Calibration process finds the optimal parameter values that minimize the objective function.it is also used to estimate the parameters that have no physical meaning i.e. parameters which cannot be estimated by observation or measurement. There are two ways to achieve calibration of model i.e. manual or automated. In automated calibration parameters of models are adjusted automatically by computer until minimum value of selected objective function is achieved whereas the success of manual calibration depends on the knowledge of user regarding physical properties of basin and expertise in hydrological modeling. Automatic calibration uses a single overall objective function to measure the goodness of fit of calibrated model which is often inadequate to measure properly the simulation of all important properties of system which give rise to doubt for applying automatic calibration (Madsen, 2000). In case of manual calibration it is difficult to determine the best fit or to determine a clear point indicating the end of calibration process and hence different result will be obtained by different modelers(Wheater, 2002). The calibration process can either be manual or automatic however in practice is often a combination of the both methods.

Once the model is calibrated it is validated for different data set of available record of observed value. The purpose of validation is to strengthen belief in predictive ability of hydrologic model for practical purposes. Validation testing is designed to confirm that the calibrated model is applicable over the limited range of conditions defined by calibration and validation data sets. Therefor it is important that calibration and validation data must cover the range of condition over which predictions are desired. The collected data should be such that calibrated parameters are fully independent of the validation data (Himesh et al, 2000).

Sudheer, Chaubey, Garg and Migliaccio (2007) evaluated the impact of calibration-time scale on model predictive ability. The results demonstrated that performance of model for small time scale cannot be ensured by calibrating them for a large time scale. Model evaluation should be done by considering their behavior in various aspect of simulation, such as predictive uncertainty, hydrograph characteristics, ability to preserve statistical properties of the historical flow series etc. This study suggested calibration of watershed model on daily time step in order to preserve the hydrological behavior of the watershed effectively.

2.7 Sensitivity Analysis

Sensitivity analysis evaluates the impact of changes in the model parameters, input or states on the model output of interest. Sensitivity analysis is a modeling tool that if properly used can provide model designer with a better understanding of the correspondence between the model and the physical processes being modeled (McCuen, 1973). It is potentially valuable in the formulation, calibration and verification of hydrologic model. The region around the best parameter estimate in which the function value varies from the best function value by only a small value is called the region of indifference. Sensitivity analysis helps in determining the correspondence among parameters. According to Wagener & Kollat (2007) sensitivity analysis can be broken up into two components i.e. investigation of model parameter space, and numerical or visual measure of the impact of sampled parameters on the model output of interest.

There are two types of sensitivity analyses: Local sensitivity analysis and Global sensitivity analysis. Local sensitivity analysis assesses the impact of change in parameter values within the local region of indifference on the output of model hence inherently limiting its ability to identify all potentially relevant feature of response surface; i.e. the effect of each parameter is determined separately by keeping other parameter model constant. This type of sensitivity analysis is particularly useful when considering only local region of indifferences. Nominal range and differential analysis method are two local sensitivity methods (Helton and Davis, 2002).

Global sensitivity analyses try to explore the full parameter space within predefined feasible parameter range. General variability of the objective function over space or sub-dimension of space is measured by statistic. The literature identifies different global sensitivity analysis methods like regional sensitivity analysis, variance based method, regression based approach, and Bayesian sensitivity analysis.

Calibration and validation of HEC-HMS model for Subarnarekha river basin in eastern India was undertaken by Roy et al., (2013) by dividing the study basin into three sub basins in order to account for spatial variability of precipitation and runoff response characteristics. Sensitivity analysis showed soil storage, tension zone storage and groundwater1 storage coefficient to be sensitive parameters for simulated stream flow.

2.8 Impact of Catchment Scale on Model Performance

Distributed hydrological modelling is found to be more accurate than lumped one as runoff is a function of both temporal and spatial variability in distributed model while runoff is a function of only time in lumped model. Investigation of spatial variability and catchment scale effect on model performance by comparing lumped and distributed model have been carried out by many (Wood et al., 1988). Runoff per unit area decreases with increase in sub catchment size as concluded from a study carried out to investigate catchment scale effect by developing a distributed model (Canfield & Goodrich, 2003).Variability of soil and rainfall in an area plays a secondary role in runoff generation whereas it is strongly influenced by size and shape of sub catchment (Wood et al., 1988).

Assuming uniform distribution of rainfall in space can lead to large error in simulated peak runoff and volume (Faurès, Goodrich, Woolhiser, & Sorooshian, 1995). Rainfall runoff model developed by Nandalal and Ratnayake (2016) using HEC-HMS in Kalu ganga basin, Sri Lanka showed no effect of sub divisions of catchment on model performance for flood prediction due to rainfall. Semi distributed model developed based on HEC-HMS in conjunction with Geospatial hydrologic modeling extension simulated peak runoff and total runoff better than the lumped model (Roy et al., 2013). Investigation of effect of sub catchment on model performance revealed that modelling performance can be increased up to certain number of sub divisions as compared to lumped one after which there is no improvement in model performance (Kanchanamala, Herath, & Nandalal, 2016). Effect of watershed sub division on calibrated parameters of HEC-HMS model showed most of the calibrated parameter values are sensitive to the basin partition scheme and relative relevance of physical processes is dependent on watershed sub division (Zhang et al, 2013). Thus, a proper recognition of optimum catchment scale is necessary for efficient model performance.

Table 2-1 Literature summary of HEC-HMS application in Sri Lanka

Topic	Model	Method	Results
Event based modeling of watershed using HEC-HMS for Kalu Ganga river basin (Nandalal & Ratnayake, 2016)	Precipitation loss model	Initial and constant rate loss	0.90 <=NASH<=0.93
	Direct runoff model	Clark’s model	
	Baseflow model	Exponential recession	
	Routing model	Lag and Muskingum	

Topic	Model	Method	Results
Modeling of Event and Continuous Flow Hydrographs with HEC–HMS: Case Study in the Kelani River Basin (De Silva, Weerakoon and Herath, 2014)	Precipitation loss model	Five-layer soil moisture	NASH=0.88
	Direct runoff model	Clark unit hydrograph	
	Baseflow model	Recession	
Development of rainfall runoff model for Kalu Ganga Basin of Sri Lanka using HEC-HMS (Jayadeera, 2016)	Precipitation loss model	Deficit and constant loss rate	The model matching of time of peak flow occurrence was at an accuracy of 60% while the peak flow magnitude accuracy was 75%.
	Direct runoff model	(SCS) unit hydrograph	
	Baseflow model	Recession	
	Routing model	Muskingum	
HEC-HMS Model for Runoff Simulation of the Deduru Oya River Basin (Sampath, Weerakoon and Herath, 2014)	Precipitation loss model	Five-layer soil moisture	NASH=0.80
	Direct runoff model	Clark unit hydrograph	
	Baseflow model	Recession	
	Routing model	Muskingum	

3 MATERIALS AND METHODS

3.1 General

Methodology used for achieving overall objective and specific objectives of this study is presented in detail in this Chapter. Different methods used to reach results are discussed at length. Material used for study purpose, their sources and resolutions are also listed. Methodology flow chart which was followed for the study is given in Figure 3-1 and general description of different steps involved in flow chart is given in Chapter 3.2.

3.2 Methodology Development

Methodology adopted for this research is shown in Figure 3-1. After identification of research need and establishment of overall objective and specific objectives of the study, an extensive literature review was carried out to identify the various types of hydrological models available, their applications and different objective functions for assessing the model performance during calibration and validation processes. Rainfall and streamflow data collected from Meteorological Department and Irrigation Department, respectively, for six years was checked for homogeneity and consistency by using different statistical methods. Missing data periods were filled by the data from the closest station using patching method. Option analysis was carried out for different baseflow and loss models.

Among nine different loss methods available in HEC-HMS to simulate precipitation loss, only the Deficit and Constant methods and Soil Moisture Accounting (SMA) method can be used for continuous hydrological modelling. In case of baseflow, Linear Reservoir method can be used only in combination with SMA loss model. Thus, two options were selected for this study. In First Option, loss model was selected as Deficit and constant rate with Recession method as baseflow while in Second Option, Soil Moisture Accounting and Linear reservoir model were selected as loss and baseflow models, respectively. Clark method as transformation model was kept same for both Options.

Process of development of model, initial parameter estimation and selection of objective function is described in Chapter 3. Calibration was carried out using data from 2006/2007 to 2008/2009 and the verification was carried out for the balance data set from 2010/2011 to 2013/2014. Manual calibration approach was used for optimizing parameter values. Mean Ratio of Absolute Error (MRAE) was used as an objective function for this study while two other statistical goodness of fit measures, NASH and Percent Error in Volume (PEV) were also checked as an observation. Model performance was evaluated for both Options and objective function value was used as criteria for selection of the best Option. Lumped model was then divided into 3, 6, 9 and 16 sub-divisions to investigate model performance with respect to catchment scale. Loss and baseflow methods of the best Option selected as described above was used for distributed modelling. Routing was carried out by using Lag method. Model performance for different sub divisions were analyzed and model performance with optimum number of subdivisions was compared with that of the lumped model.

Sensitivity analysis carried out for both options is described in Chapter 4. Values of objective function for lumped as well as distributed model and their comparisons are also given in Chapter-4.

Chapter 5 presents the Discussion, comparing and contrasting results with those available in the literatures with reasoning for any deviations observed.

Conclusions and recommendations achieved from this study are listed in Chapter- 6.

3.3 Methodology Flow Chart.

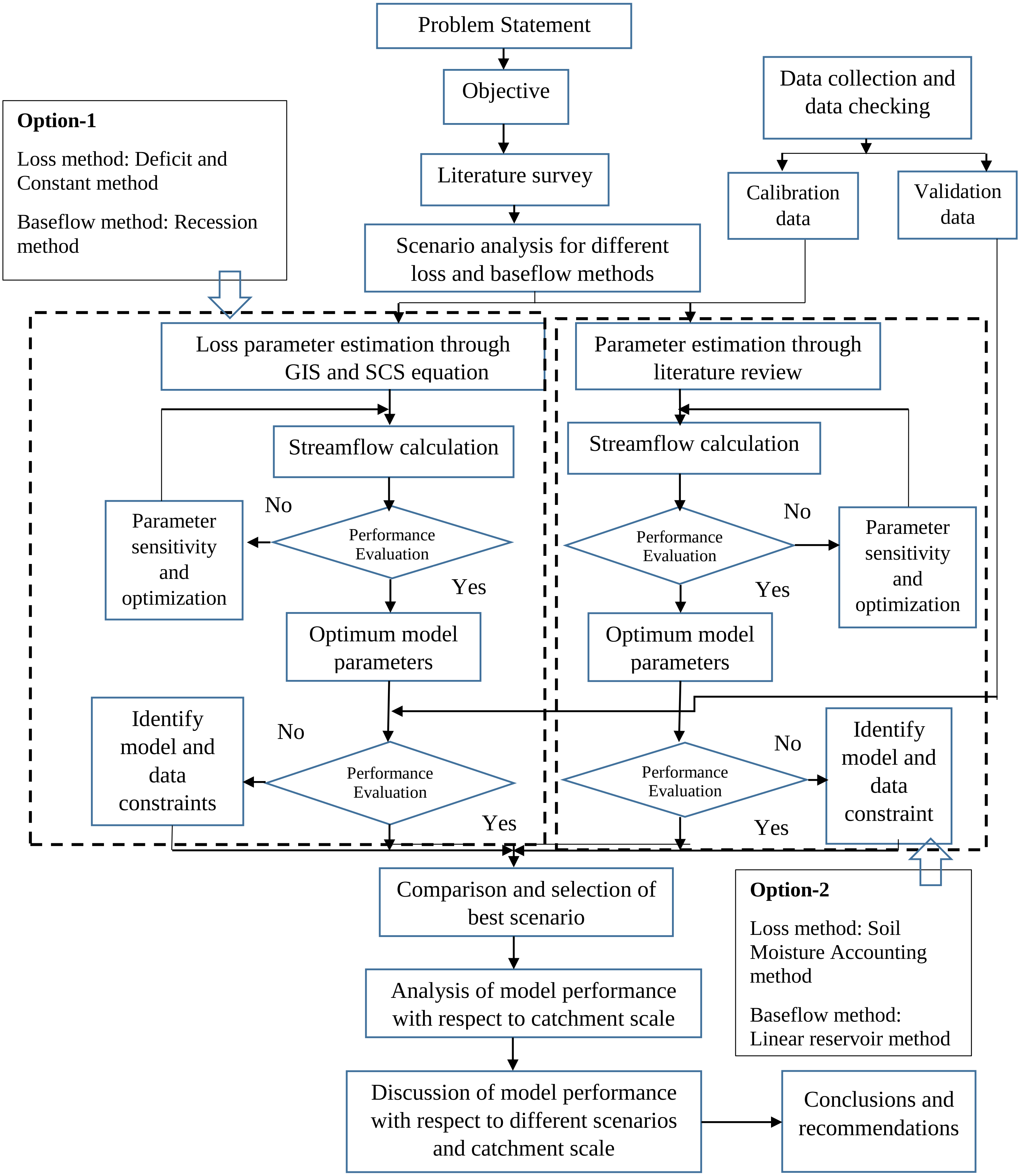


Figure 3-1 Methodology flow chart

3.4 Study Area

Glencorse sub watershed of Kelani river basin was selected for this research. Drainage area of Glencorse watershed is 1507 km^2. Stream gauging station is at Glencorse and four rain gauging stations within the catchment were selected based on the availability of data for required period as shown in Figure 4.1. Coordinates of streamflow gauging station and rainfall gauging station are given in Table 3-1. Land use map obtained from Survey Department was classified into five classes as shown in Figure 3.3 and its corresponding composition values are shown in Table 3.2. Project area map is shown in Figure 3.2. Land use map of Glencorse watershed is shown in Figure 3.3.

Table 3-1 Coordinate location of gauging stations

Gauging station	**Location (Decimal Degree)**
Norton	6.91N, 80.52E
Kennel worth	6.99N, 80.47E
Vincit	6.92N, 80.21E
Yatiyantota	6.90N, 80.25E
Glencorse river gauging	6.88N, 80.12E

Table 3-2 Land use composition of Glencorse catchment

Land use type	**Area (%)**	**Area (km^2)**
Agricultural	66.6	100.4
Forest	14.8	223.7
Residential	16.2	243.3
Rock	1.1	16.2
Water bodies	1.3	19.0

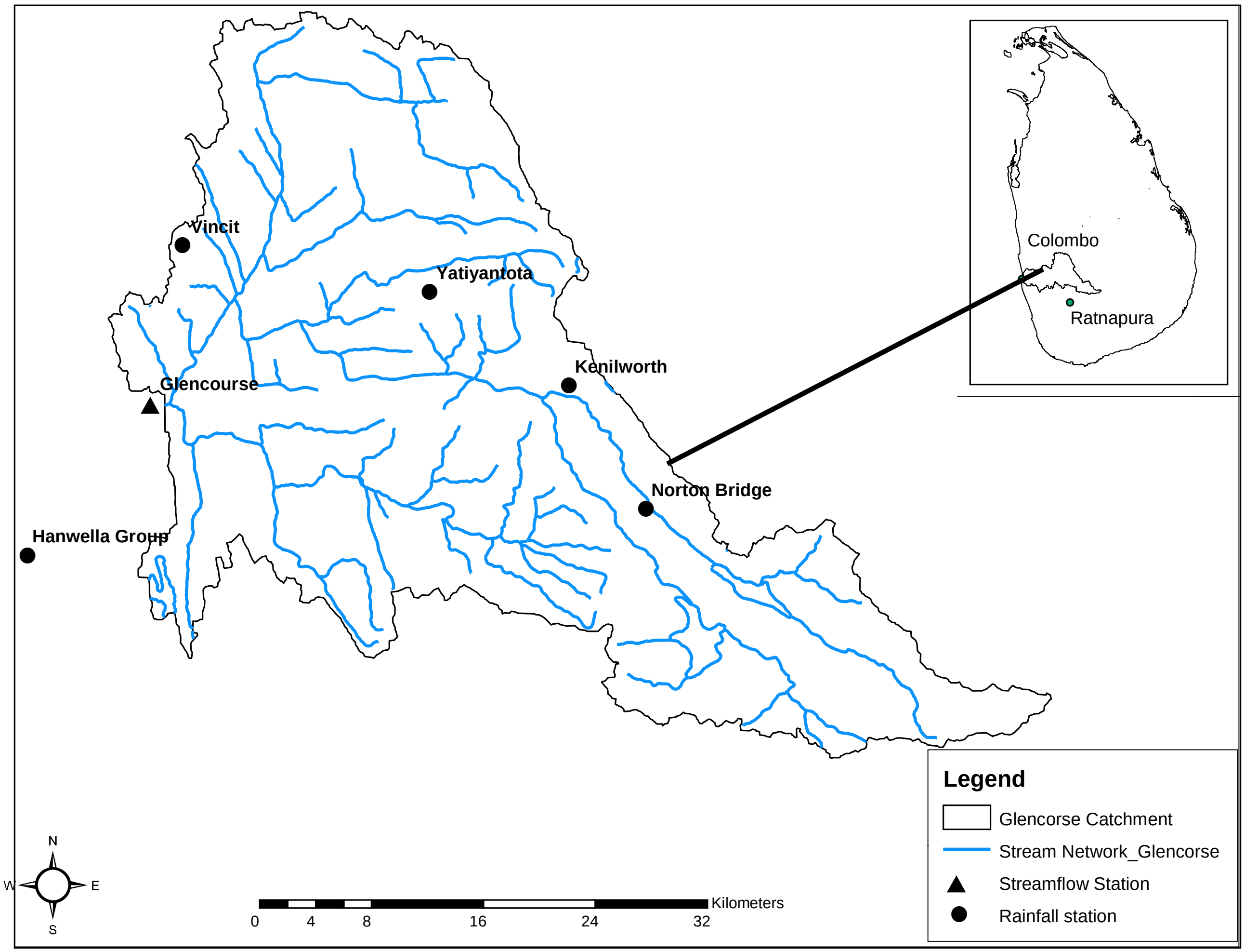


Figure 3-2: Glencorse Catchment Map with Gauging Stations (Source: Survey Department, Sri Lanka)

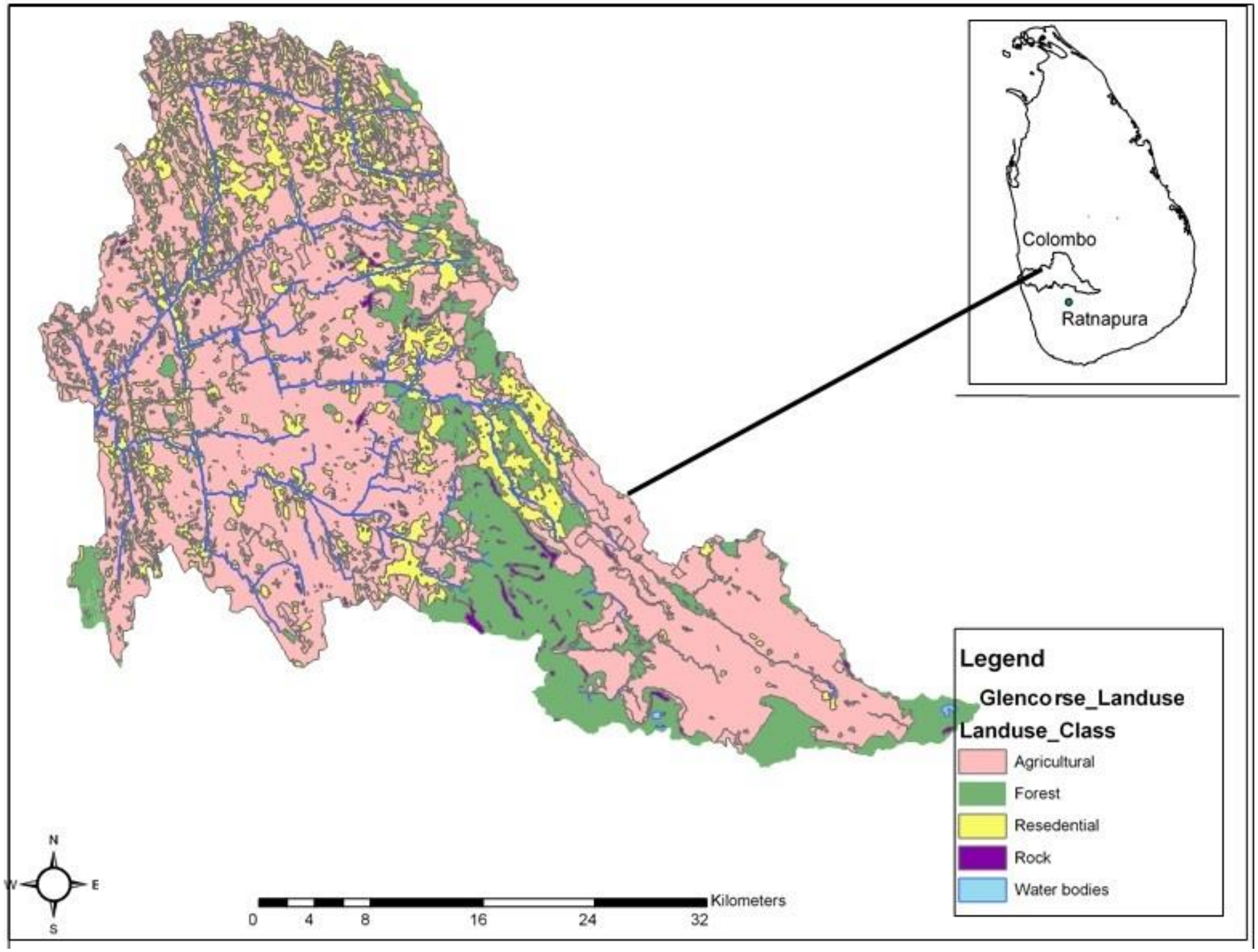


Figure 3-3 Land use map of Glencorse watershed Same as above (Source: Survey Department, Sri Lanka)

3.5 Data and Data Checking

Main data used in this study are daily rainfall, daily streamflow and topographic data.

3.5.1 Data Sources and Data Resolution

Irrigation Department and Meteorological Department are responsible for maintenance of rainfall and streamflow gauging stations in Sri Lanka. Streamflow data was collected from Irrigation Department while rainfall data was collected from Meteorological Department. The data sources with resolutions used for this study are shown in Table 3-3.

Table 3-3 Data sources and Resolutions

Data type	**Temporal resolution**	**Data period**	**Data source**
Rainfall	Daily	October 2006 to September 2014	Dept. of Meteorology
Stream flow	Daily		Dept. of Irrigation
Contour	1:10,000		Dept. of Survey
Land use	1:50,000		Dept. of Survey

3.5.2 Visual Data Checking

Prior to model development, the available hydrological data requires checking to identify the abnormalities in data. In order to check inconsistencies in data, visual checking was carried out. The response of streamflow against rainfall was plotted for each gauging station and for each year. The periods during which streamflow was non responsive to rainfall were identified.

Glencorse streamflow is showing non responsiveness to the rainfall of Vincit, Yatiyantota and Kennelworth during January 2009 and February 2009. These non-responsiveness periods are marked as purple circles. It is also not responsive to Vincit rainfall in February 2012. Streamflow response with rainfall of each station for two critical years identified through water balance is shown in Figure 3-4 and Figure 3-5. Streamflow response of Glencorse watershed to rainfall in other years are shown in Appendix A.

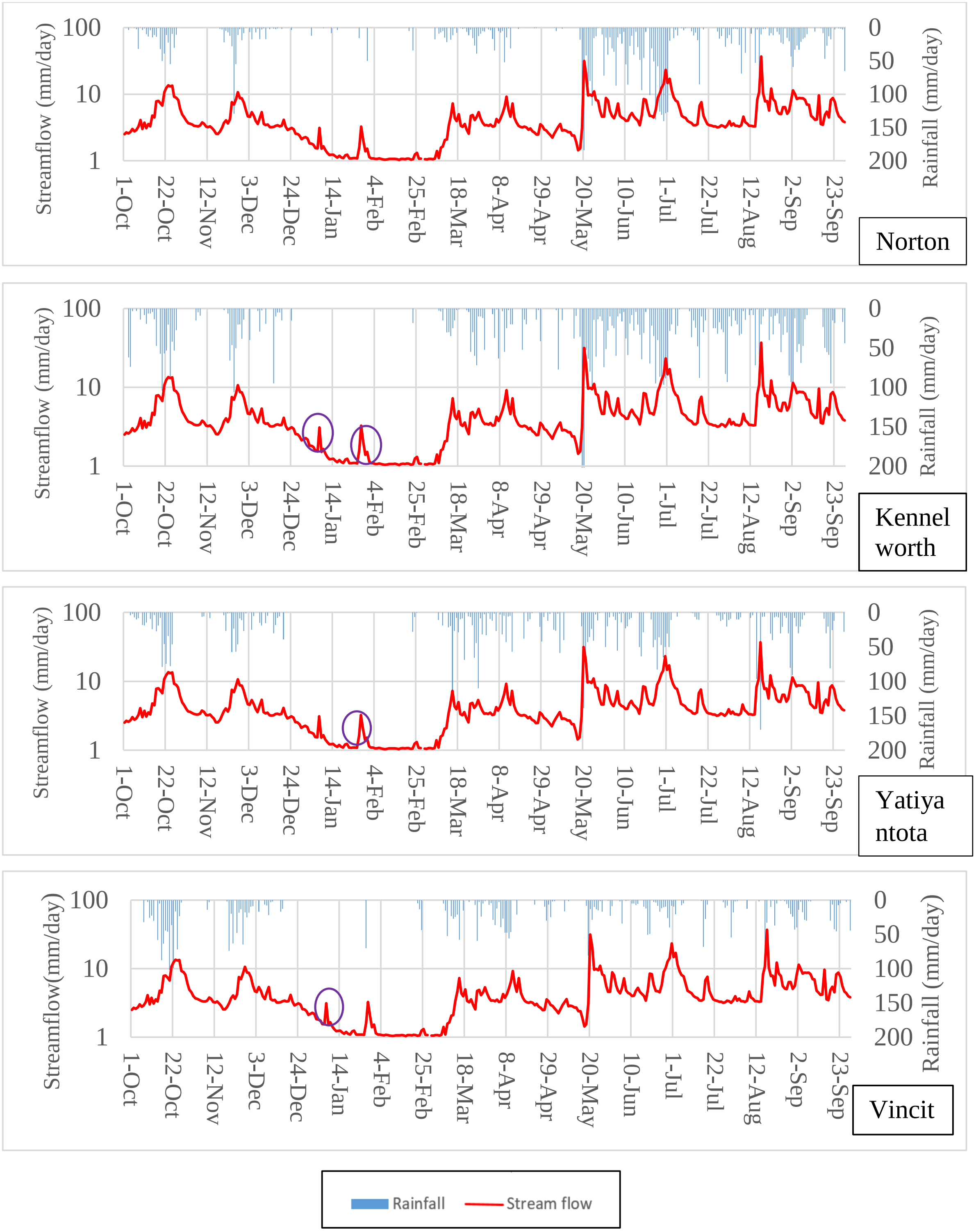


Figure 3-4 Glencorse streamflow response with rainfall in 2008/2009

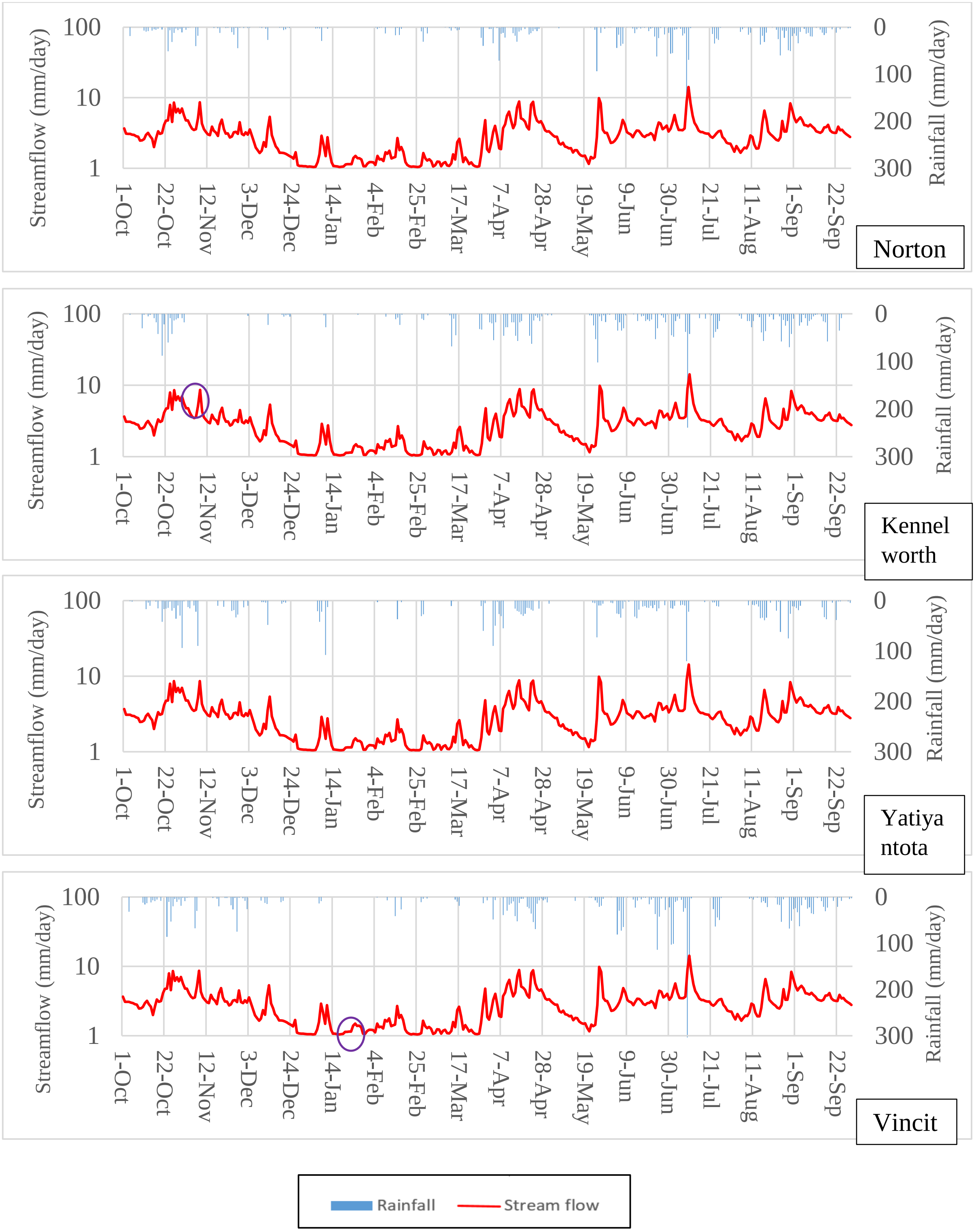


Figure 3-5 Glencorse streamflow response with rainfall in 2011/2012

Annual Water Balance

Annual water balance was carried out for Glencorse watershed in order to compare annual volume of stream flow, rainfall, evaporation and annual runoff coefficient. Annual water balance of Glencorse watershed is shown in Table 3-4.

Table 3-4 Annual water balance calculation of Glencorse catchment

Year	Annual rainfall (mm/year)	Annual streamflow (mm/year)	Annual evaporation (mm/year)	Annual runoff coefficient
2006/2007	4731	1768	2963	0.37
2007/2008	4568	2036	2533	0.45
2008/2009	4801	1675	3126	0.35
2010/2011	4979	2190	2789	0.44
2011/2012	2787	1082	1705	0.39
2012/2013	4903	2398	2504	0.49
Average	4418	1815	2604	0.41

3.5.2.1. Variation of Annual Runoff Coefficient and Evaporation

The runoff coefficient value ranges from 0.37 to 0.49 during the study period. The lowest value of runoff coefficient is in year 2008/2009. In this year, stream flow is not showing good response to rainfall due to which evaporation is maximum in this year. This year was marked as an abnormal year and monthly water balance was carried out for this year for each rainfall station in order to identify the problem. In 2102/2013, the value of runoff coefficient is the highest as streamflow shows good response as compared to other years with rainfall while the evaporation is minimum**.** Variation of annual runoff coefficient with annual evaporation for Glencorse watershed is shown in Figure 3-6.

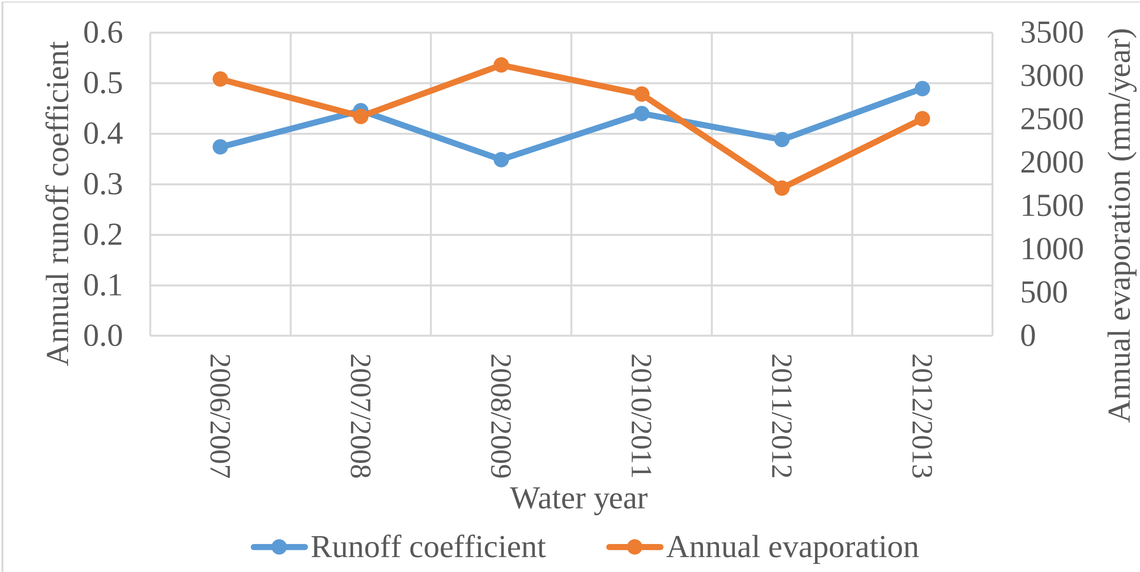


Figure 3-6 Variation of runoff coefficient and annual evaporation

3.5.2.2 Variation of Annual Rainfall and Streamflow

Variation of annual streamflow with annual rainfall for Glencorse watershed is shown in Figure 3-7. It can be observed from figure that rainfall in 2011/2012 reduced significantly due to which streamflow has also decreased. The 2011/2012 is the driest year during the study period as both rainfall and streamflow have their minimum values during the study period. This year was marked as an abnormal year and literature review carried out on the previous researches conducted in the surrounding area using similar period data showed a similar behavior for Kalu Ganga basin as rainfall and streamflow significantly reduced to a low value resulting in a high evaporation and low runoff coefficient value. This revealed that there may be some inconsistencies in data. In 2008/2009, although rainfall is more than 2007/2008, but streamflow has decreased as compared to 2007/2008. Apart from these years' streamflow and rainfall are showing satisfactory relation. With the increase in rainfall streamflow is also increasing and vice versa.

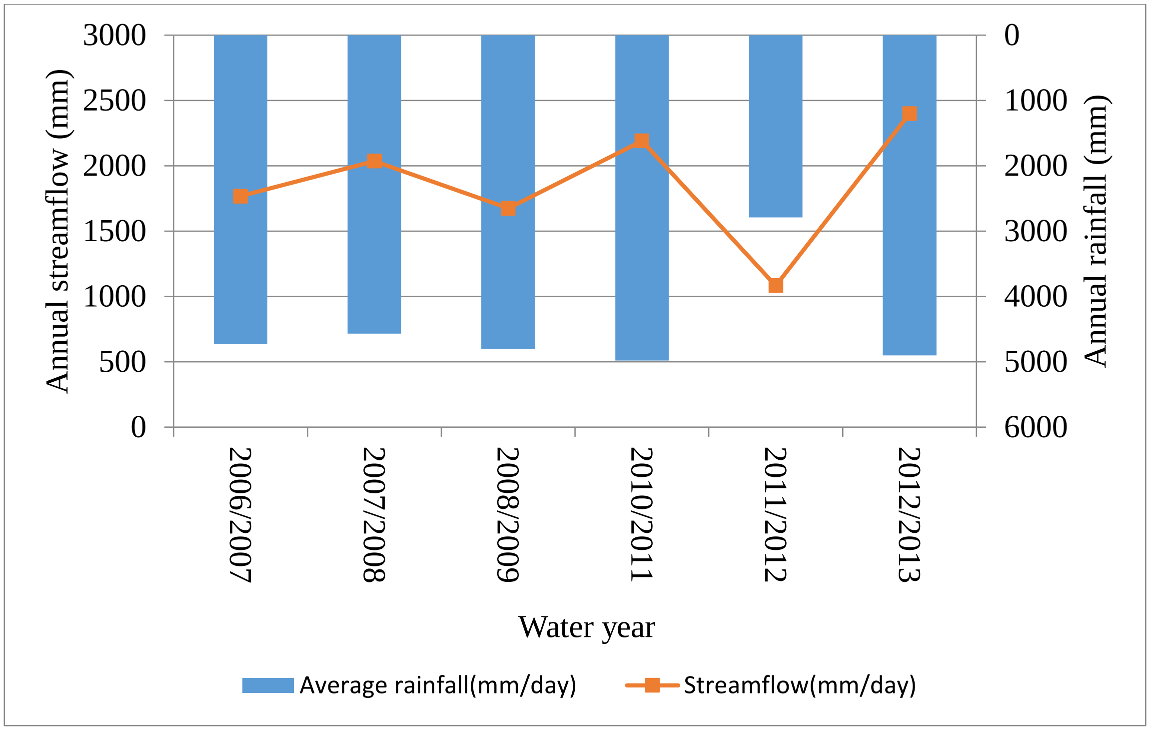


Figure 3-7 Variation of annual rainfall and streamflow of study period

3.5.3 Thiessen Average Rainfall

In order to calculate catchment average rainfall, Thiessen polygon method was used. Thiessen polygon was developed for each rainfall station by using Arc GIS (ESRI, USA) and Thiessen weight for each rainfall station was determined. Thiessen polygon developed for Glencorse watershed is shown in Figure 3-6. Thiessen weight for different rainfall gauging station are shown in Table 3-5. Thiessen averaged rainfall was calculated by multiplying rainfall of each station with corresponding Thiessen weight.

Thiessen averaged rainfall and streamflow for Glencorse watershed are plotted in same plot for each year. Thiessen average rainfall with Glencorse streamflow for each year is given in Figure 3-7 and Figure 3-8. It can be observed from the figures that most of the peaks are matching and responding well with rainfall.

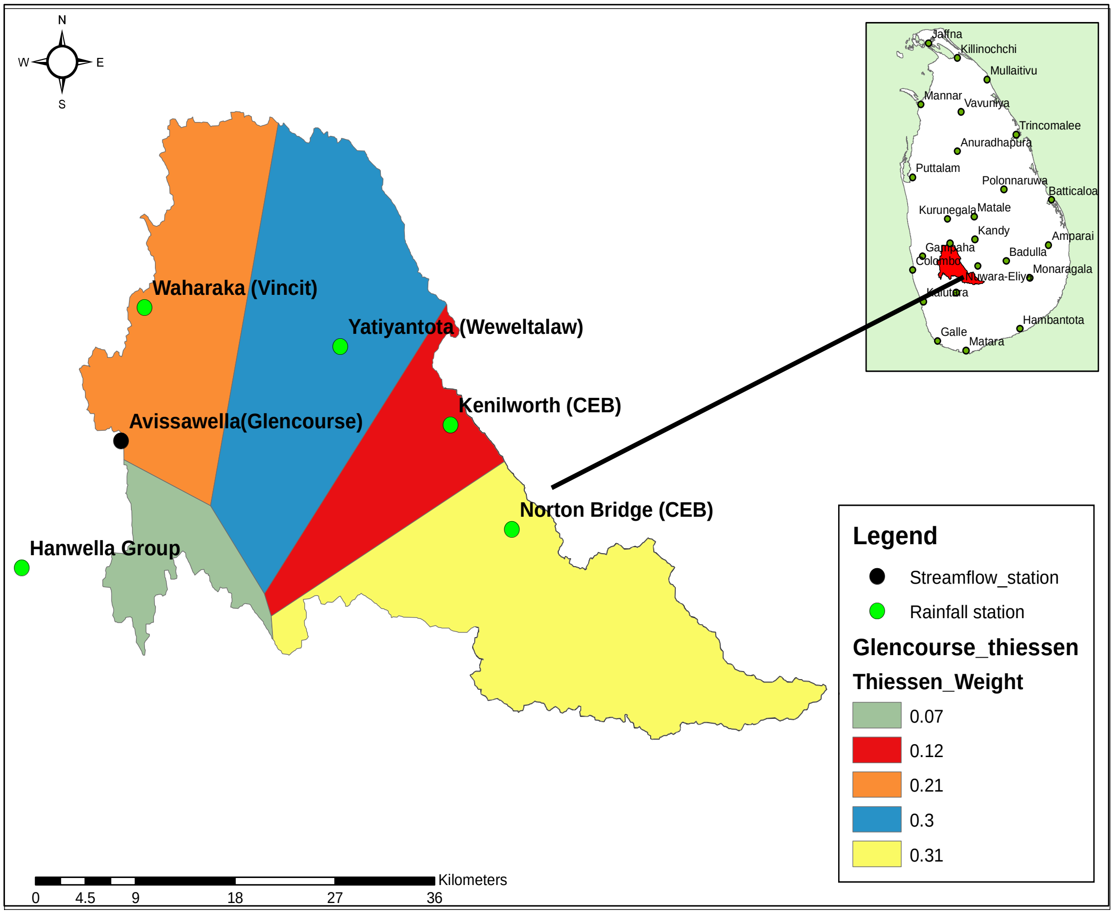


Figure 3-6 Thiessen polygon of Glencorse catchment

Table 3-5 Thiessen weight of rainfall gauging station

Rainfall station	**Area (km^2)**	**Thiessen weight**
Norton	463.5	0.31
Kennel worth	178.2	0.12
Vincit	312.5	0.21
Yatiyantota	452.5	0.30
Hanwella	100.3	0.07

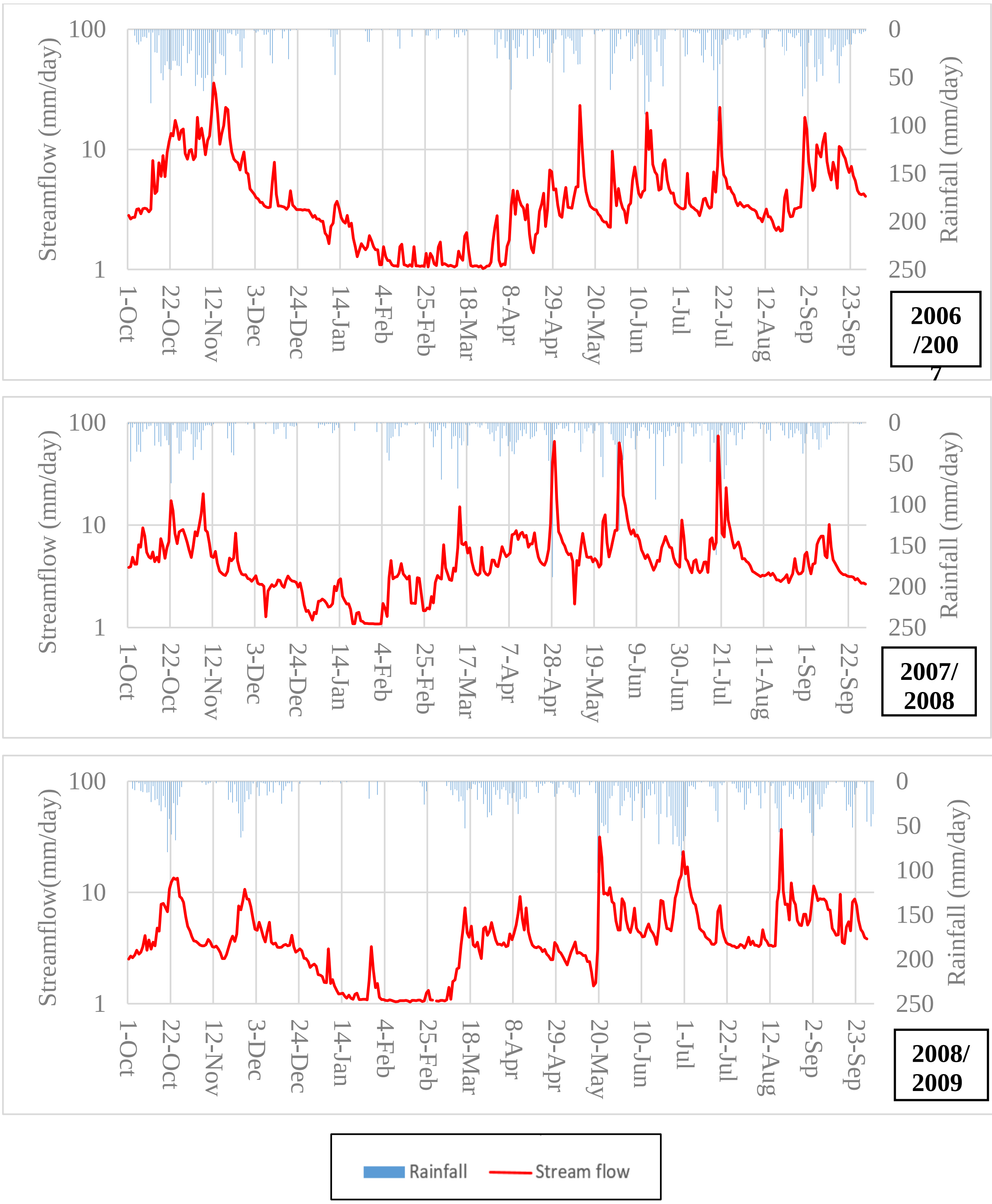


Figure 3-7 Streamflow with Thiessen average rainfall (Calibration period)

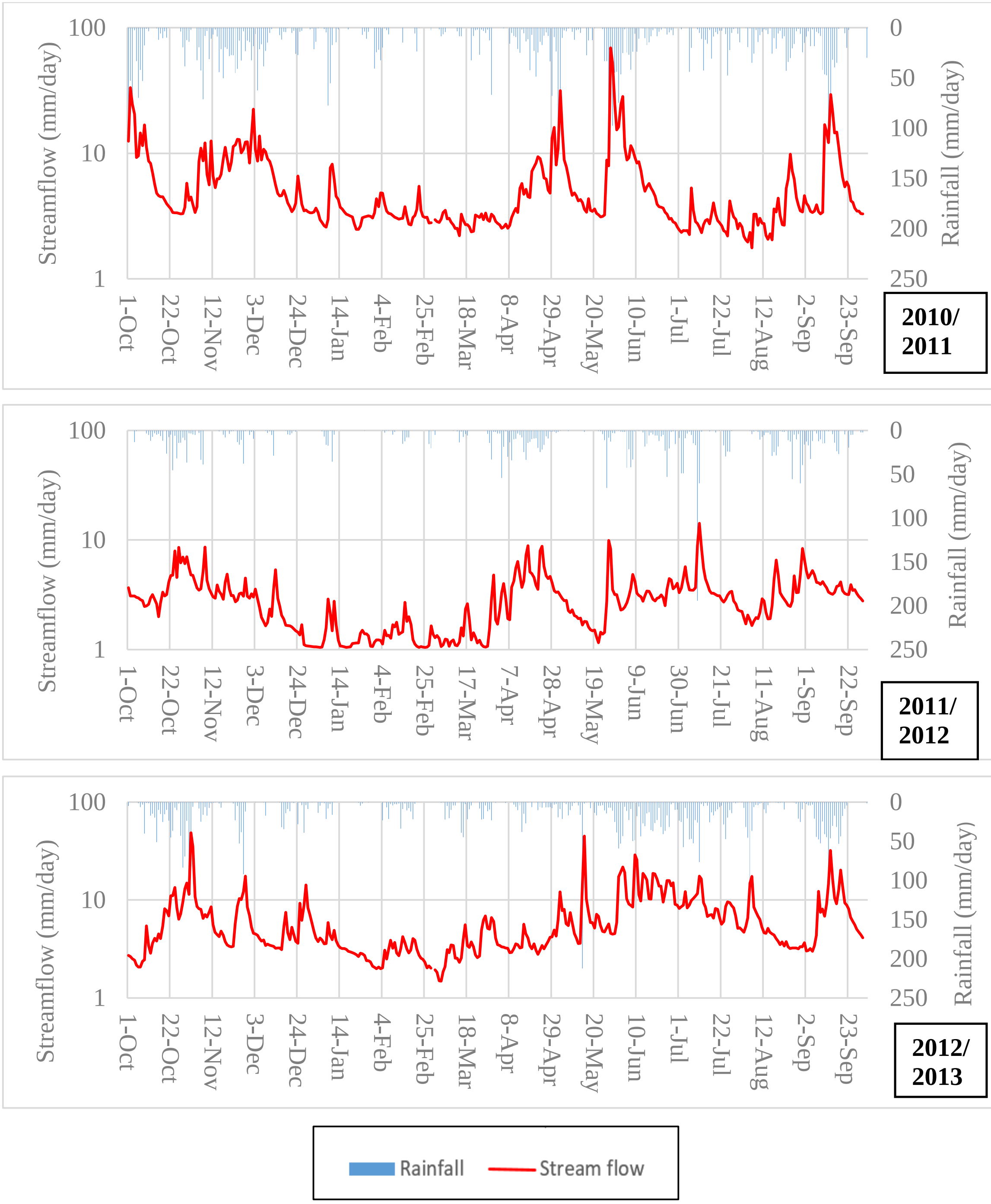


Figure 3-8 Streamflow with Thiessen average rainfall (Validation period)

3.5.4 Single Mass Curve

Single mass curve was plotted for each rainfall station in order to analyze the trend of different rainfall stations over time. Hydrological data obtained from meteorological data had some missing values. Missing rainfall values have to be estimated in order to have a complete data set especially for modelling which is objective of this study. Gaps in meteorological data can be due to many reasons such as absence of observers, loss of records, etc. In the presence of number of available methods for estimating missing rainfall data, the closest station patching method was used for estimating missing rainfall data for this study (Tang, Kassim and Abubakar, 1996). Missing values were filled by substituting data from other stations which showed same trend as that of the station that had missing values. This substituted values were then multiplied by a factor which was obtained by taking the ratio of slope of station from which data was substituted to the slope of stations in which data was filled. Single mass curve for different rainfall stations used in this study are shown in Figure 3-9.

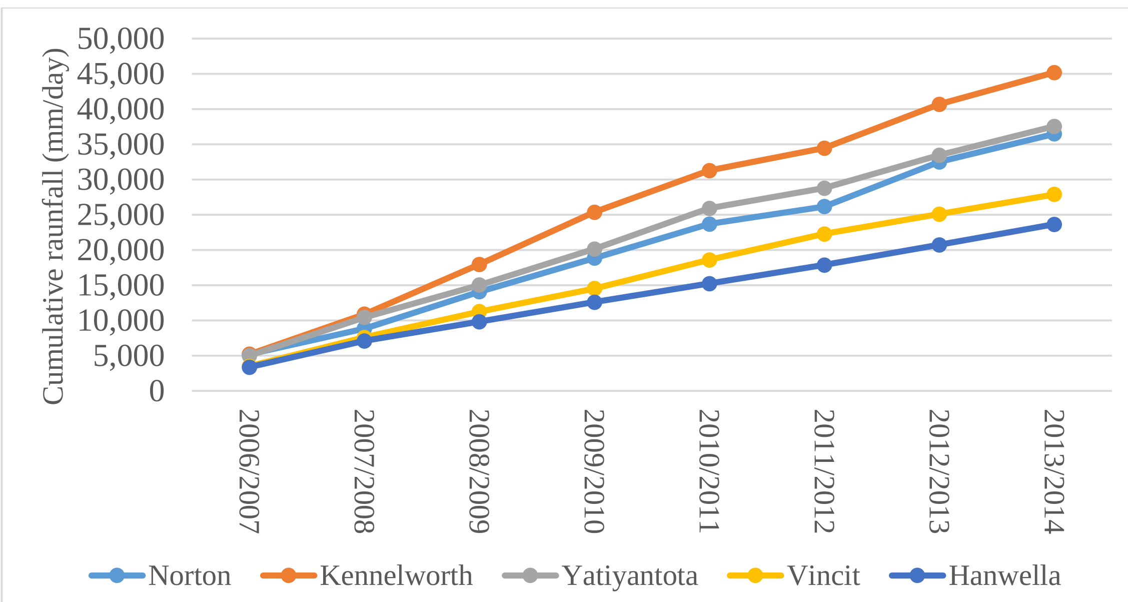


Figure 3-9 Single mass curve

3.5.5 Double Mass Curve

Double mass curve is used for investigating the behavior of records made of hydrological or meteorological data at a number of locations by comparing the data for a single station with that of pattern composed of the data from several other stations in the area. Straight line graph between the cumulative data of one variable versus cumulative data of related variable indicates a fixed ratio relation between the variables. Breaks in the graph can occur due to many reasons such as change in measuring instrumentation, change in observation procedure, etc. In order to check the consistency of hydrological data used for this study, double mass curve for each rainfall station was plotted. Graph obtained was a straight line indicating a fixed ratio relation, hence there is no significant variation is assumed in rainfall data. Double mass curve of Norton station is given in Figure 3-10 while plots for other rainfall stations are given in Appendix B.

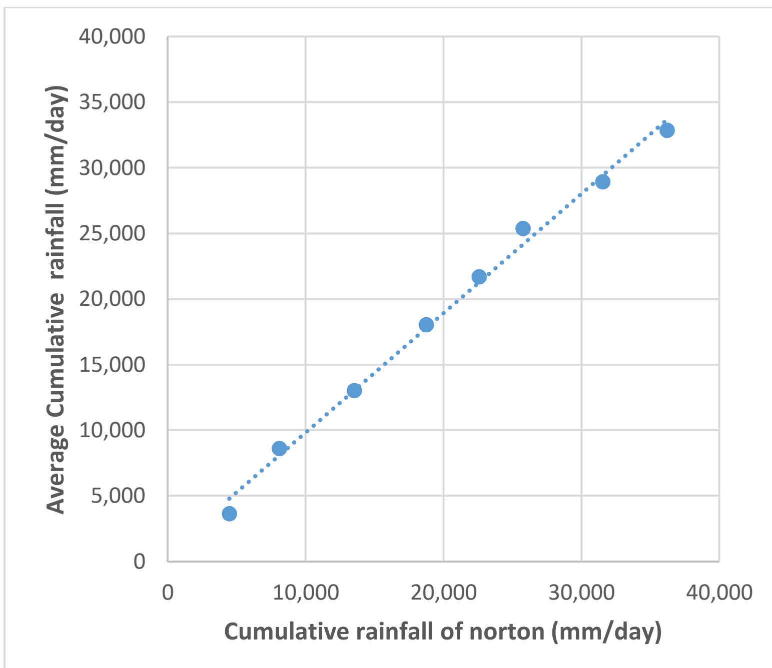


Figure 3-10: Double Mass Curve-Norton Bridge

3.6 Selection of Model

Due to its availability in public domain, peer reviewed and free availability from HEC's website, after reviewing different hydrological models, HEC-HMS model was selected for this study.

3.7 Option Analysis for Different Loss and Baseflow Methods

Proper estimation of runoff is essential for optimum management of water resource in a basin. Selection of appropriate method for simulating precipitation loss and baseflow plays an important role in accurate runoff estimation. Among nine different loss methods available in HEC-HMS for simulating precipitation loss, only Deficit and constant rate method and Soil Moisture Accounting method can be used for continuous hydrological modelling. All other methods are designed for event based simulation. Each method has its own pro and cons. Selection of appropriate method depends upon many factors such as behavior of outflow hydrograph, physical characteristics of project area, etc. Same is the case with baseflow methods. Some available methods for simulating baseflow in HEC-HMS can be used only in conjunction with some other loss model such as linear reservoir model can be used only for simulating baseflow when Soil Moisture Accounting is used as a loss model. Each method has its own advantages and disadvantages like recession method does not preserve mass balance while linear reservoir model preserve model balance. These two are most commonly used method for baseflow simulation in HEC-HMS. Thus according to literature survey (Chapter 2) and data availability, the two Options were selected for analyzing model performance under two different loss and baseflow methods. Clark method as transformation model was kept same for both of these Options. Deficit and Constant method as loss method and recession as baseflow method was selected for simulating streamflow for the First Option while Soil Moisture Accounting and linear reservoir model were selected as loss and baseflow method for the Second Option.

3.8 HEC-HMS Model Development

3.8.1 Selection of Objective Function

Literature review was carried out to get an idea about different objective functions used by different researchers in the past. The selection of objective function is dependent on the objective of modeling exercise, therefore, a qualitative analysis was carried out among different objective functions to identify which objective function would serve objectives of this study. Mean Ratio of Absolute Error (MRAE) and Nash Sutcliff objective function (NASH) were selected for evaluating the model performance after reviewing advantages and disadvantages of different objective functions.

Nash Sutcliff captures peak more efficiently while sensitivity of MRAE is not so efficient in peak matching. In flow duration curve, when flow was classified as high, medium and low based on their probability of occurrence, Nash Sutcliff showed more sensitivity in high and medium flow region as compared to low flow region. The MRAE showed more sensitivity in medium and low flow regions while little in high flow region. Therefore, for overall matching of flow duration curve, using MRAE as objective function is recommended while if objective of the study is the prediction of extreme events like flood, only then using Nash Sutcliff as objective function would better serve the purpose.

Since the purpose of this study is overall matching of flow not only high flows, the MRAE was selected as the objective function. As the concerned study is continuous simulation rather than event based, therefore, apart from using MRAE as main objective function, another two statistical goodness of fit measures such as Nash Sutcliff and Percent Error in Volume were also checked as an observation.

3.8.2 Selection of Simulation Time Interval

Simulation time interval according to USACE (2000) should be less than 0.29 times lag time of sub basin. Sub basins selected for this study have lag time less than 24 hours but since temporal resolution of available data is 24 hours, therefore, it was not possible to reduce simulation time interval. Simulation time interval was selected as one day.

3.8.3 Development of Basin Model

Creation of basin model to convert atmospheric conditions into streamflow at specific points in watershed is the first step in development of HEC-HMS model. The purpose of this study is to model the river flow at Glencorse river gauging station where daily streamflow for required period is available. Lumped model was delineated initially and then it was divided into small sub divisions to incorporate the effect of catchment scale.

Triangular Irregular Network (TIN) and Digital Elevation Model (DEM) were developed from contours obtained from survey department before delineation of sub basins and stream network was generated by using a threshold value of 25,000.

3.8.4 Development of Precipitation Loss Model

3.8.4.1 Option-1 (Deficit and constant loss method)

Deficit and constant method was selected for simulation of precipitation loss for Option-1. Four parameters associated with modellling are, initial deficit, maximum storage and constant loss and percentage of drainage basin that is impervious. Impervious area for the Glencorse watershed was estimated from GIS by classifying the land use map of project area into five classes which served as an initial estimated for this parameter. Since different land use can be found in project area weighted Curve Number (CN) was calculated by considering land use, antecedent moisture condition and hydrological soil group. Soil of Glencorse watershed was classified as hydrological group C. The CN value was initially calculated from standard tables by considering antecedent moisture condition 2 and hydrological soil group C. Weighted CN value comes out to be 84 and calculation for curve number is shown in Table 3-6.

Table 3-6 Curve number calculations

Land use type	Area (%)	CN	Weighted CN
Agricultural	66.6	88	59
Forest	14.8	77	11
Residential	16.2	74	12
Rock	1.1	95	1
Water bodies	1.3	98	1
Total	**100**		**84**

Maximum storage was calculated by using SCS equation and it comes 47.3 mm. Initial abstraction was calculated by using the equation given by SCS and it comes out to be 11.2 mm. These values obtained from mathematical expression given by SCS served as an initial estimate of these parameter which were then slightly change based on their sensitivity during calibration procedure to reach to the optimum value. Constant rate was the only parameter which was determined based on the calibration in this process.

3.8.4.2 Option-2 (Soil Moisture Accounting loss method)

Soil Moisture Accounting was used in order to simulate precipitation loss for Option-2. Dynamic movement of water in and above the soil are represented by using five layers in the soil moisture accounting loss method. The layers include canopy interception, surface depression storage, soil, upper groundwater and lower ground water. Initial conditions for these five layers must be specified as the percentage of water in the respective storage layer before the start of simulation. Surface storage represents maximum amount of water that can be stored in the soil layer before surface runoff begins. The maximum infiltration rate is specified as maximum rate of water that can be enter from surface storage into soil. Saturation hydraulic conductivity for different soil types were identified from literature and was considered as initial estimated of maximum infiltration rate. Percentage impervious area represents the area expressed within each watershed where there will be no infiltration losses. Land use map obtained from Survey Department for project area was classified into five classes in Arc GIS for initial estimation of percentage impervious area. Soil storage represents the total storage of water that can be stored in upper layer of soil that can be removed by both evapotranspiration and percolation to lower layers while tension storage represents the water held in the pores of soil which will lose water through evaporation only. Initial estimates of both these parameters were done through previous work done in the project area. Soil type in the project area was recognized through soil map obtained from Survey Department and percolation rate of different soils were identified from literature which served as an initial estimate. The percolated water from soil then enters into the groundwater storage. Initial estimates of groundwater storage and percolation rate were obtained by previous work carried out in the project area. Deep percolation from Groundwater 2 is considered to be lost from system as aquifer is not modelled in Soil Moisture Accounting loss model.

3.8.5 Development of Transform Model

Calculation of surface runoff is performed by transform model contained within the sub basin. HEC-HMS offers seven different transform models. Literature review was carried out to identify the most suitable transform model to meet the objective of study. Clark unit hydrograph was selected as transform model through literature review. Previous similar studies conducted in project area and also in the other parts of world mentioned in literature review section had used this Clark unit hydrograph as transform model. Two parameters required for this model are time of concentration (t_c) and Storage coefficient. Two critical processes of translation of excessive rainfall and attenuation due to storage like reservoirs in the sub basins are directly represented by Clark unit hydrograph method. Project area has small reservoirs within it which stores water and release afterward which justified the use of this method as this method take care of storage effect. Time of concentration was calculated from Kirpich formula which requires calculation of length of the longest water course and slope of watershed. These parameters were calculated for each sub basin. Initial estimates of storage coefficient were obtained from previous studied conducted in the area. Fine tuning for both parameters were done in calibration process to obtain optimum parameter values. Transform model was kept same for both Options.

3.8.6 Development of Baseflow Model

3.8.6.1 Option-1 (Recession baseflow method)

Recession method was selected to simulate baseflow for Option-1. The input parameters for this method are initial flow, recession constant and ratio to peak. Initial flow specifies the discharge prior to simulation interval. Initial estimation of this parameter was done by observing the observed hydrograph. Recession constant represents the baseflow ratio at the present time to one-day earlier flow. It represents baseflow rate decay whereas ratio to peak represents threshold flow below which baseflow occurs in accordance to recession constant. The range given in HEC-HMS for both recessions constant and ratio to peak is between 0 and 1. The value of these parameters were changed in between this limit during manual calibration in order to arrive at optimum values.

3.8.6.2 Option-2 (Linear reservoir baseflow method)

Linear reservoir model was selected as baseflow method for Option-2. The HEC HMS suggests using linear reservoir baseflow model in combination with SMA method as it ensures the preservation of the water balance between the water that infiltrates in the different layers of soil and the one that leaks out of them through the linear reservoir and for evapotranspiration. In this way, both loss rate and baseflow methods are designed for continuous simulation therefor eventually linear reservoir model was selected for this Option. Three parameters required for this model are initial discharge, groundwater coefficient and number of reservoirs. Initial estimates of parameter, initial discharge was obtained by following the observed outflow hydrograph whereas both groundwater coefficient and number of reservoir parameter was estimated through manual calibration.

3.8.7 Development of Routing Model

The HEC-HMS offers six different models for routing flow from one point to another. Qualitative analysis was carried out for each model by considering criteria like number of parameters, slope of channel and channel geometry. Lag model was then eventually selected as routing model based on the evaluation criteria. Only one parameter is required for this model; i.e. lag time. Lag time for different reaches were calculated through mathematical expression which served as an initial estimate of parameters. Manual calibration of parameters was done to reach the optimum value.

3.8.8 Control Specification

Control specification refers to duration during which is required to run the program. For calibration, control specification was set as 01 Oct 2006 to 30 Sep 2009 and for validation as 01 Oct 2010 to 30 Sep 2013.

3.8.9 Model Simulation

Simulation run was created for developed basin model, precipitation model for each option and simulation period for model was set.

3.9 Sensitivity Analysis

Sensitivity analysis is carried out to understand the behavior of each parameter and to identify the most sensitive parameter. Small change in sensitive parameter may result in huge difference between observed and simulated values, therefore, it is necessary to identify the most sensitive parameters before performing manual calibration. First, the model was run with the parameter value estimated initially as mentioned in the chapter above. In order to perform the sensitivity analysis, the value of each parameter was changed from -50% to 50% from initial estimate in the increment of 10% while keeping values of other parameters constant. The difference in objective function value was observed with the change in each parameter value. Greater the change in the value of objective function, greater the sensitivity of parameter under consideration. In this way, the sensitivity of each parameter was identified and ranked from the most sensitive to the least sensitive. Sensitivity analysis was carried out for both Options and results of the sensitivity analysis are given in Chapter 5.

3.10 Model Calibration

Credibility of model depends upon how reliable it can estimate streamflow as compared to observed streamflow. In order to achieve good agreement between model and observed streamflow, model was calibrated for sensitive parameters identified through sensitivity analysis. Mean Ratio of Absolute Error (MRAE) was used as objective function to assess the performance of model. Apart from MRAE, two other statistical goodness of fit measure, NASH and Percent Error in Volume (PEV) were also checked as an observation. Parameter values were converged to optimum value by changing the initial estimates of the parameters until the change in objective function becomes negligible. Automatic calibration process in HEC-HMS was not used in this study as in built parameter optimizer was not leading toward optimum result, therefore, manual calibration approach was adopted. Values of objective function for both Options, for different classification of flows and comparison are given in Chapter 5.

3.11 Model Validation

After the calibration of the model, the model must be validated for another dataset to estimate the model accuracy. Observed daily streamflow data and rainfall data from 2010/2011 to 2013/2014 was used for verification purpose. Same optimum values of parameter obtained during calibration procedure were used for verification period. Performance of the model was assessed with the same statistical measures which were used in the calibration. The objective function values with NASH and percent error in volume value for both Options during validation period is given in Chapter 5.

3.12 Selection of Best Option

Calibration and validation of model for both Options were carried out and then objective function values for overall flow as well as for different classes of flow classified on the basis of their probability on occurrence were analyzed. Objective function value was used as criteria for selection of the best Option. The Option with the least value of MRAE for overall matching of flow was selected as the best Option. Objective function value for each Option and their comparison are given in Chapter 5.

3.13 Catchment Scale Effect

Glencorse lumped model developed for this study was divided into different combinations of smaller number of sub divisions in order to investigate model performance with respect to catchment scale. Lumped model was divided into 3, 6, 9 and 16 sub divisions, respectively, through Arc Hydro tool box in ARC GIS (ESRI, USA). Sub divisions were attained on the basis of drainage area. Loss and baseflow method in order to simulate streamflow for distributed model was selected from the best Option selected as described above. Soil Moisture Accounting and linear reservoir baseflow method was selected for simulating precipitation loss and baseflow while transformation model was selected as Clark unit hydrograph. Lag method was selected as routing model based on the evaluation criteria. Initial estimate of parameter for each sub divisions were given as optimized parameter values obtained from lumped model and then these parameters were slightly changed during calibration process in order to improve model performance. As one move toward higher number of sub divisions the number of parameters also increased to a very large number thus manual calibration approach no longer remain feasible. Therefore, for this study, the selected parameter values were changed for distributed model in order to have a good matching of observed and simulated hydrographs. After model parameter optimization, the model was run for validation period by using the same parameters and model performance for each sub division was evaluated. Optimum number of sub divisions was selected on the basis of objective function value. Performance of lumped model and distributed model with optimum number of sub divisions were compared with each other in order to investigate model performance by shifting toward distributed modelling. Objective function value for each sub divisions is given in Chapter 5 together with comparison of lumped and distributed model performance.

4 ANALYSIS AND RESULTS

4.1 General

In this chapter, the analysis carried out to achieve overall objective of the study and results of different steps achieved by following methodology as described in Chapter 3 are listed. Matching of observed and simulated hydrographs, objective function values and flow duration curves for different loss and baseflow methods as well as for lumped and distributed model are presented. Analysis carried out in order to recommend efficient use of software for water resource management is also given in this chapter.

4.2 Sensitivity Analysis

Sensitivity analysis was carried out for Option-1 in order to determine model performance with respect to different parameters and to identify the most sensitive parameters. Each parameter value was changed from -50% to +50% from its initial value in the increment of +10% while keeping the other parameter values constant.

4.2.1 Option-1 (Deficit and constant loss and recession baseflow method)

Sensitivity analysis was carried out for entire set of parameters. Results of sensitivity analysis for Option-1 are shown in Figures 4-1 and 4-2. Sensitivity of parameters for both objective function MRAE as well as other statistical goodness of measure NASH was checked. Parameters sensitivity to main objective function MRAE is shown in Figure 4-1 while sensitivity with respect to NASH is shown in Figure 4-2. Sensitivity of parameters to MRAE was selected as criteria for ranking of parameter sensitivity. Impervious area and recession constant were found out to be the most sensitive parameters for Option-1 as percent change in objective function value was observed to be significantly varying from initial value in response to ± 50% increment in parameter value. The time of concentration, initial deficit and maximum deficit were classified as the least sensitive parameters because change in objective function value with respect to change in objective function value was negligible.

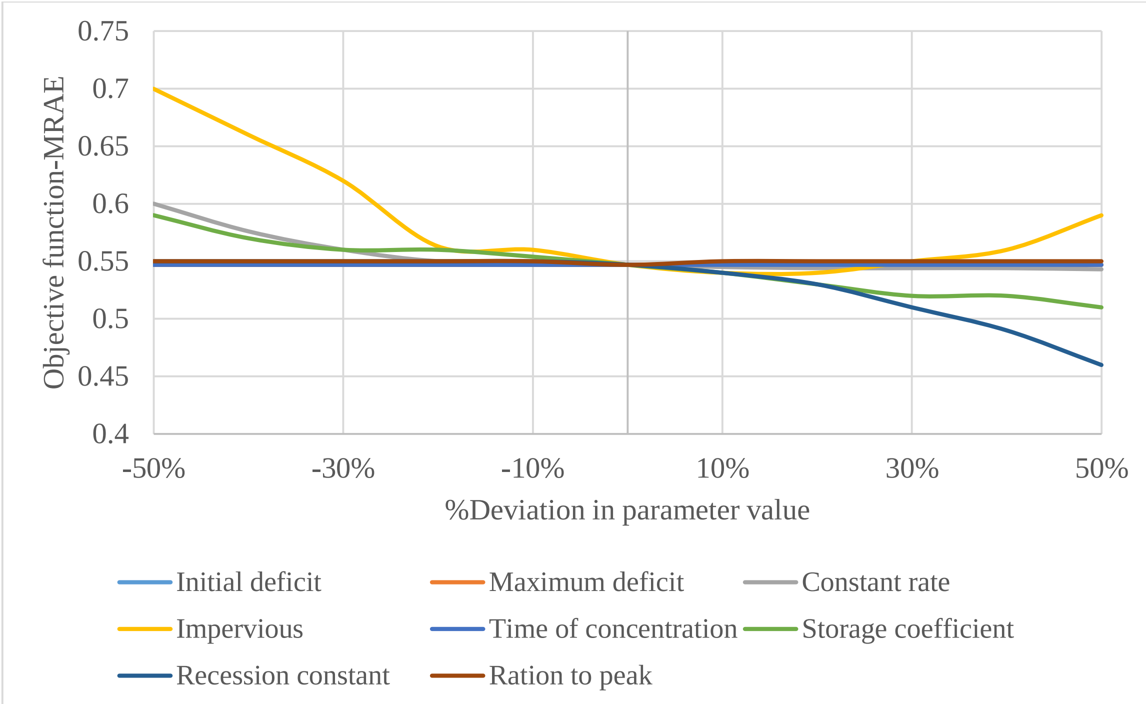


Figure 4-1 Parameter sensitivity to MRAE-Objective function (Option-1)

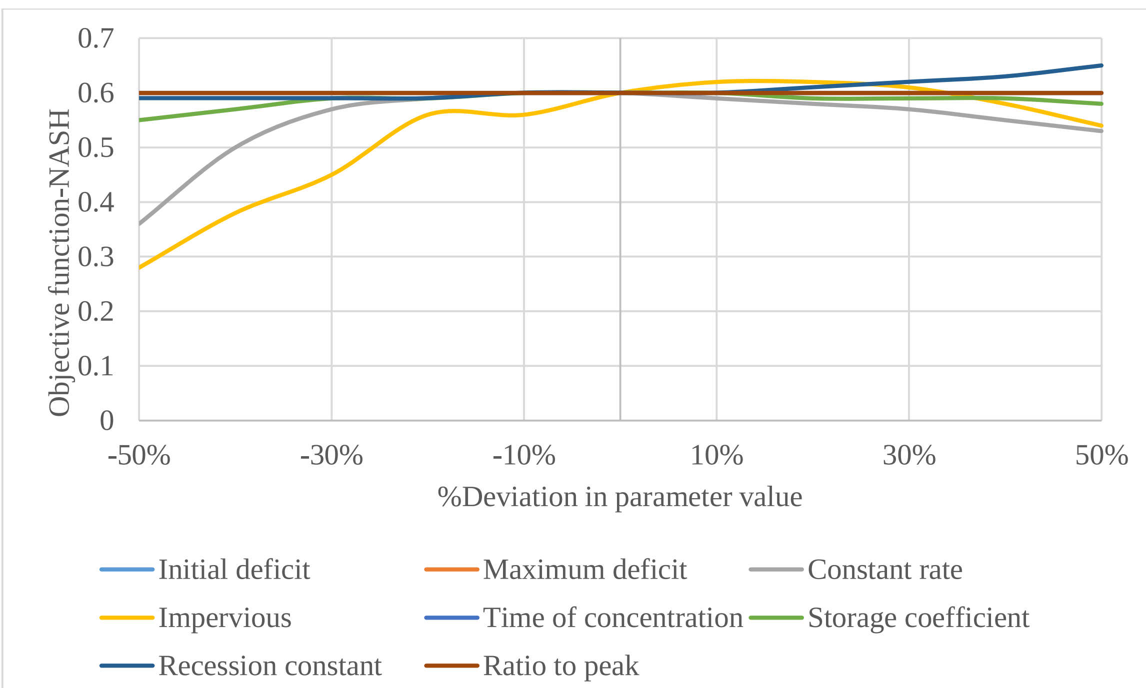


Figure 4-2 Parameter sensitivity to NASH (Option-1)

4.2.2 Option-2 (SMA loss and linear reservoir baseflow method)

Sensitivity analysis was carried out for the entire set of parameters and results of the sensitivity analysis for Option-2 are shown in Figures 4-3 and 4-4. Sensitivity of parameters for both objective function MRAE as well as other statistical goodness of measure NASH was checked. Parameters sensitivity to main objective function MRAE is shown in Figure 4-3 while sensitivity with respect to NASH is shown in Figure 4-4. Sensitivity of parameters to MRAE was selected as criteria for ranking of parameter sensitivity. Groundwater1 coefficient and groundwater1 percolation were found out to be the most sensitive parameters for Option-2 as percent change in objective function value was observed to be significantly varying from initial value in response to ± 50% increment in parameter value. The time of concentration, tension storage and soil percolation were classified as the least sensitive parameters because the change in objective function value with respect to change in objective function value was negligible.

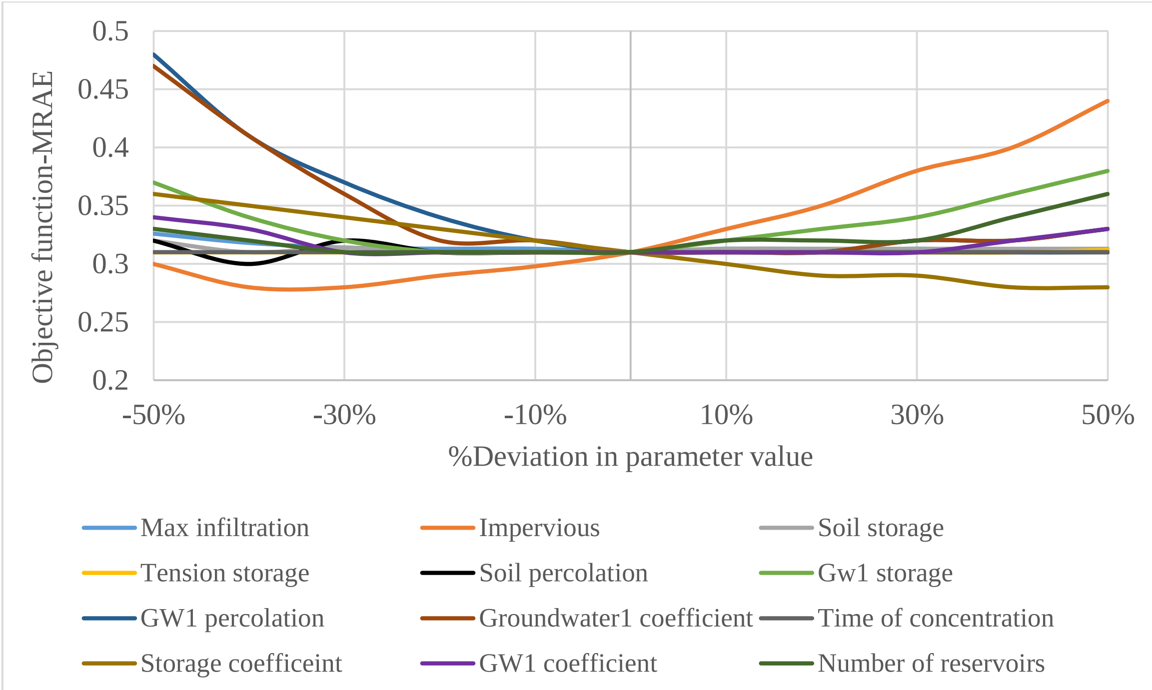


Figure 4-3 Parameter sensitivity to MRAE-Objective function (Option-2)

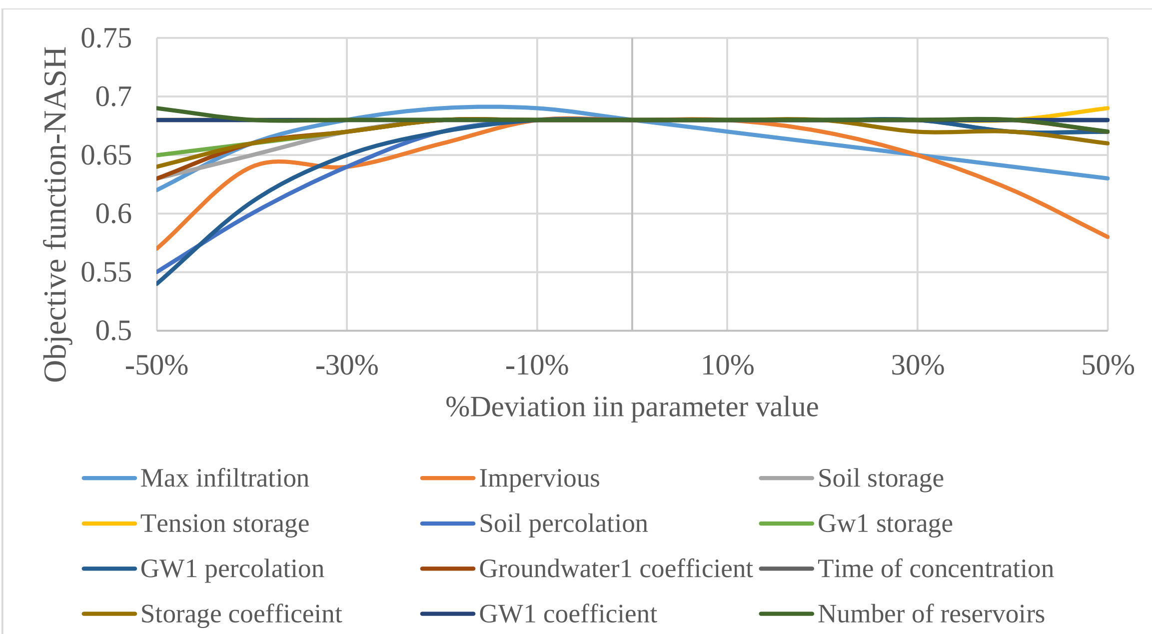


Figure 4-4 Parameter sensitivity to NASH (Option-2)

4.3 Lumped Model Calibration Result

4.3.1 Option-1 (Deficit and constant loss and recession baseflow method)

4.3.1.1 Statistical Goodness of Fit Measure

Calibration of Glencorse lumped model for Option-1 was performed by matching simulated flow with observed discharge at Glencorse gauging station. Table 4-1 shows the Mean Ratio of Absolute Error, Nash Sutcliff and Percent Error in Volume for hydrograph matching of Glencorse lumped model for Option-1. The error values are also stated in the same table. Model showed satisfactory performance in hydrograph matching. The MRAE is 0.38 and Nash Sutcliff coefficient is 0.67 for overall matching of flow duration curve. For high flow region of flow duration curve, the MRAE is 0.30 and Nash Sutcliff value is 0.53 while for the medium region of flow duration curve having probability of exceedance in between 15% to 75%, the MRAE is 0.31. In low flow region of flow duration curve, the MRAE is 0.36. Model showed good performance in high and medium flow regions whereas model performance is poor in low flow region.

Table 4-1 Calibration results for Option-1

Glencorse-Gauging station	**Nash-Sutcliff**	**MRAE**	**Mass Balance Error %**	**Flow Duration Curve**					
				High		**Medium**		**Low**	
				Nash-Sutcliff	**MRAE**	**Nash-Sutcliff**	**MRAE**	**Nash-Sutcliff**	**MRAE**
Calibration	0.67	0.38	4.62	0.53	0.30	-1.55	0.32	-2.93	0.57

4.3.1.2 Model Parameters

Optimized parameters of Glencorse catchment obtained after manual calibration are given in Table 4-2.

Table 4-2 Optimized parameter values for Option-1

Name of parameter	Unit	Value
Initial storage	%	1
Maximum storage	mm	6
Initial Deficit	mm	9.5
Maximum Deficit	mm	48
Constant rate	mm/hr.	3.5
Impervious	%	25
Time of concentration	hr	12
Storage coefficient	hr	31
Initial discharge	m^3/sec	50
Recession constant	-	0.85
Ratio to peak	-	0.4

4.3.1.3 Matching Observed and Simulated Hydrographs

For Option-1, the observed and simulated hydrographs in semi log scale for calibration period is shown in Figure.4-5. Flow duration curve was divide into high, medium and low flow regions based on the probability of exceedance. Flows having exceedance probability less than 15% were classified as high while flows which were with exceedance probability lying from 15% to 75% were classified as medium flow region. Flows having exceedance probability greater than 75% were termed as low flow region. Flow duration curve for each year is shown in Figure 4-6. Performance of model in each of the above three regions is given in Table 4-1.

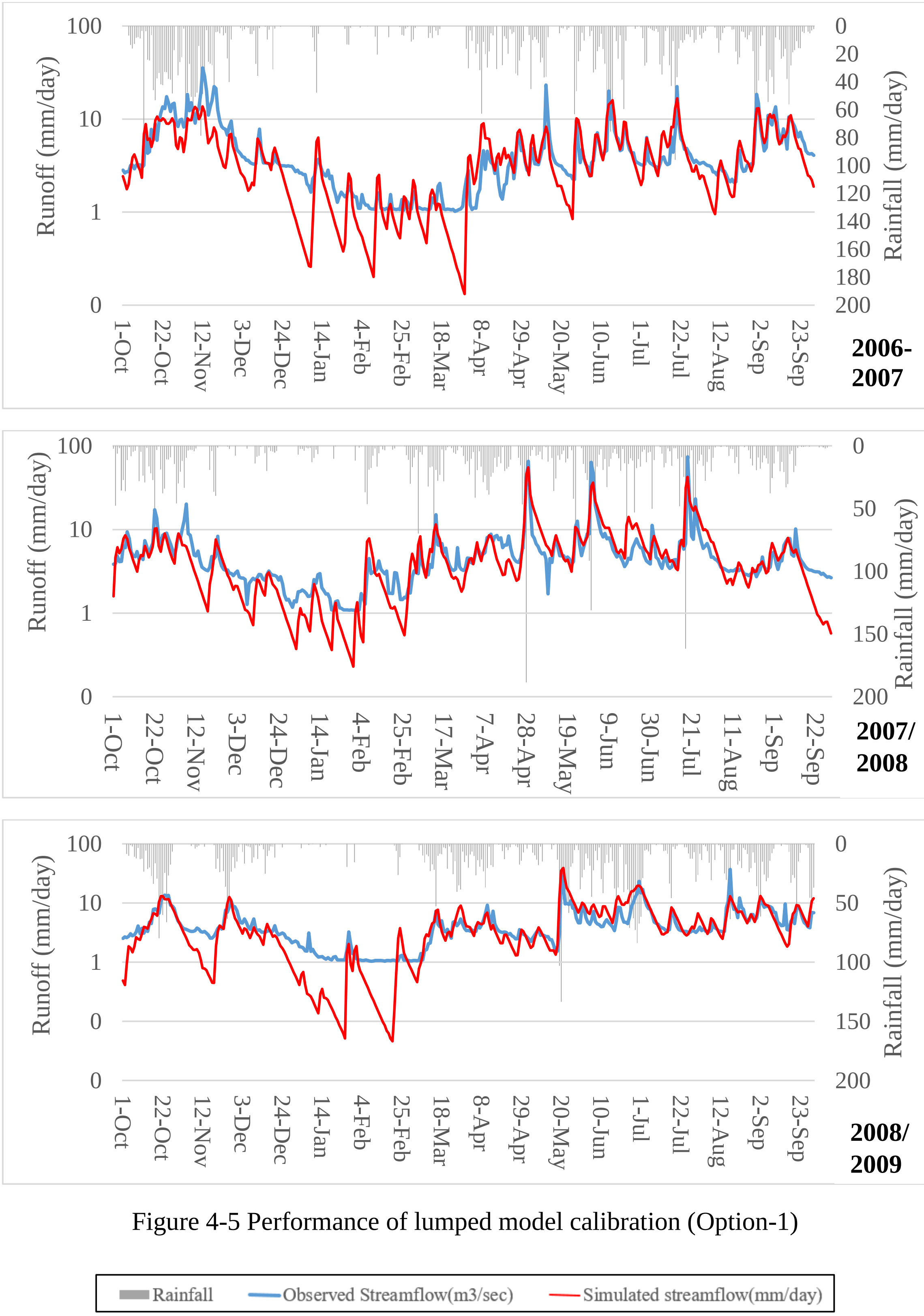


Figure 4-5 Performance of lumped model calibration (Option-1)

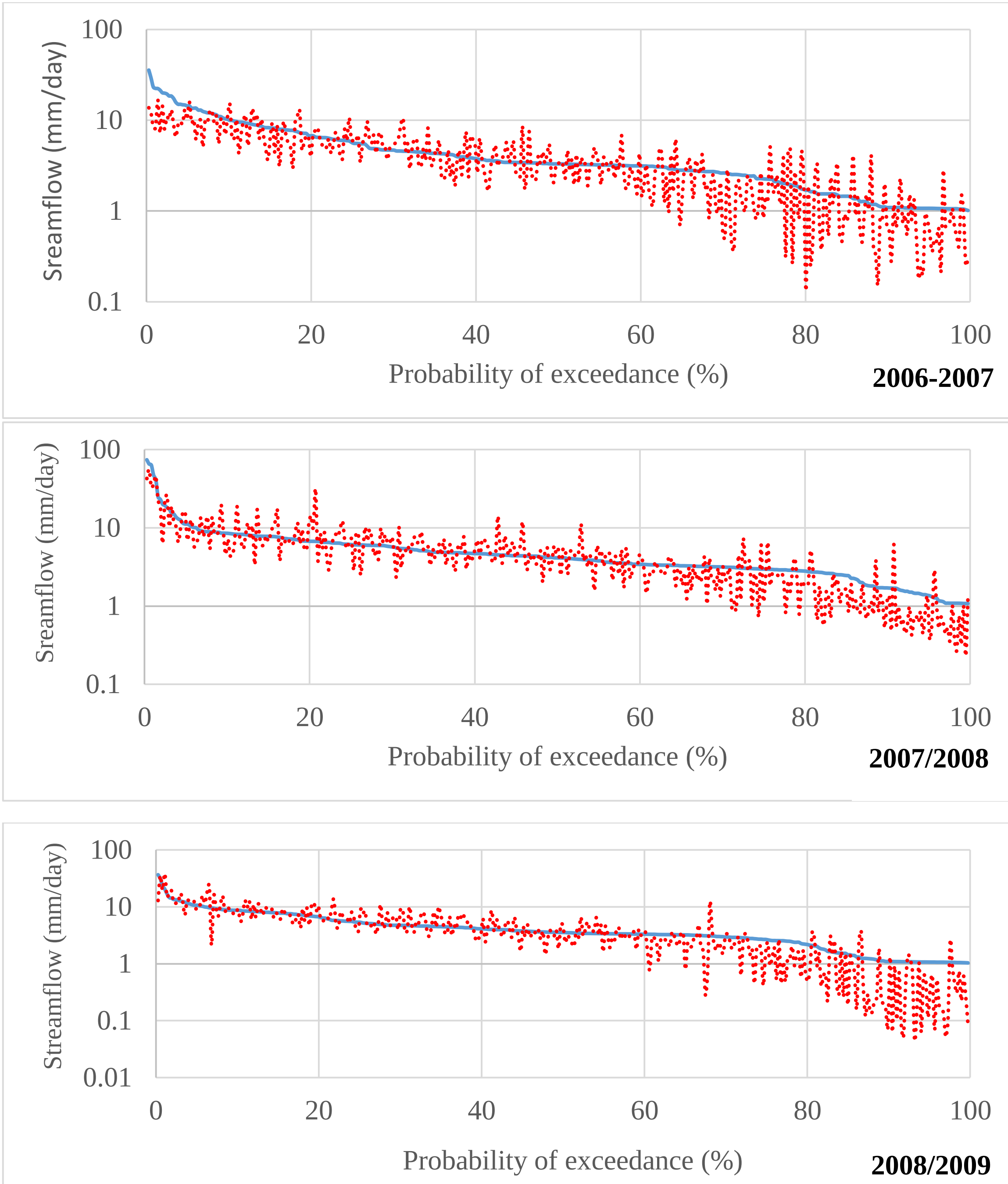
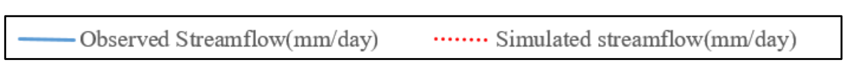


Figure 4-6 Flow duration curve of lumped model calibration(Option-1)



Yearly averaged observed and simulated streamflow and monthly mass balance error at Glencorse during calibration phase for Option-1 is given in Table 4-3 along with observed runoff as well as runoff calculated from simulated streamflow. It can be observed that the highest error in mass balance is in year 2006/2007 while the lowest is in 2007/2008. Percent Error in Volume are in acceptable limit. Simulated runoff coefficient and observed runoff coefficient show close matching. Graphical representation of observed streamflow with simulated streamflow during calibration phase for Option-1 is shown in Figure 4-7.

Table 4-3 Annual percent error in Volume-Calibration period (Option-1)

Year	Rainfall (mm)	Observed Streamflow (mm/day)	Simulated Streamflow (mm/day)	Mass balance error	Observed runoff coefficient	Simulated runoff coefficient
2006/ 2007	4731	1768	1516.	14.2	0.37	0.32
2007/ 2008	4568	2036	1991	2.2	0.45	0.44
2008/ 2009	4801	1675	1717	-2.5	0.35	0.36

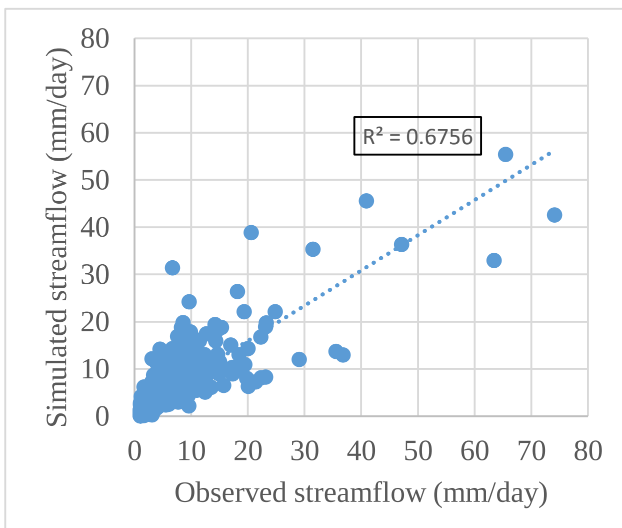


Figure 4-7 Daily observed and simulated streamflow- Calibration period (Option-1)

4.3.2 Option-2 (SMA loss and linear reservoir baseflow method)

4.3.2.1 Statistical Goodness of Fit Measure

Calibration of Glencorse lumped model for Option-2 was attained by matching simulated discharge with observed discharge at Glencorse gauging station. Table 4-4 presents the calibration result for Option-2 which shows the Mean Ratio of Absolute Error, Nash Sutcliff and percent error in volume for hydrograph matching of Glencorse lumped model. The error values are also stated in the same table. Model showed satisfactory performance in hydrograph matching. The MRAE is 0.31 and Nash Sutcliff value is 0.7 for overall matching of flow duration curve. For high flow region of flow duration curve, the MRAE is 0.27 and Nash Sutcliff value is 0.51while for medium region of flow duration curve having probability of exceedance in between 15% to 75%, the MRAE is 0.31. In low flow region of flow duration curve, the MRAE is 0.36. Model performance was significantly improved in low flow region when compared with Option-1 during calibration phase.

Table 4-4 Calibration result for Option-2

Glencorse-Gauging station	**Nash-Sutcliff**	**MRAE**	**Mass Balance Error %**	**Flow Duration Curve**					
				High		**Medium**		**Low**	
				Nash-Sutcliff	**MRAE**	**Nash-Sutcliff**	**MRAE**	**Nash-Sutcliff**	**MRAE**
Calibration	0.70	0.31	2.90	0.51	0.27	-0.84	0.31	-0.71	0.36

4.3.2.2 Model Parameters

Optimized parameters of Glencorse catchment obtained after manual calibration are given in Table 4-5.

Table 4-5 Optimized parameter for Option-2

Name of parameter	Unit	Value
Max infiltration	mm/hr	8
impervious area	%	21
Soil storage		285
Tension storage	mm	30
Soil percolation	mm/hr	4.3
GW1 storage	mm	60
GW1 percolation	mm/hr	2.5
GW1 coefficient	hr	100
Time of concentration	hr	12
Storage coefficient	hr	30
GW1 initial flow	m^3/sec	45
GW1 coefficient	hr	210
GW1 reservoir	Number	5

4.3.2.3 Matching Observed and Simulated Hydrographs

Observed and simulated hydrographs of Option-2 in semi log scale for calibration period is shown in Figure 4-8. Flow duration curve was divide into high, medium and low flow region based on the probability of exceedance. Flows having exceedance probability less than 15% were classified as high while flows which exceedance probability lying from 15% to 75% were classified as medium flow region. Flows having exceedance probability greater than 75% were termed as low flow region. Flow duration curve for each year is shown in Figure 4-9. Performance of model in each of the above three regions is given in Table 4-4.

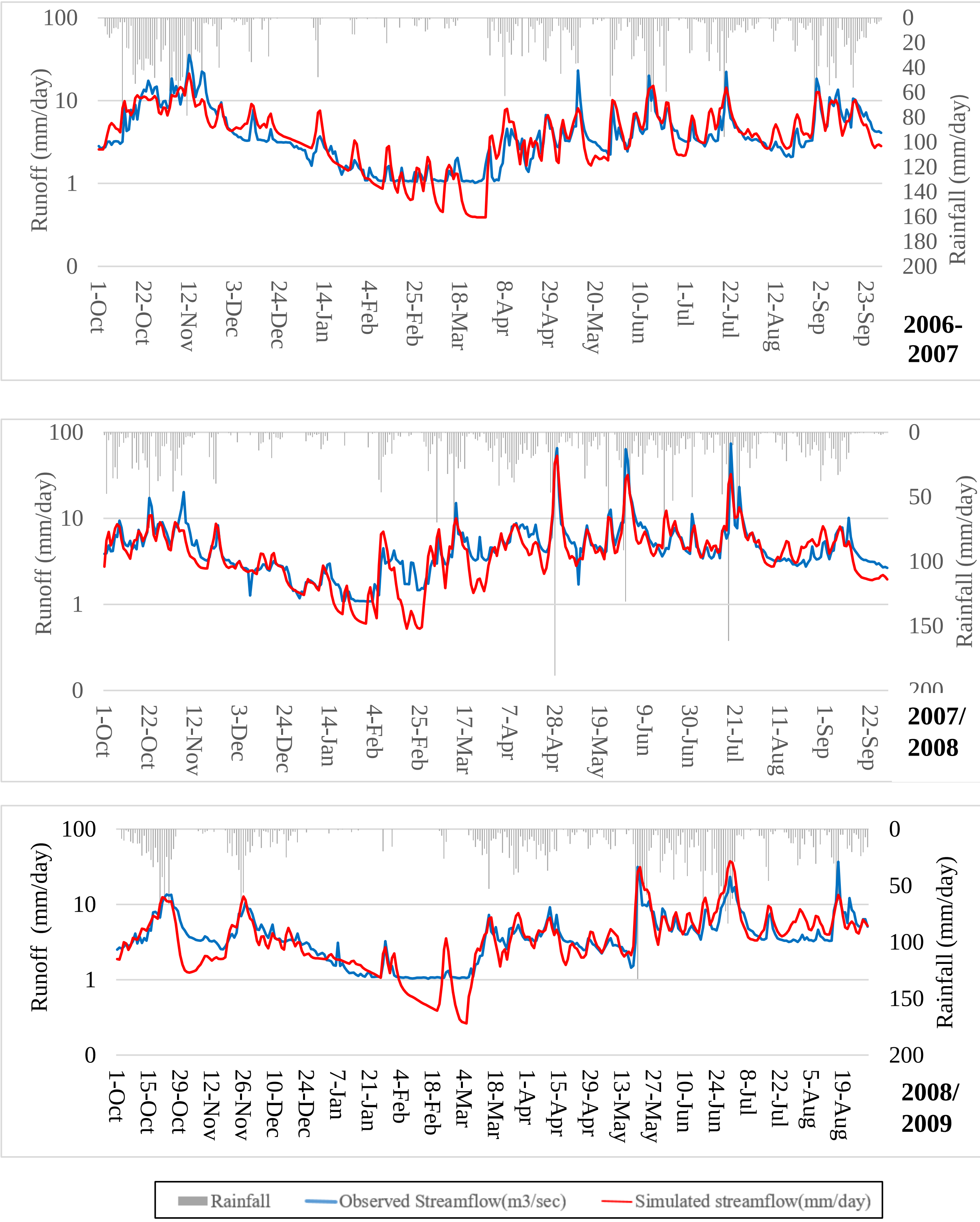


Figure 4-8 Performance of lumped model calibration (Option-2)

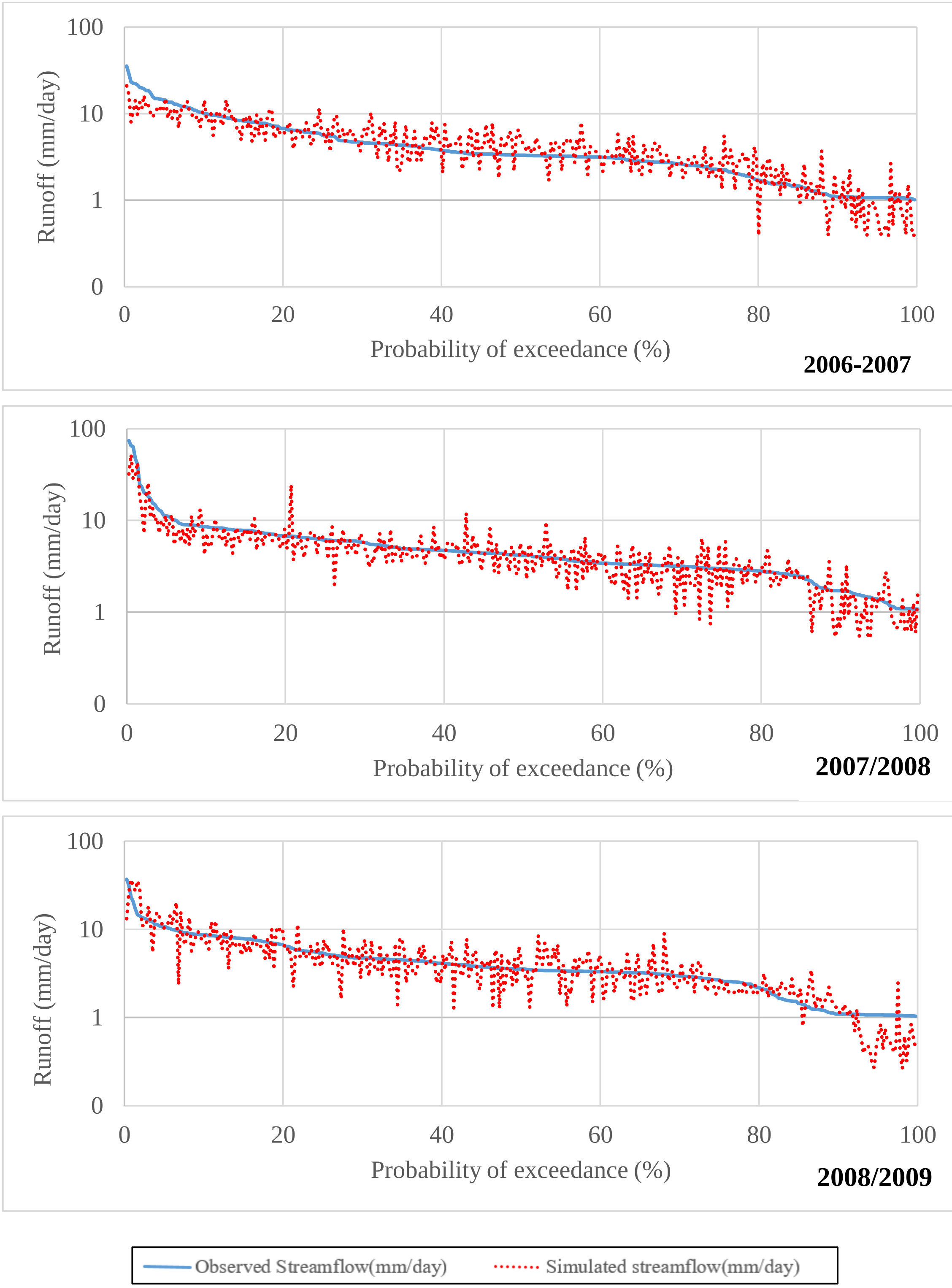


Figure 4-9 Flow duration curve of lumped model calibration (Option-2)

Yearly averaged observed and simulated streamflow and monthly mass balance error at Glencorse during calibration phase for Option-2 is given in Table 4-6 along with observed runoff as well as runoff calculated from simulated streamflow. It can be observed that highest error in mass balance is in year 2007/2008 while lowest is in 2008/2009. Simulated runoff coefficient and observed runoff coefficient also shows close matching. Graphical representation of observed streamflow with simulated streamflow during calibration phase for Option-2 is shown in Figure 4-10. Coefficient of determination value comes out to be 0.68.

Table 4-6 Annual percent error in Volume-Calibration period (Option-2)

Year	Rainfall (mm/day)	Observed Streamflow (mm/day)	Simulated Streamflow (mm/day)	Mass balance error	Observed runoff coefficient	Simulated runoff coefficient
2006/ 2007	4731	1768	1872	-5.9	0.37	0.40
2007/ 2008	4568	2036	1821	10.6	0.45	0.40
2008/ 2009	4801	1675	1751	-4.5	0.35	0.36

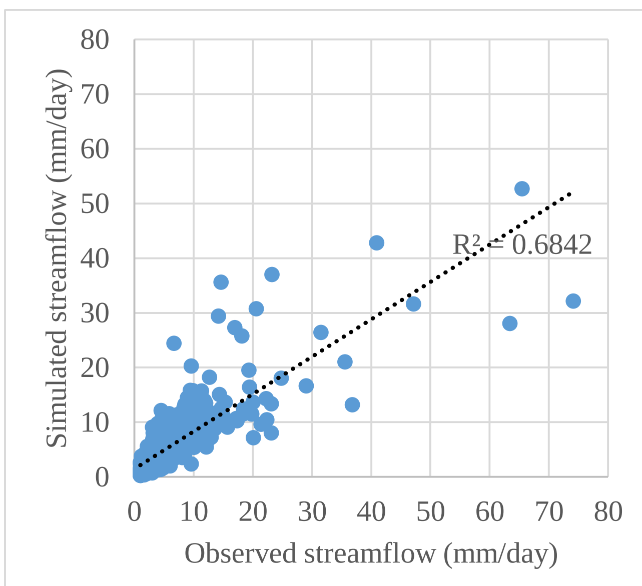


Figure 4-10 Daily observed and simulated streamflow- Calibration period-(Option-2)

4.4 Lumped Model Verification Results

4.4.1 Option-1 (Deficit and constant loss and recession baseflow method)

4.4.1.1 Statistical Goodness of Fit Measures

Performance of model for Option-1 during verification period assessed by statistical measure are shown in Table 4-7. The MRAE is 0.40 and Nash Sutcliff value is 0.42 for overall matching of flow duration curve. For high flow region of flow duration curve, the MRAE is 0.35 while for medium region of flow duration curve, the MRAE is 0.37. In low flow region of flow duration curve, the MRAE is 0.53. Model performance is satisfactory in high and medium flow regions but it showed poor performance in low flow region.

Table 4-7 Verification result for Option-1

Glencorse-Gauging station	**Nash-Sutcliff**	**MRAE**	**Mass Balance Error %**	**Flow Duration Curve**					
				High		**Medium**		**Low**	
				Nash-Sutcliff	**MRAE**	**Nash-Sutcliff**	**MRAE**	**Nash-Sutcliff**	**MRAE**
Verification	0.42	0.40	11.00	0.00	0.35	-2.00	0.37	-3.28	0.53

4.4.1.2 Matching Observed and Simulated Hydrograph

For Option-1, the observed and simulated hydrographs in semi log scale for validation period is shown in Figure 4-11. Flow duration curve was divided into high, medium and low flow regions based on the probability of exceedance. Flows having exceedance probability less than 15% were classified as high while flows with exceedance probability lying from 15% to 75% were classified as medium flow region. Flows having exceedance probability greater than 75% were termed as low flow region. Flow duration curve for each year is shown in Figure 4-12. Performance of model in each of the above three regions is given in Table 4-7.

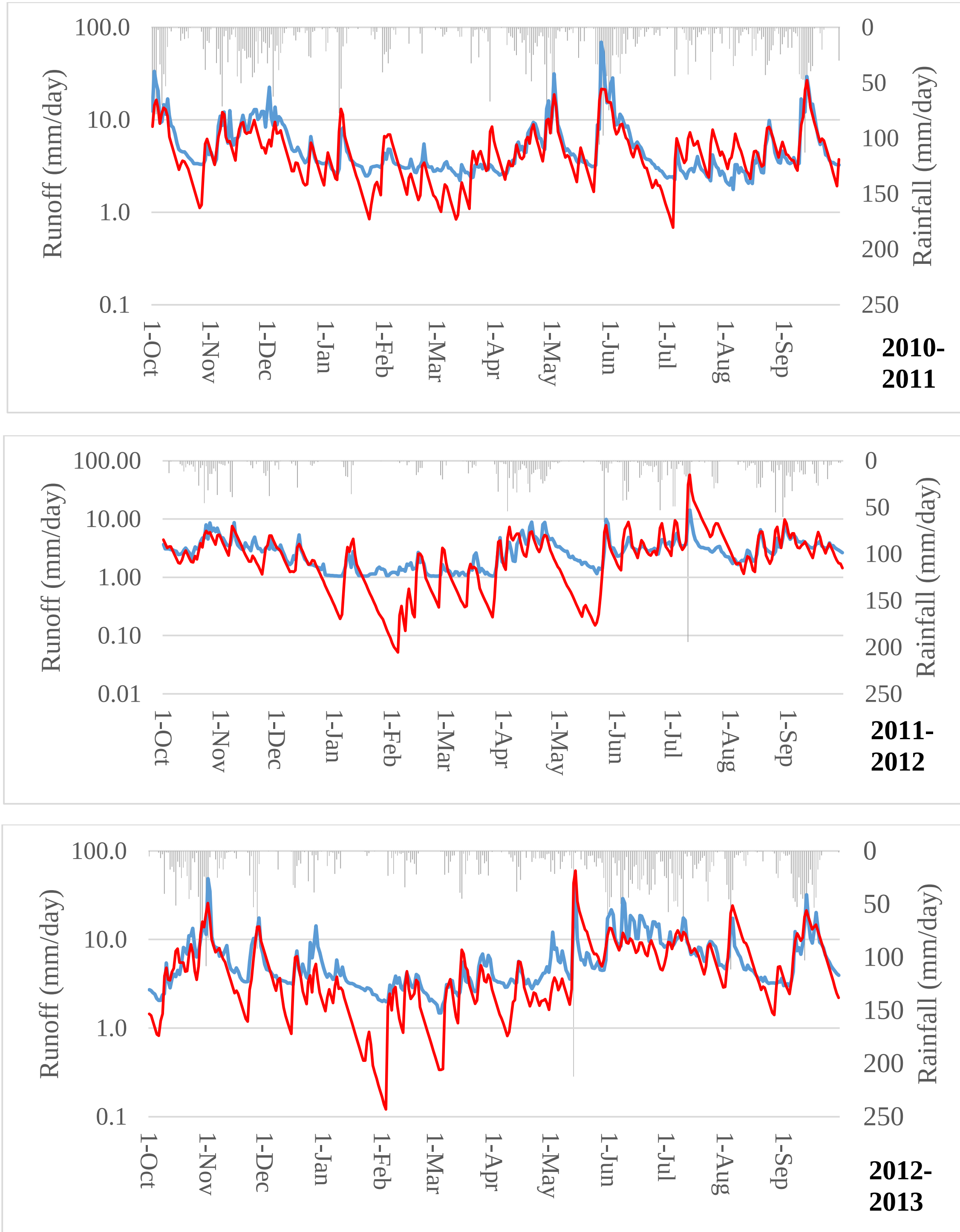
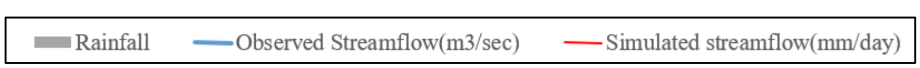


Figure 4-11 Performance of lumped model -Validation period(Option-1)



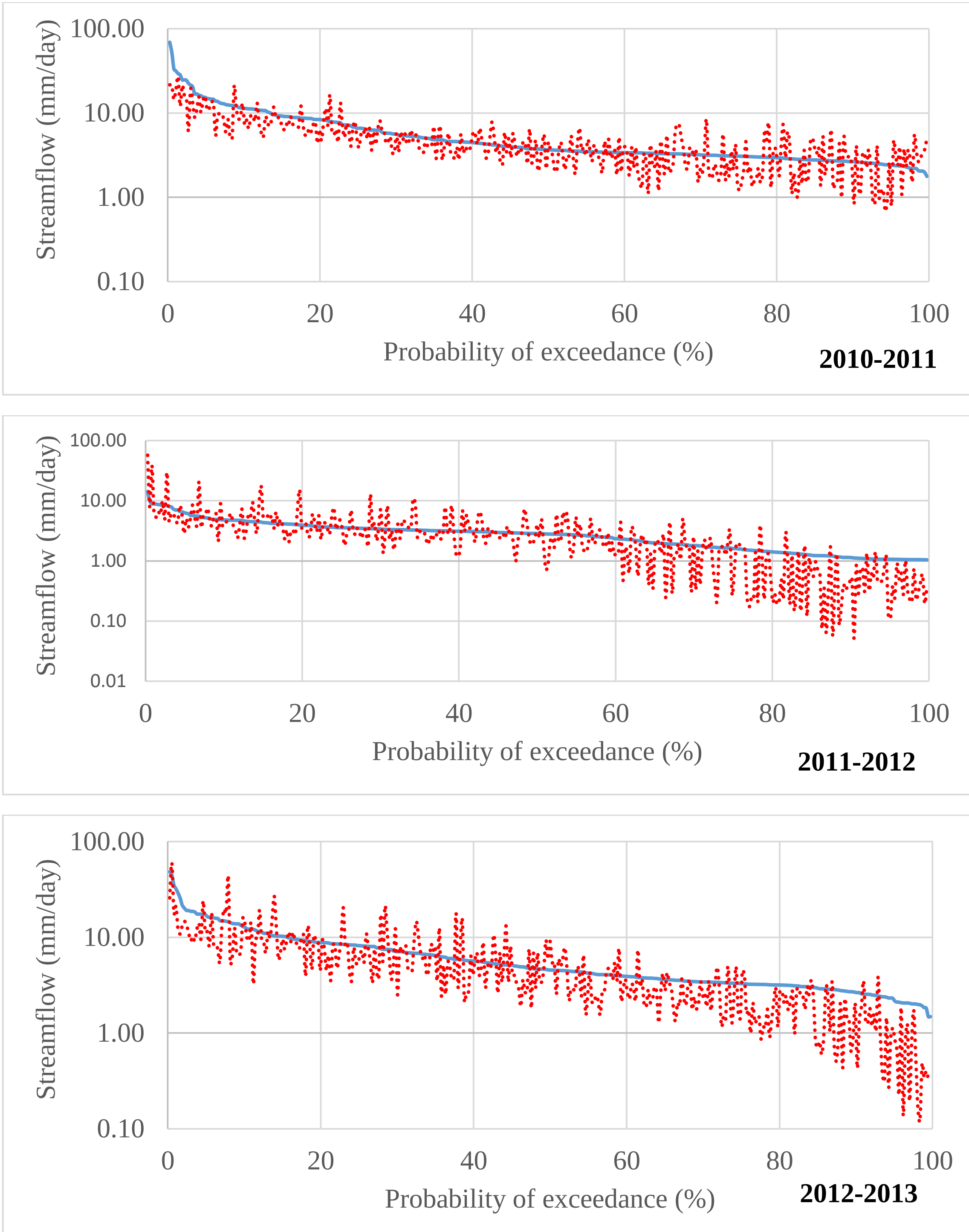


Figure 4-12 Flow duration curve of lumped model -Validation(Option-1)

Observed Streamflow(mm/day) Simulated streamflow(mm/day)

Yearly averaged observed and simulated streamflow and monthly mass balance error during validation phase for Option-1 is given in Table 4-8 along with observed runoff as well as runoff calculated from simulated streamflow. It can be observed that the highest error in mass balance is in year 2010/2011 where mass balance error value is 15.9% while the lowest is in 2011/2012 where model is underestimating flows by 8.2% with respect to observed discharge. Difference of 0.8 can be observed between observed and simulated runoff coefficient during year 2011/2012. Graphical representation of observed streamflow with simulated streamflow during validation phase for Option-2 is shown in Figure 4-13.

Table 4-8 Annual percent error in Volume-Verification period (Option-1)

Year	**Rainfall (mm/day)**	**Observed Streamflow (mm/day)**	**Simulated Streamflow (mm/day)**	**Mass balance error**	**Observed runoff coefficient**	**Simulated runoff coefficient**
2010/ 2011	4979	2190	1842	15.9	0.44	0.37
2011/ 2012	2787	1082	1171	-8.2	0.39	0.42
2012/ 2013	4903	2398	2034	15.2	0.49	0.41

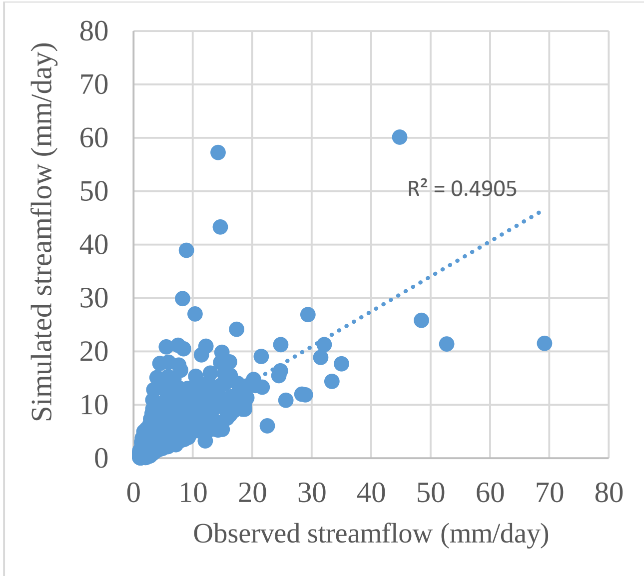


Figure 4-13 Daily observed and simulated streamflow- Validation period-(Option-1)

4.4.2 Option-2 (SMA loss and linear reservoir baseflow method)

4.4.2.1 Statistical Goodness of Fit Measures

Performance of model for Option-2 during verification period assessed by statistical measure are shown in Table 4-9. The MRAE is 0.34 and Nash Sutcliff value is 0.57 for overall matching of flow duration curve. For high flow region of flow duration curve, the MRAE is 0.34 and Nash Sutcliff is 0.00 while for medium region of flow duration curve, the MRAE is 0.30. In low flow region of flow duration curve, the MRAE is 0.41. Model performance in low flow region during validation period is significantly improved when compared with Option-1. Figure 4-14 and Figure 4-15 show satisfactory performance in high and medium flow regions while some non-responsive points where streamflow is not responding well with rainfall can also be observed.

Table 4-9 Verification result for Option-2

Glencorse-Gauging station	**Nash-Sutcliff**	**MRAE**	**Mass Balance Error %**	**Flow Duration Curve**					
				High		**Medium**		**Low**	
				Nash-Sutcliff	**MRAE**	**Nash-Sutcliff**	**MRAE**	**Nash-Sutcliff**	**MRAE**
Verification	0.57	0.34	14.8	0.00	0.34	-0.56	0.30	-2.00	0.41

4.4.2.2 Matching Observed and Simulated Hydrograph

For Option-2, the observed and simulated hydrographs in semi log scale for calibration period is shown in Figure 4-14. Objective function value for each classification of flow estimated on the basis of their probability of occurrence are listed in Table 4-9. Flow duration curve for each year during verification period is shown in Figure 4-15.

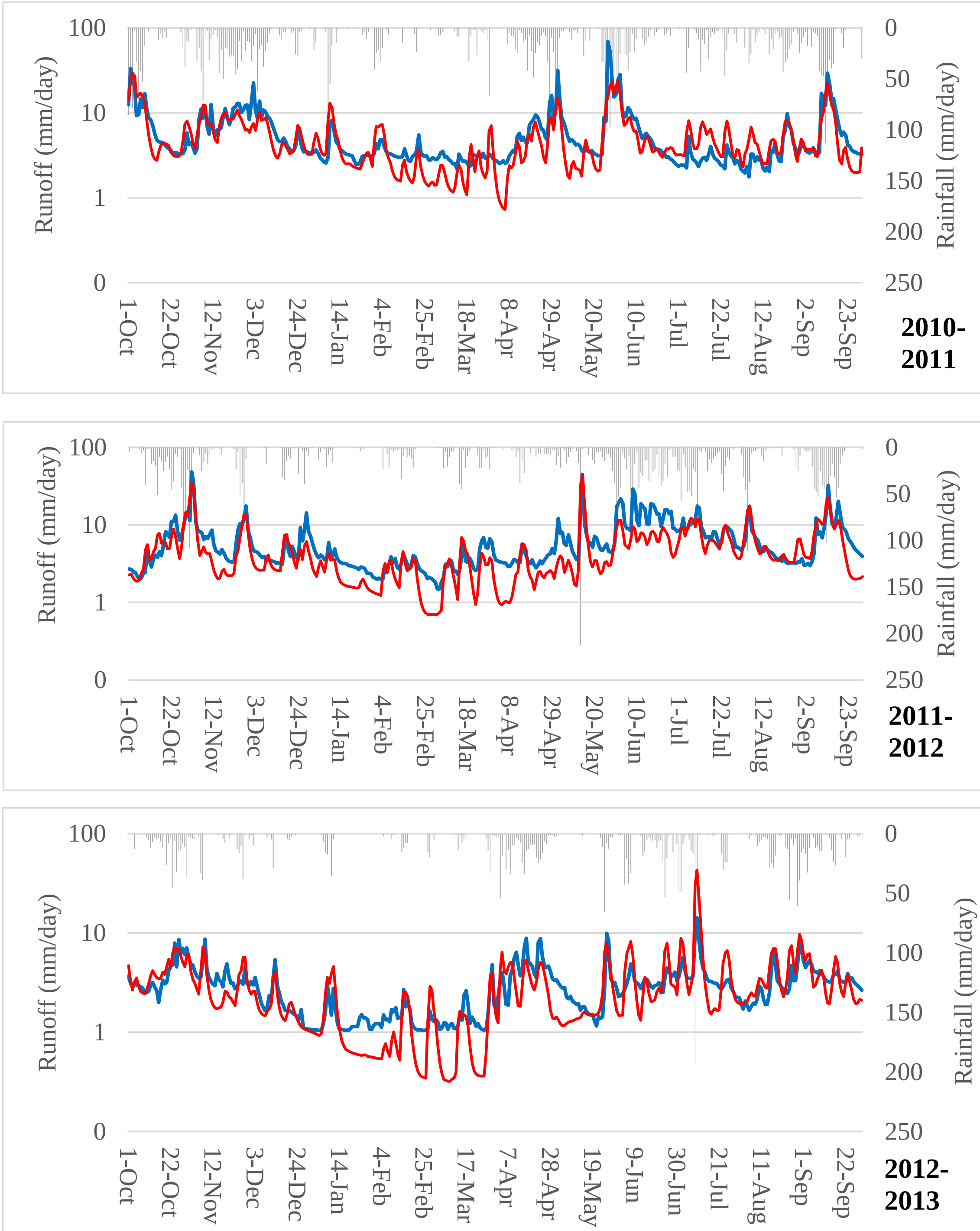
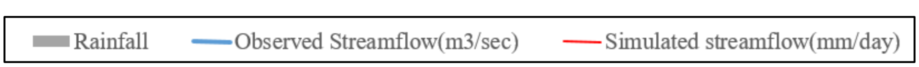


Figure 4-14 Performance of lumped model -Validation period(Option-2)



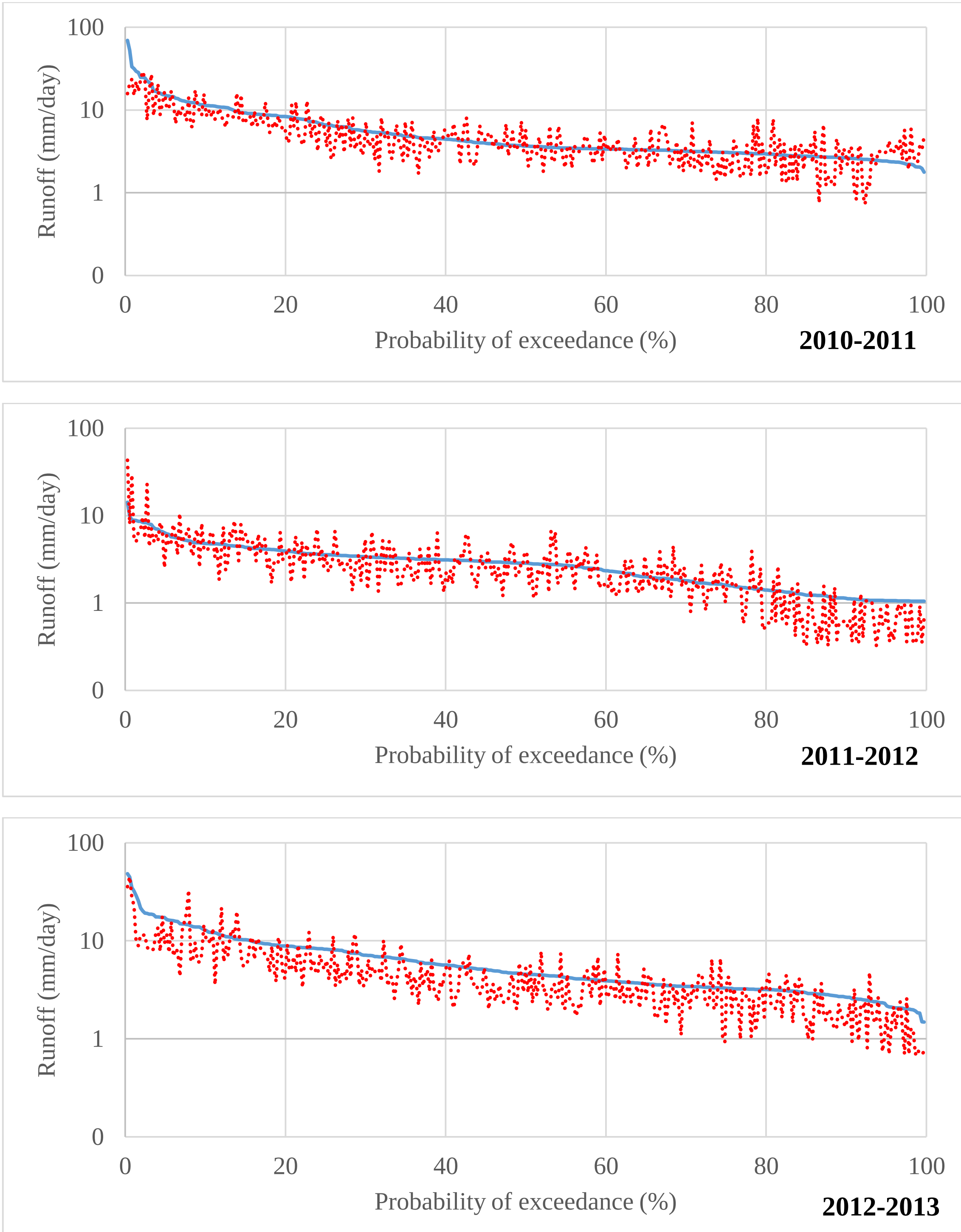
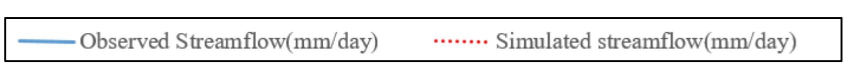


Figure 4-15 Flow duration curve of lumped model -Validation(Option-2)



Yearly averaged observed and simulated streamflow and monthly mass balance error during validation period for Option-1 is given in Table 4-10 along with observed runoff as well as runoff calculated from simulated streamflow. It can be observed that the highest error in mass balance is in year 2012/2013 where model is overestimating annual flows by 23.9% while the lowest is in 2008/2009 year in which model is underestimating flows by 0.7% compared to flow observed at gauging station. Highest difference between simulated runoff coefficient and observed runoff coefficient is in year 2012/2013. Graphical representation of observed streamflow with simulated streamflow during validation phase for Option-2 is shown in Figure 4-16.

Table 4-10 Annual percent error in Volume-Verification period (Option-2)

Year	Rainfall (mm/day)	Observed Streamflow (mm/day)	Simulated Streamflow (mm/day)	Mass balance error	Observed runoff coefficient	Simulated runoff coefficient
2010/ 2011	4979	2190	1915	12.6	0.44	0.38
2011/ 2012	2787	1082	1090	-0.7	0.39	0.39
2012/ 2013	403	2398	1824	23.9	0.49	0.37

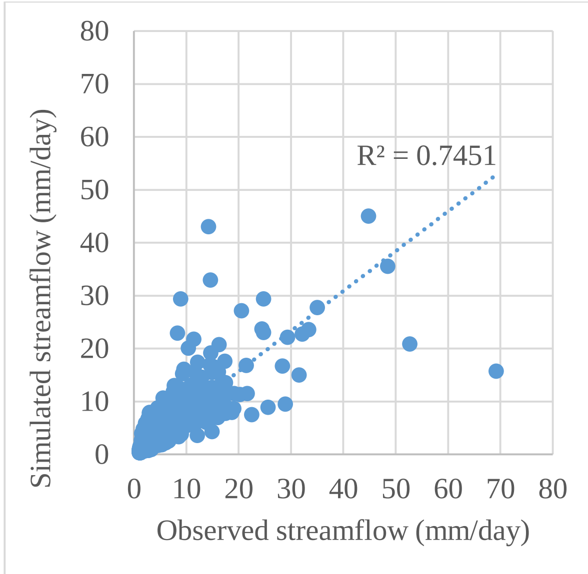


Figure 4-16 Daily observed and simulated streamflow- Validation period-(Option-2)

4.5 Comparison and Selection of Best Option

After calibration and validation of HEC-HMS model for two different loss and baseflow methods termed as Option-1 and Option-2 for this research, comparison of both Options were carried out in terms of objective function; i.e. Mean Ratio of Absolute Error and two other statistical goodness of measures, NASH and Percent Error in Volume. Objective function, MRAE was used as main criterion for selection of the best Option. Option-2 in which Soil Moisture Accounting was used in combination with linear reservoir model for simulating precipitation loss and baseflow was selected as the best Option after evaluating model performance for both Options.

4.5.1 Statistical Goodness of Measures

Value of objective function, Mean Ratio of Absolute Error with two other statistic goodness of measures, NASH and Percent Error in Volume for both Options are given in Table 4-11. Flow was classified into high medium and low based on their probability of occurrence. For each flow classification, values of statistical goodness of measure are also listed in Table 4-11. It can be observed from the Table 4-11 that model performance for Option-2 is improved especially in low flow region of flow duration curve where probability of exceedance is greater than 75%. The value of objective function MRAE which was used as main criterian for classification was improved from 0.38 to 0.31 when Soil Moisture Accounting was used in combination with linear reservoir model for simulating streamflow as compared to Option-1 where deficit and constant loss method and recession method was used for streamflow simulation in calibration period while 0.40 to 0.34 during the validation period of simulation. Major improvement in low flow region can be observed from the values of objective function given in Table 4-11 when shifting toward Option-2. Value of NASH used as another measure for assessing model performance also improved from 0.67 to 0.70 for calibration period and 0.42 to 0.57 for validation period by using Option-1 as compared to Option-2. Percent error in volume was improved from 4.62% to 2.90% during calibration phase while during validation phase, Option-1 performed better for PEV as it increased from 11.0% to 14.8% by shifting toward Option-2 when compared with Option-1. The decrease in PEV during validation phase is mainly due to underestimating of low flows and overestimating of high flows and medium flows which can be observed from flow duration curve shown in Figure 4-15. Therefore, Option-2 was selected as the best Option and was used for performing distributed modelling part.

Table 4-11 Comparison of model performance for Option-1 and Option-2

Glencorse-Gauging station	**Nash-Sutcliff**	**MRAE**	**Mass Balance Error %**	**Flow Duration Curve**					
				High		**Medium**		**Low**	
				Nash-Sutcliff	**MRAE**	**Nash-Sutcliff**	**MRAE**	**Nash-Sutcliff**	**MRAE**
Calibration-Scenraio-1	0.67	0.38	4.62	0.53	0.30	-1.55	0.32	-2.93	0.57
Verification-Option-1	0.42	0.40	11.00	0.00	0.35	-2.00	0.37	-3.28	0.53
Calibration- Scenraio-2	0.70	0.31	2.90	0.51	0.27	-0.84	0.31	-0.71	0.36
Verification-Option-2	0.57	0.34	14.80	0.00	0.34	-0.56	0.30	-2.00	0.41

4.6 Distributed Model

Comparison of Options resulted in selection of Option-2 as the best Option based on the model performance evaluation. In order to investigate the effect of catchment scale on model performance, the initial lumped model was divided into different number of sub divisions. Glencorse catchment was divided into 3, 6, 9 and 16 numbers of subdivisions, respectively. Soil Moisture Accounting and linear reservoir models were used for simulating precipitation loss and baseflow while Clark method was used for transformation. Routing was carried out through lag method. Initial estimate of parameters for each sub division was attained from optimized parameter values of the lumped model. Normal calibration approach was adopted for calibration purpose. Only selected parameters such as initial discharge, GW1 percolation, GW1 storage and Storage coefficient were changed during calibration as calibrating each parameter for each sub division was no longer feasible. Sub divisions were stopped at 16 as model performance showed no improvement thereafter. The six (6) numbers of sub divisions were identified as the optimum one based on the model performance evaluation through objective function value. Model performance was improved by shifting toward distributed modelling up to a certain number of sub divisions after which model performance started declining again. Objective function value for each sub division for calibration and validation period and their comparison with lumped one are given in this part.

4.6.1 Three Sub Divisions

Glencorse lumped model was divided into three number of sub divisions in order to investigate catchment scale effect. Delineation of sub basins was carried out by Arc Hydro tool in Arc GIS by specifying a drainage area.

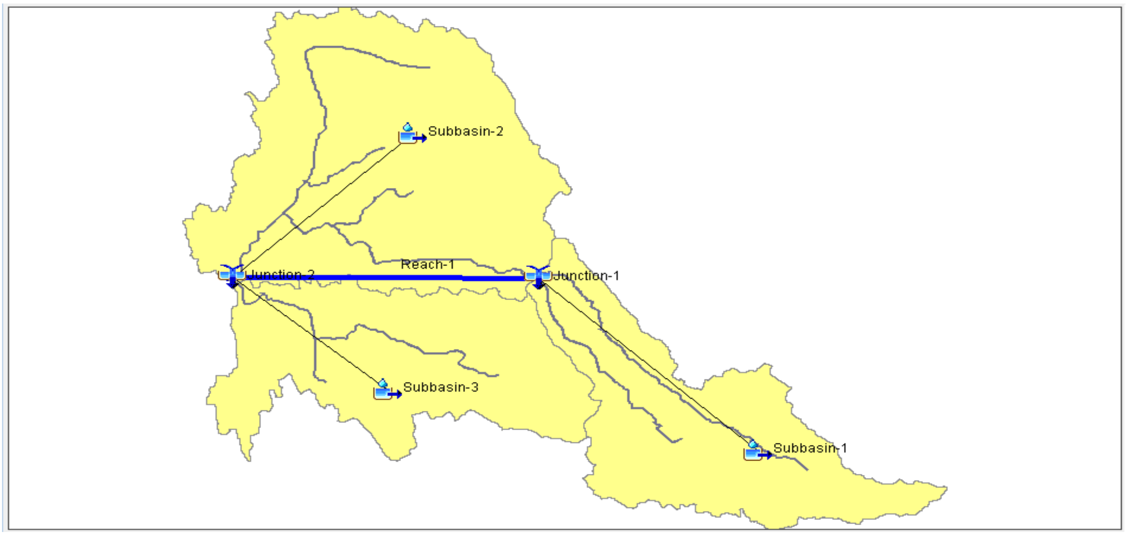


Figure 4-17 HEC-HMS distributed model (3 Sub divisions)

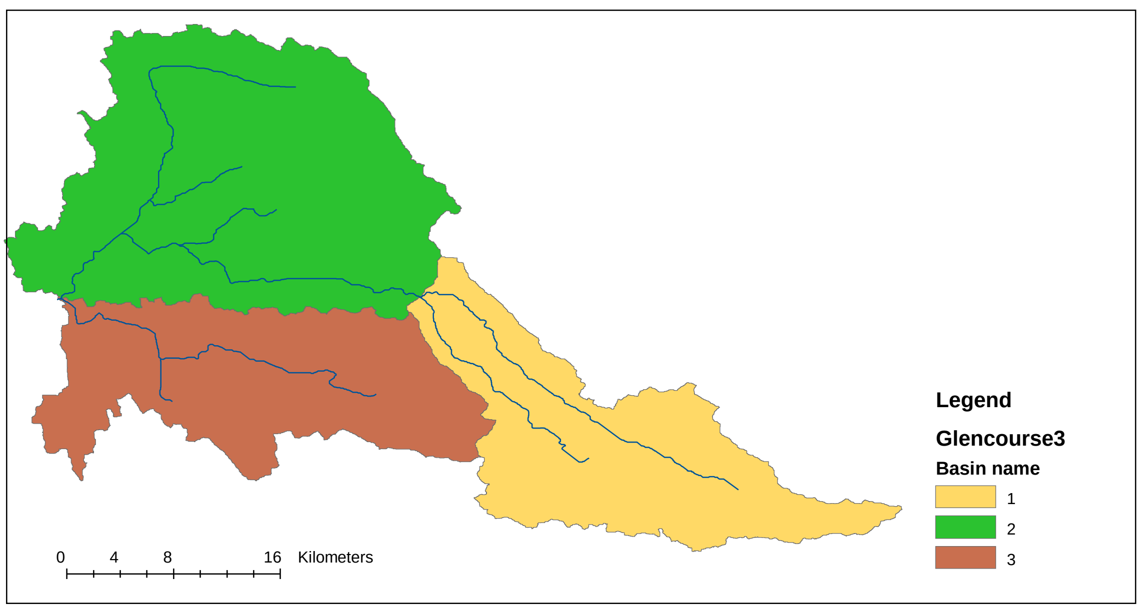


Figure 4-18 GIS distributed model (3 Sub divisions)

4.6.1.1 Calibration Results

Distributed model calibration was carried out by matching simulated streamflow with observed streamflow at Glencorse gauging station through manual approach. Table 4-12 shows the Mean Ratio of Absolute Error, Nash Sutcliff value and percent error in volume for hydrograph matching of distributed model with three number of sub divisions. The error values are also stated in the same table. Model showed satisfactory performance in hydrograph matching. Value of objective function MRAE is 0.29 and Nash Sutcliff is 0.64 for overall matching of flow duration curve. For high flow region of flow duration curve, the MRAE is 0.34 and Nash Sutcliff is 0.43 while for medium region of flow duration curve having probability of exceedance in between 15% to 75%, the MRAE is 0.34. In low flow region of flow duration curve, the MRAE is 0.29. Slight improvement in medium and low flow region can be observed from statistical measures when compared with lumped one.

Table 4-12 Calibration results of distributed model (3sub divisions)

Glencorse-Gauging station	**Nash-Sutcliff**	**MRAE**	**Mass Balance Error %**	**Flow Duration Curve**					
				High		**Medium**		**Low**	
				Nash-Sutcliff	**MRAE**	**Nash-Sutcliff**	**MRAE**	**Nash-Sutcliff**	**MRAE**
Calibration	0.64	0.29	-0.58	0.43	0.34	-1.03	0.27	-0.53	0.29

4.6.1.2 Matching Observed and Simulated hydrograph

For distributed model with 3 number of sub divisions, the observed and simulated hydrographs in semi log scale for calibration period is shown in Figure 4-19. Flow duration curve for each year is shown in Figure 4-20. Performance of model in each of the above three regions is given in Table 4-12.

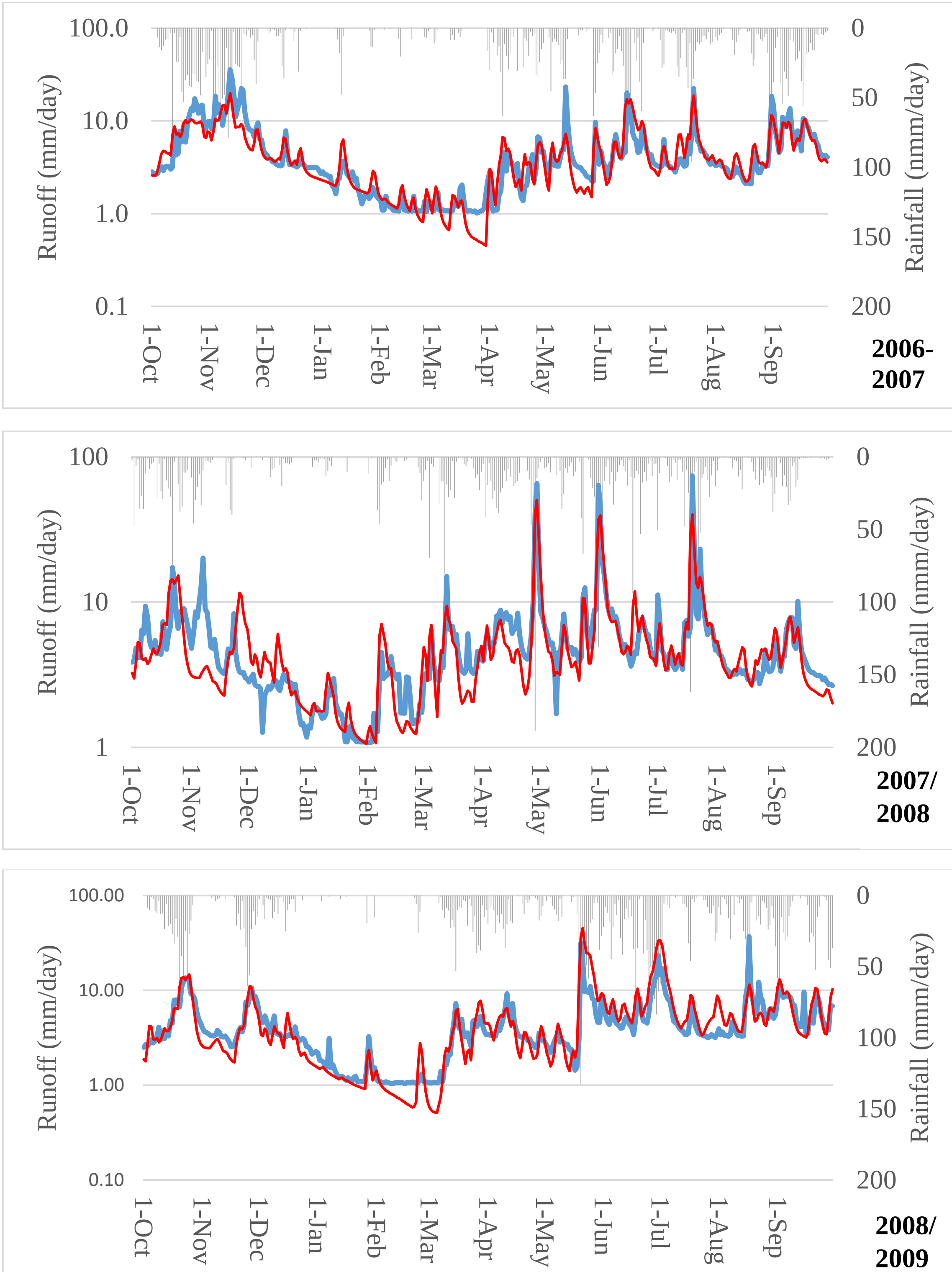


Figure 4-19 Performance of distributed Model-Calibration period (3 sub divisions)

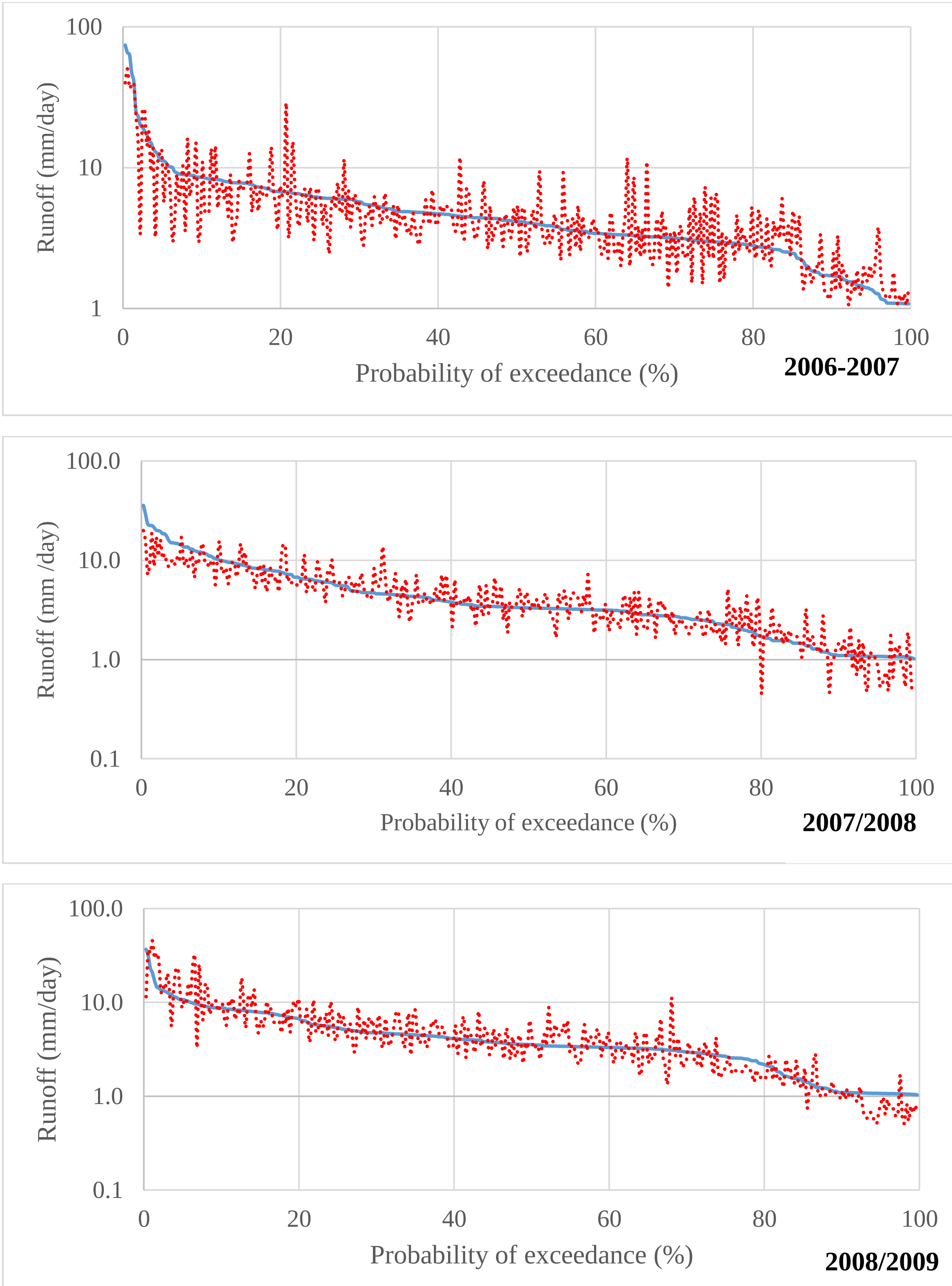


Figure 4-20 Flow duration curve of distributed model -Calibration (3 Sub divisions)

4.6.2 Six Sub Divisions

Glencorse lumped model was then divided into six number of sub divisions in order to investigate catchment scale effect. Delineation of sub basins was carried out by Arc Hydro tool in Arc GIS by specifying a drainage area.

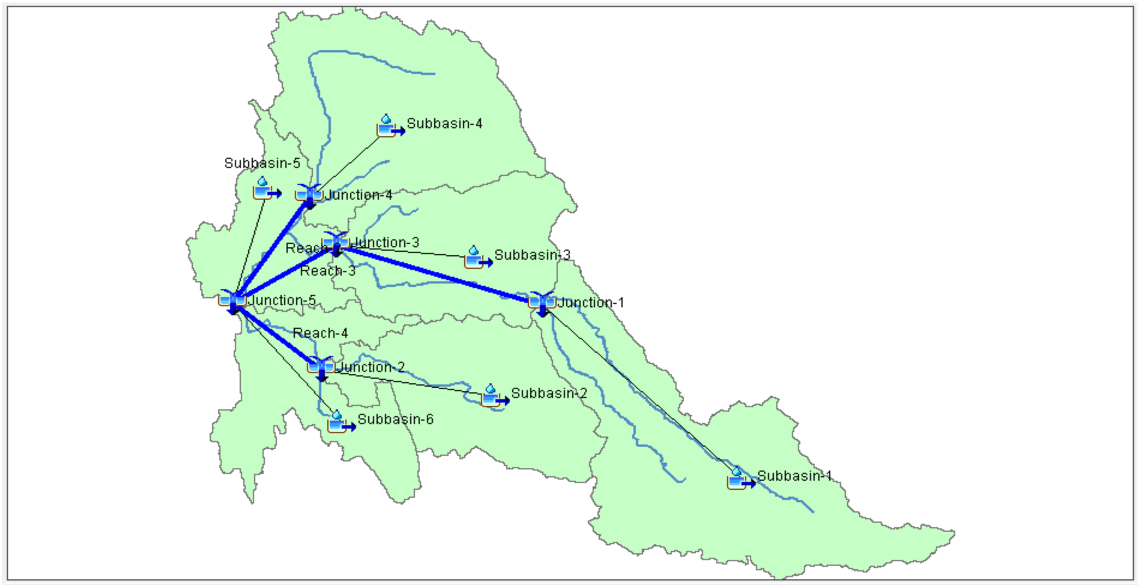


Figure 4-21 HEC-HMS distributed model (6 Sub divisions)

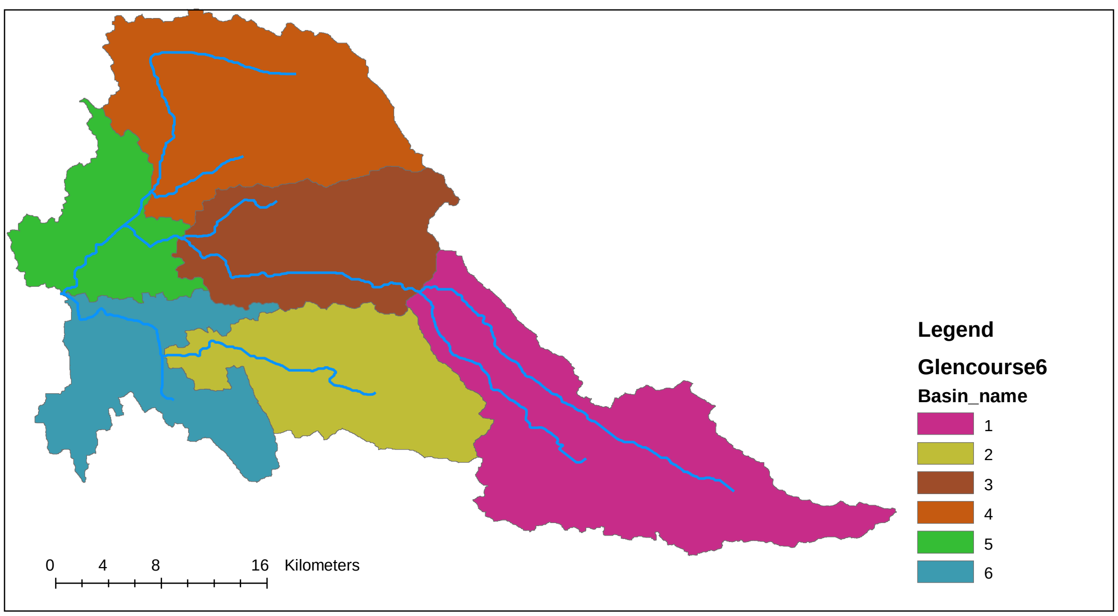


Figure 4-22 GIS distributed model (6 Sub divisions)

4.6.2.1 Calibration Results

Distributed model calibration was carried out by matching simulated streamflow with observed streamflow at Glencorse gauging station through manual approach. Table 4-13 shows the Mean Ratio of Absolute Error, Nash Sutcliff value and percent error in volume for hydrograph matching of distributed model with six number of sub divisions. The error values are also stated in the same table. Model showed satisfactory performance in hydrograph matching. Value of objective function MRAE is 0.28 and Nash Sutcliff is 0.63 for overall matching of flow duration curve. For high flow region of flow duration curve, the MRAE is 0.33 and Nash Sutcliff is 0.37 while for medium region of flow duration curve, the value of MRAE is 0.34.

Table 4-13 Calibration results of distributed model (6sub divisions)

Glencorse-Gauging station	**Nash-Sutcliff**	**MRAE**	**Mass Balance Error %**	**Flow Duration Curve**					
				High		**Medium**		**Low**	
				Nash-Sutcliff	**MRAE**	**Nash-Sutcliff**	**MRAE**	**Nash-Sutcliff**	**MRAE**
Calibration	0.63	0.28	2.40	0.37	0.33	-0.52	0.26	-0.49	0.30

4.6.2.2 Matching Observed and Simulated hydrograph

For Glencorse distributed model, the observed and simulated hydrographs in semi log scale for calibration period is shown in Figure 4-23. Flow duration curve for each year is shown in Figure 4-24. Performance of model in each of the three flow regions i.e. High, Medium and Low is given in Table 4-13.

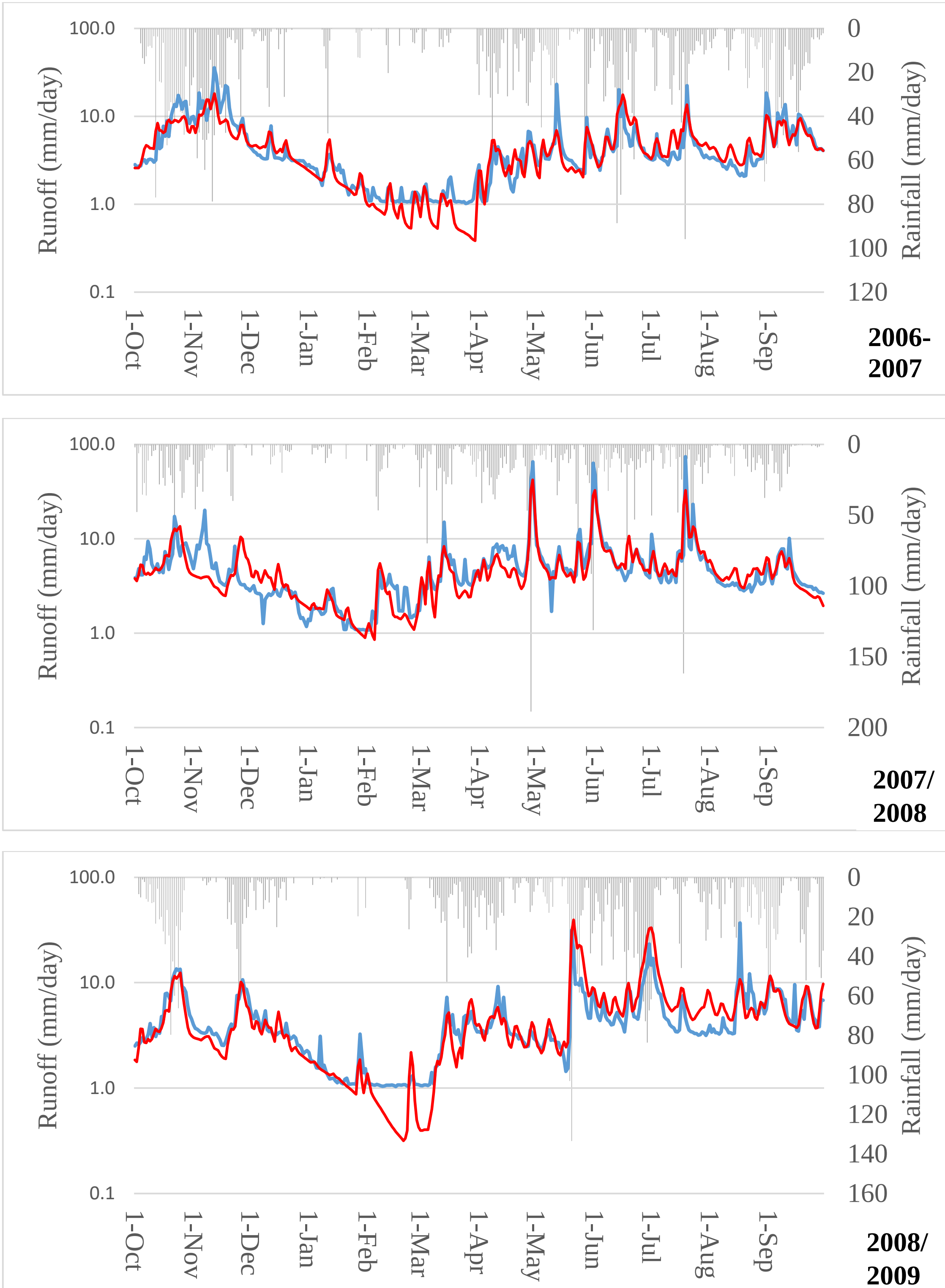
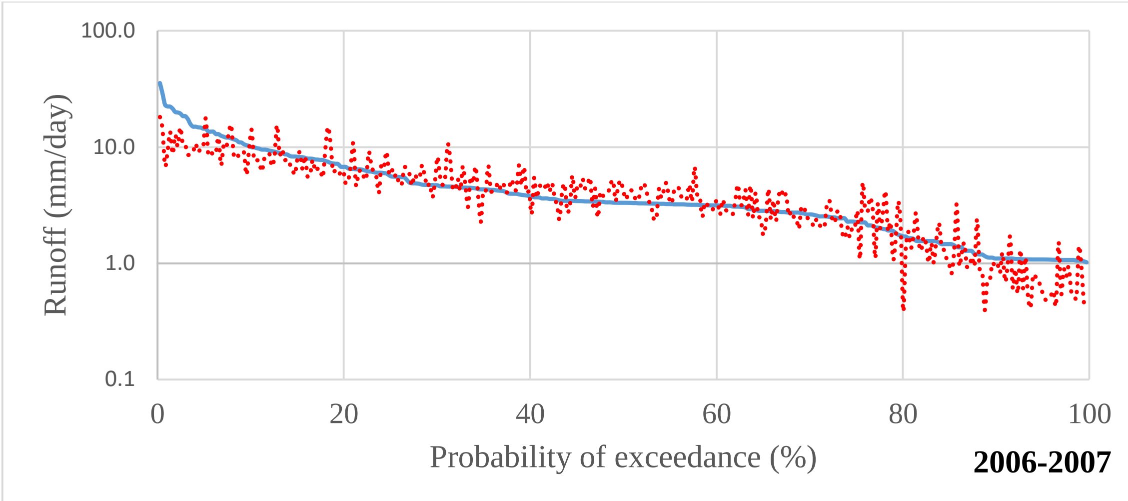
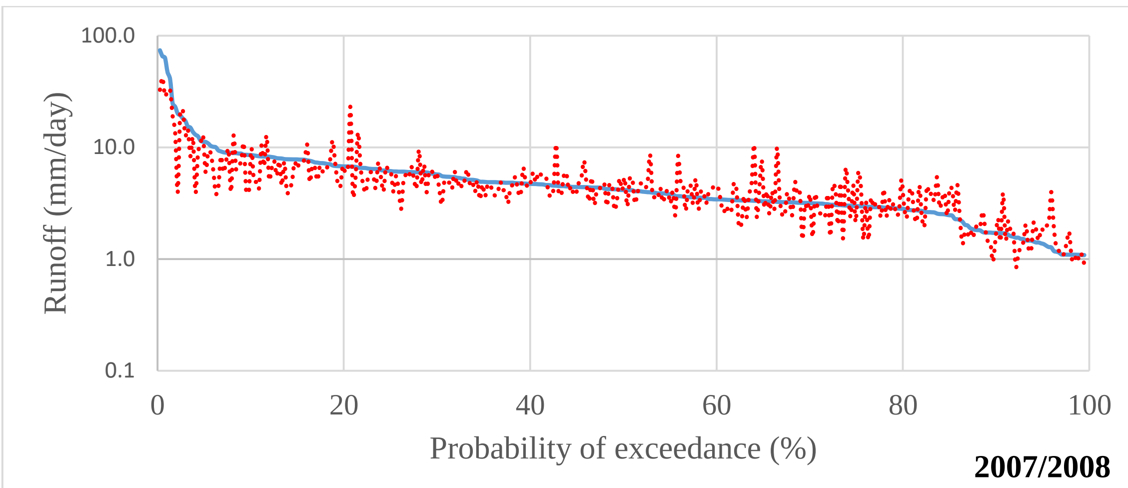


Figure 4-23 Performance of distributed Model-Calibration period (6 sub divisions)





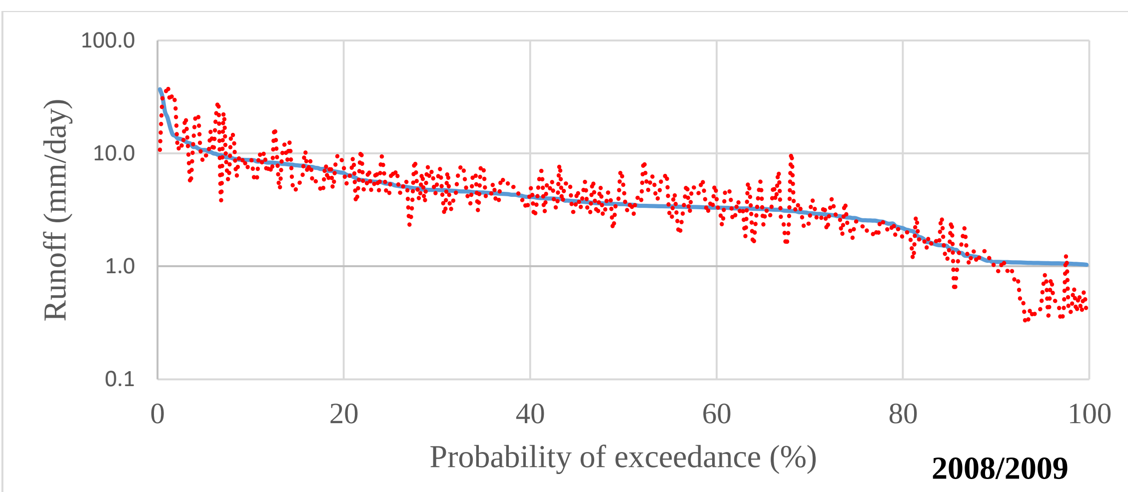


Figure 4-24 Flow duration curve of distributed model -Calibration (6 Sub divisions)

4.6.3 Nine Sub Division

Glencorse lumped model was divided into nine number of sub divisions. Delineation of sub basins was carried out by Arc Hydro tool in Arc GIS by specifying a drainage area. HEC-HMS model for distributed model with nine sub division is given in Figure 4-25.

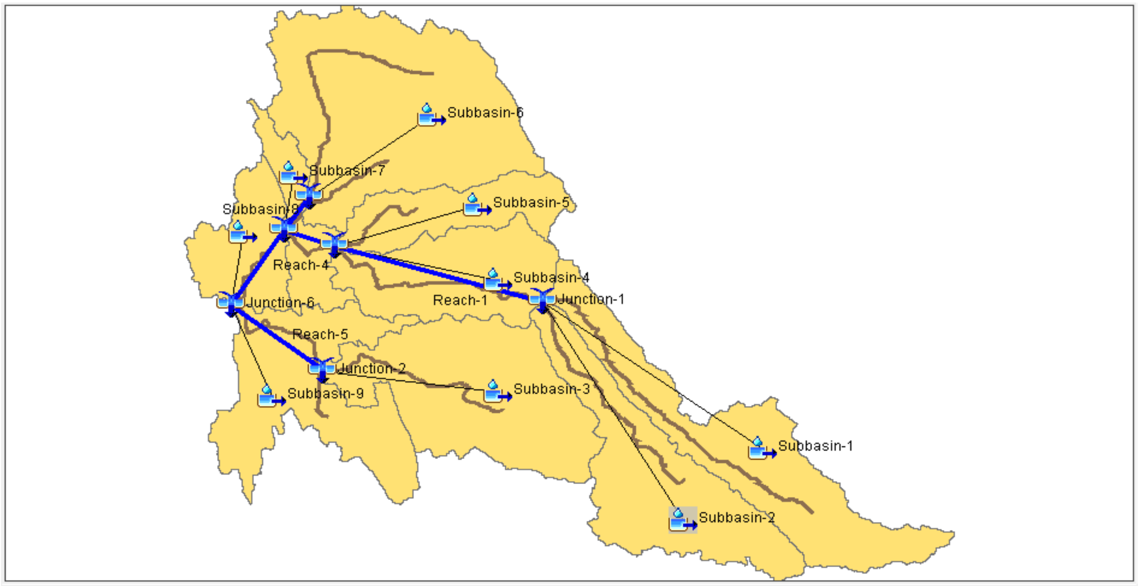


Figure 4-25 HEC-HMS distributed model (9 Sub divisions)

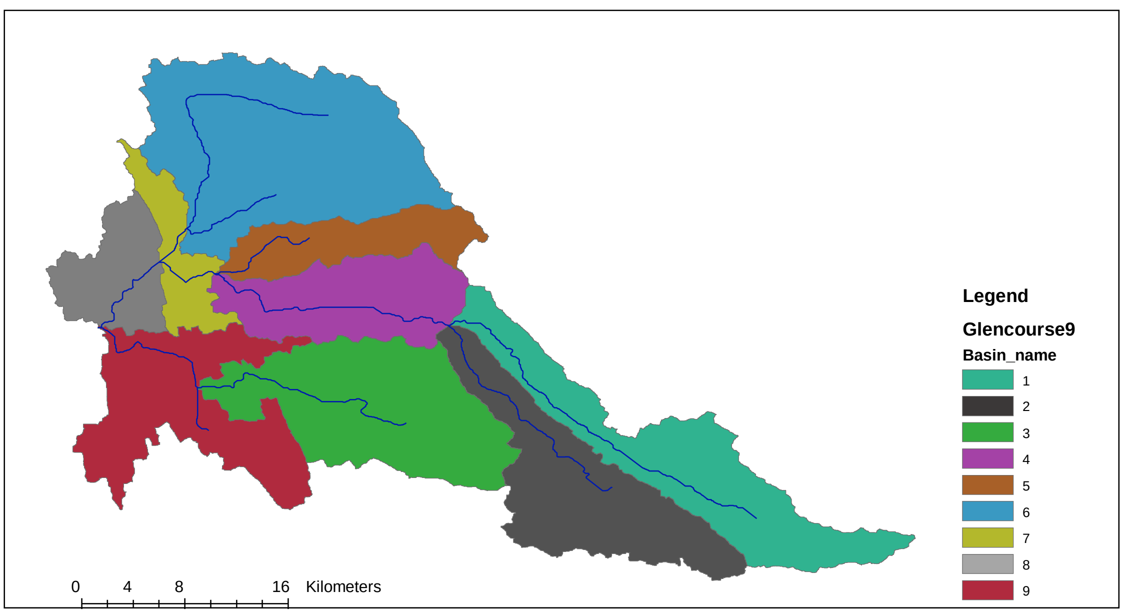


Figure 4-26 GIS distributed model (9 Sub divisions)

4.6.3.1 Calibration Results

Distributed model calibration was carried out by matching simulated streamflow with observed streamflow at Glencorse gauging station for nine sub divisions through manual approach. Table 4-14 shows the Mean Ratio of Absolute Error, Nash Sutcliff value and Percent Error in Volume for hydrograph matching of distributed model with nine number of sub divisions. The error values are also stated in the same table. Model showed satisfactory performance in hydrograph matching. Value of objective function MRAE is 0.26 and Nash Sutcliff is 0.62 for overall matching of flow duration curve. For high flow region of flow duration curve, the MRAE is 0.29 and Nash Sutcliff is 0.32 while for medium region of flow duration curve, the MRAE is 0.23. In low flow region of flow duration curve, the MRAE is 0.30. Model showed satisfactory performance for overall matching in flow duration curve.

Table 4-14 Calibration results of distributed model (9sub divisions)

Glencorse-Gauging station	**Nash-Sutcliff**	**MRAE**	**Mass Balance Error %**	**Flow Duration Curve**					
				High		**Medium**		**Low**	
				Nash-Sutcliff	**MRAE**	**Nash-Sutcliff**	**MRAE**	**Nash-Sutcliff**	**MRAE**
Calibration	0.62	0.26	12.5	0.32	0.29	-0.09	0.23	-0.18	0.30

4.6.3.2 Matching Observed and Simulated Hydrographs

For distributed model with nine number of sub divisions, the observed and simulated hydrographs in semi log scale for calibration period is shown in Figure 4-27. Flow duration curve for each year is shown in Figure 4-28. Performance of model in each of the above three regions is given in Table 4-14.

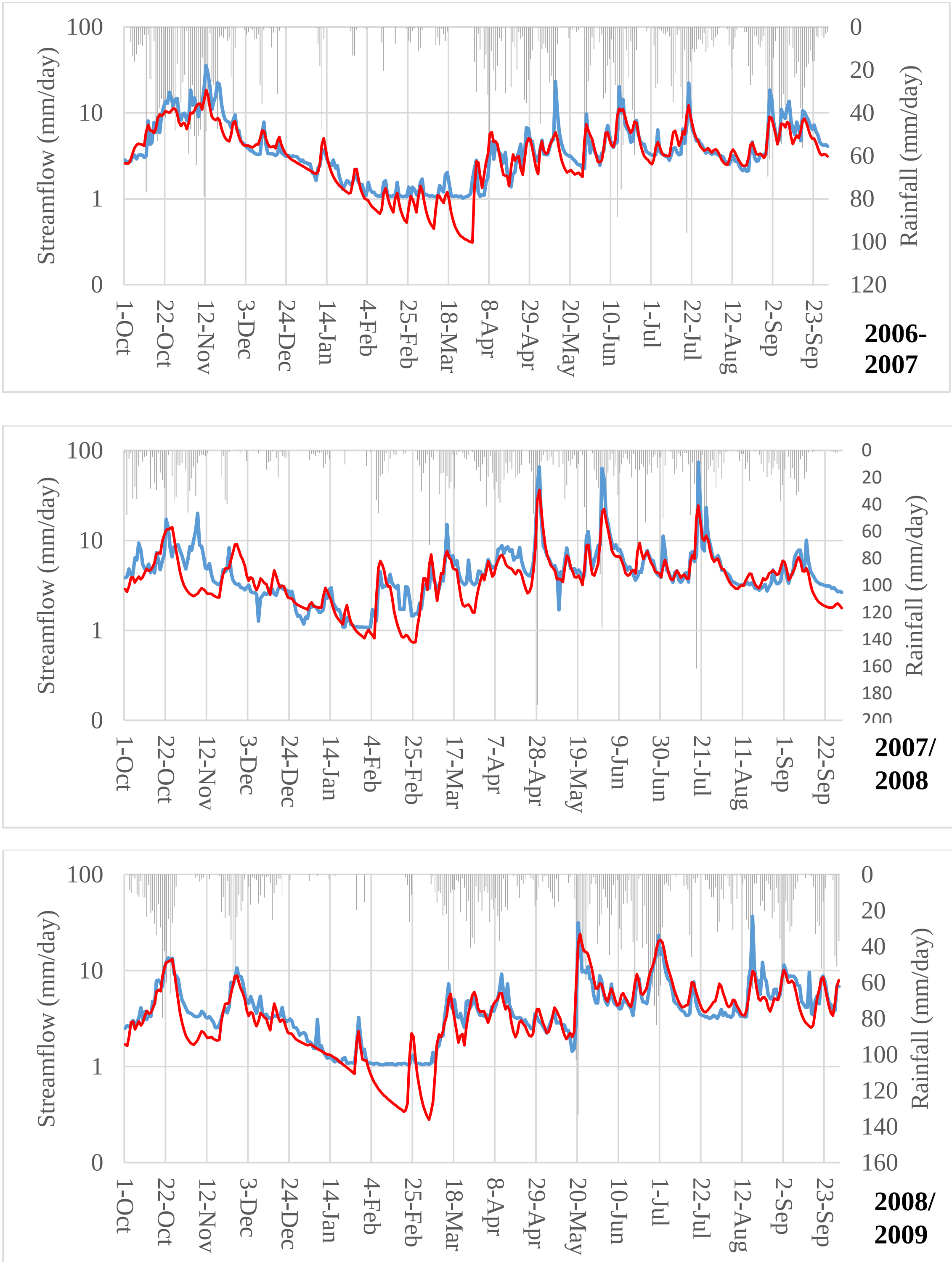


Figure 4-27 Performance of distributed Model-Calibration period (9 sub divisions)

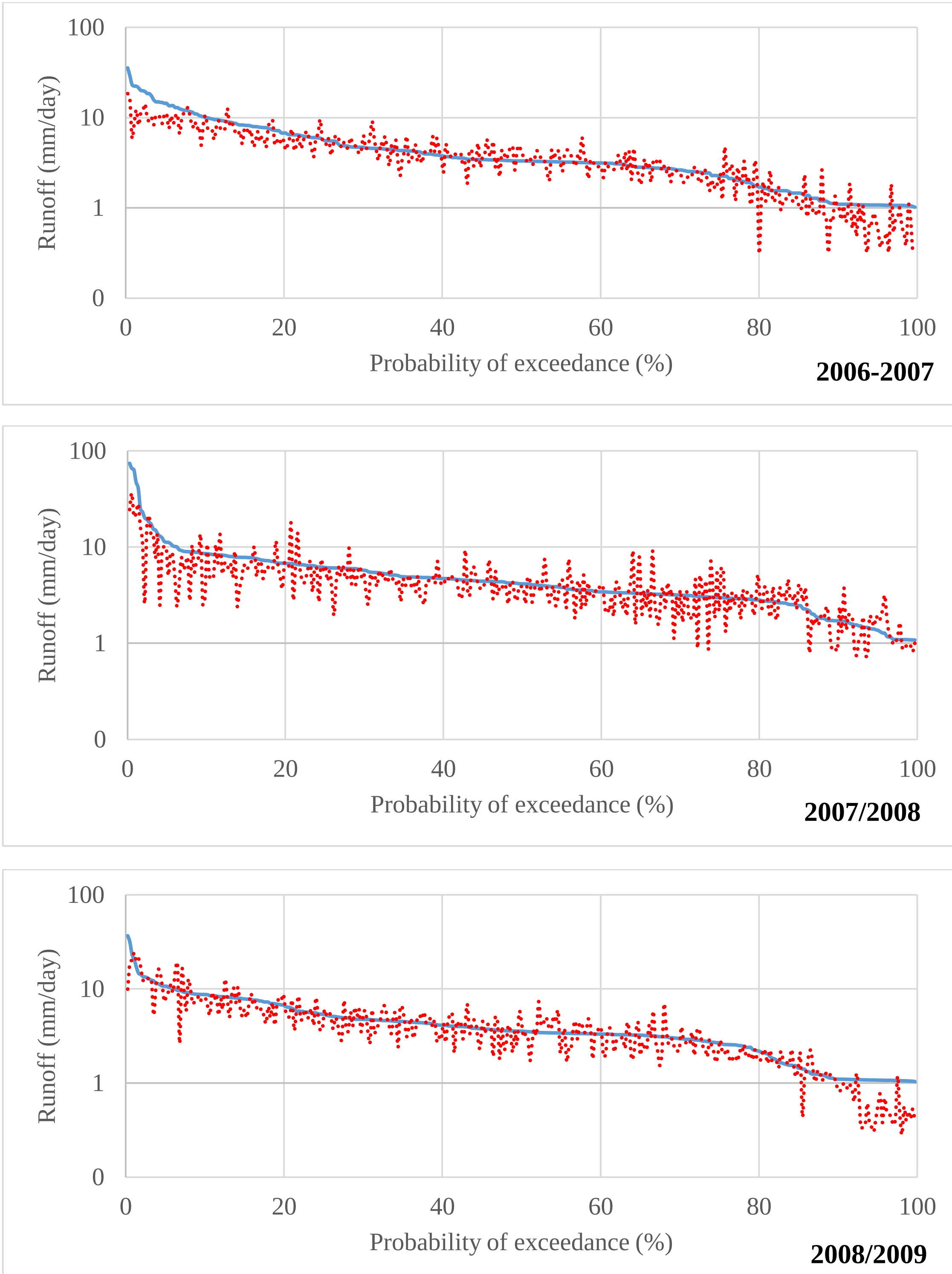


Figure 4-28 Flow duration curve of distributed model -Calibration (9 Sub divisions)

4.6.4 Sixteen Sub Divisions

Glencorse lumped model was divided into sixteen number of sub divisions. Sub divisions were stopped at sixteen number. Delineation of sub basins was carried out by Arc Hydro tool in Arc GIS by specifying a drainage area. The HEC-HMS model for sixteen sub division is given in Figure4-29.

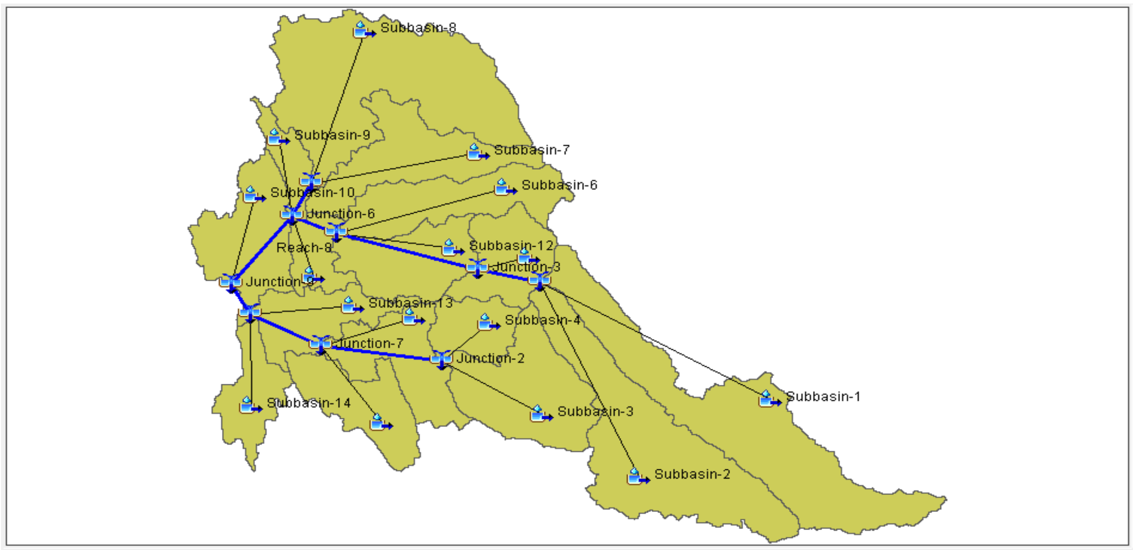


Figure 4-29 HEC-HMS distributed model (16 sub divisions)

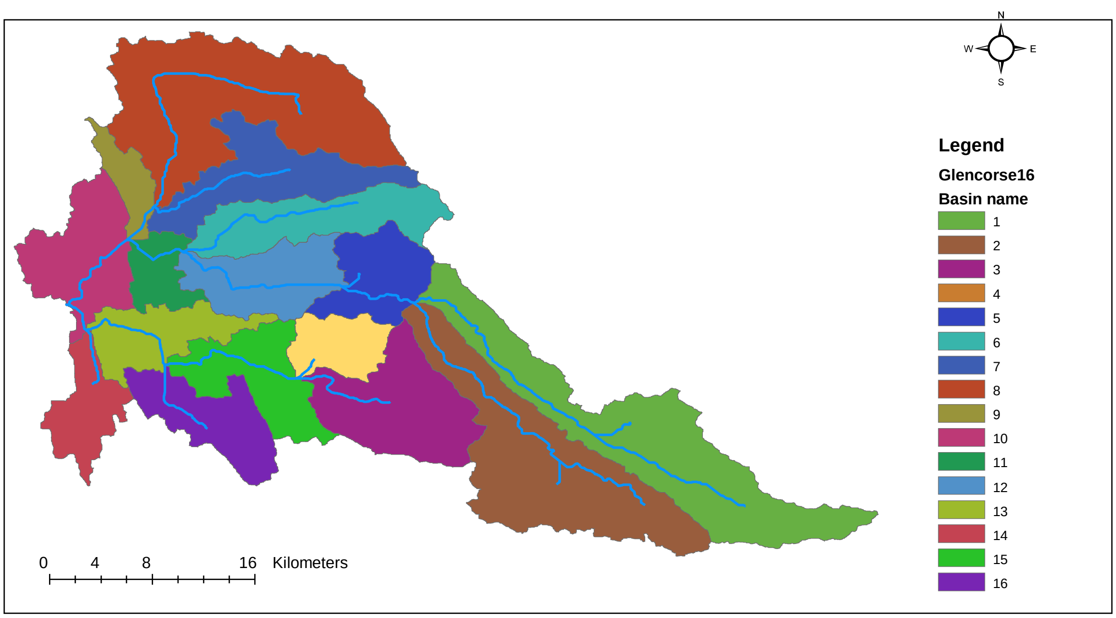


Figure 4-30 GIS distributed model (16 sub divisions)

4.6.4.1 Calibration Results

Values of statistical measures used for assessing model performance are given in this section. Table 4-15 shows the Mean Ratio of Absolute Error, Nash Sutcliff values and Percent Error in Volume for hydrograph matching of distributed model with sixteen number of sub divisions. The error values are also stated in the same table. Value of objective function MRAE is 0.3and Nash Sutcliff is 0.62 for overall matching of flow duration curve. For high flow region of flow duration curve, the MRAE is 0.32 and Nash Sutcliff is 0.37 while for medium region of flow duration curve, the MRAE is 0.29. In low flow region of flow duration curve, the MRAE is 0.33. Performance of model for overall matching declined when moving toward 16 number of sub divisions as compared to that of nine sub divisions.

Table 4-15 Calibration results of distributed model (16sub divisions)

Glencorse-Gauging station	**Nash-Sutcliff**	**MRAE**	**Mass Balance Error %**	**Flow Duration Curve**					
				High		**Medium**		**Low**	
				Nash-Sutcliff	**MRAE**	**Nash-Sutcliff**	**MRAE**	**Nash-Sutcliff**	**MRAE**
Calibration	0.62	0.30	-1.70	0.37	0.32	-0.74	0.29	-0.57	0.33

4.6.4.2 Matching Observed and Simulated Hydrograph

For distributed catchment with sixteen sub divisions, the observed and simulated hydrographs in semi log scale for calibration period is shown in Figure 4-31. Flow duration curve for each year of calibration period is shown in Figure 4-32. Performance of model in each of the above three regions is given in Table 4-15.

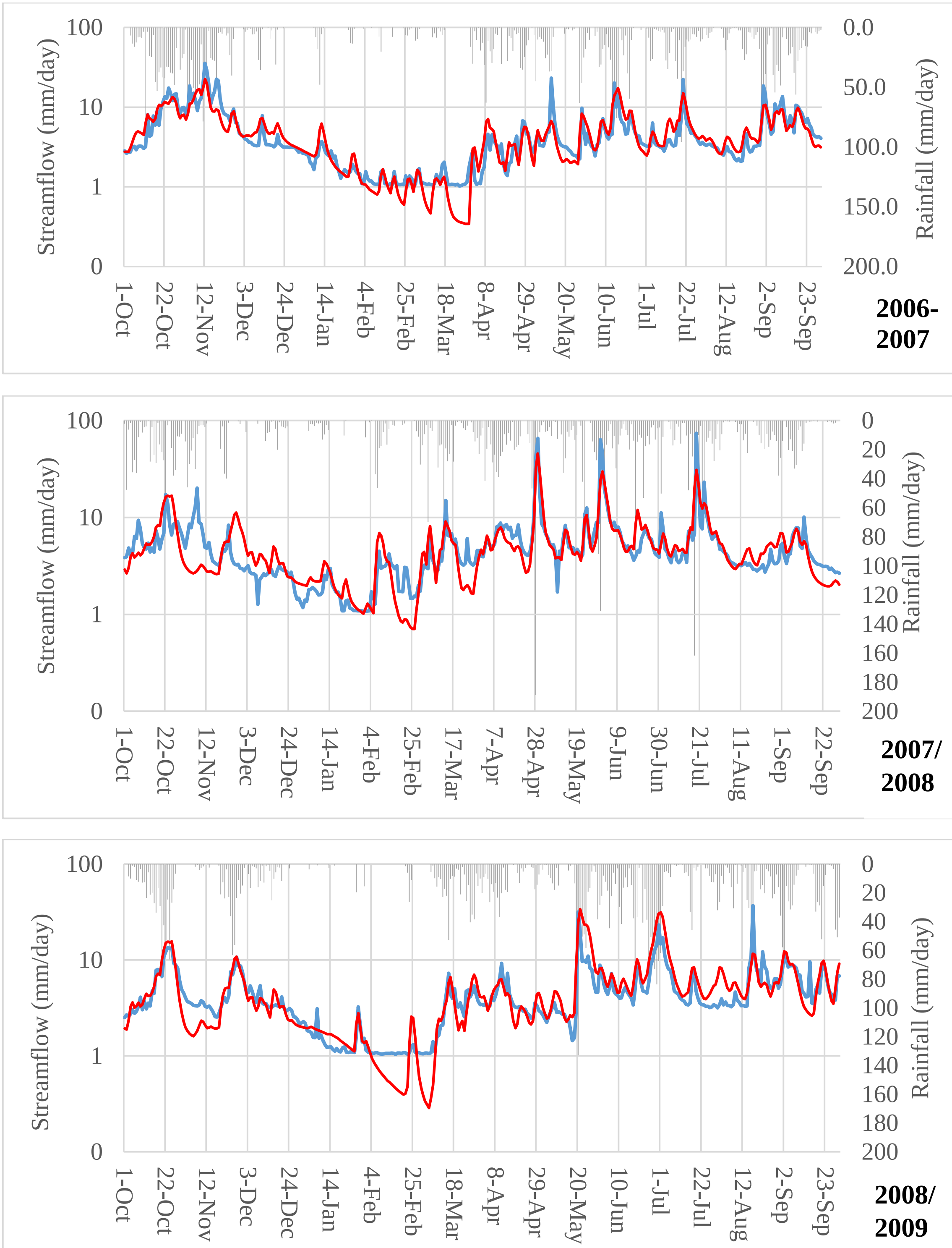


Figure 4-31 Performance of distributed Model-Calibration period (16 sub divisions)

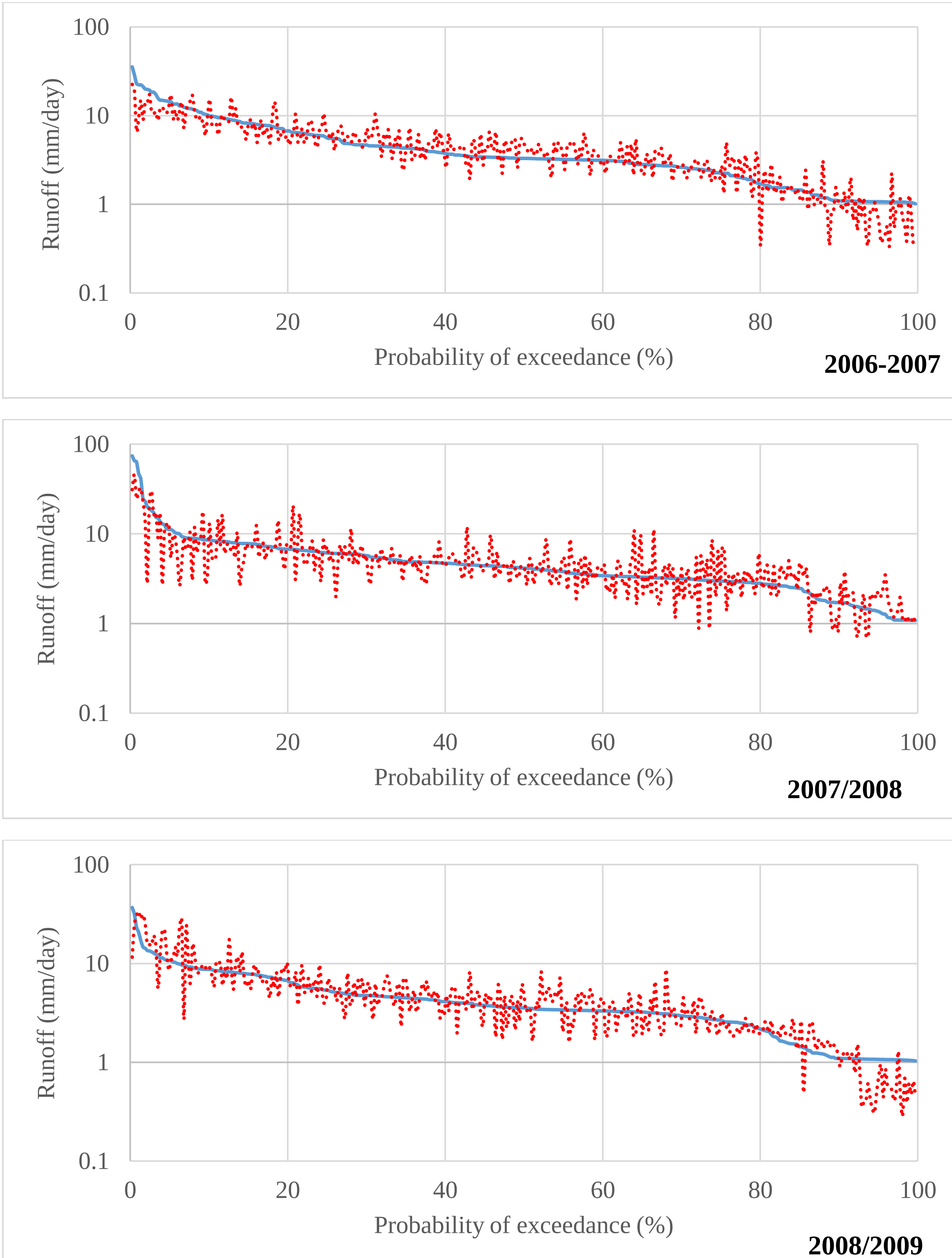


Figure 4-32 Flow duration curve of distributed model -Calibration (16 Sub divisions)

4.7 Distributed Model Validation Results

4.7.1 Three Sub Divisions

Performance of model for distributed model with three number of sub divisions during verification period assessed by statistical measure are shown in Table 4-16. The MRAE is 0.29 and Nash Sutcliff is 0.48 for overall matching of flow duration curve. For high flow region of flow duration curve, the MRAE is 0.34 while for medium region of flow duration curve, the MRAE is 0.34. In low flow region of flow duration curve, the MRAE is 0.33.

Table 4-16 Validation results of distributed model (3 sub divisions)

Glencorse-Gauging station	Nash-Sutcliff	MRAE	Mass Balance Error %	Flow Duration Curve					
				High		Medium		Low	
				Nash-Sutcliff	MRAE	Nash-Sutcliff	MRAE	Nash-Sutcliff	MRAE
Validation	0.48	0.29	13.83	-1.11	0.34	-0.57	0.27	-0.82	0.33

4.7.1.1 Matching Observed and Simulated hydrograph

For distributed model with three number of sub divisions, the observed and simulated hydrographs in semi log scale for validation period is shown in Figure 4-33. Flow duration curve for each year is shown in Figure 4-34. Performance of model in each of the above three regions is given in Table 4-16.

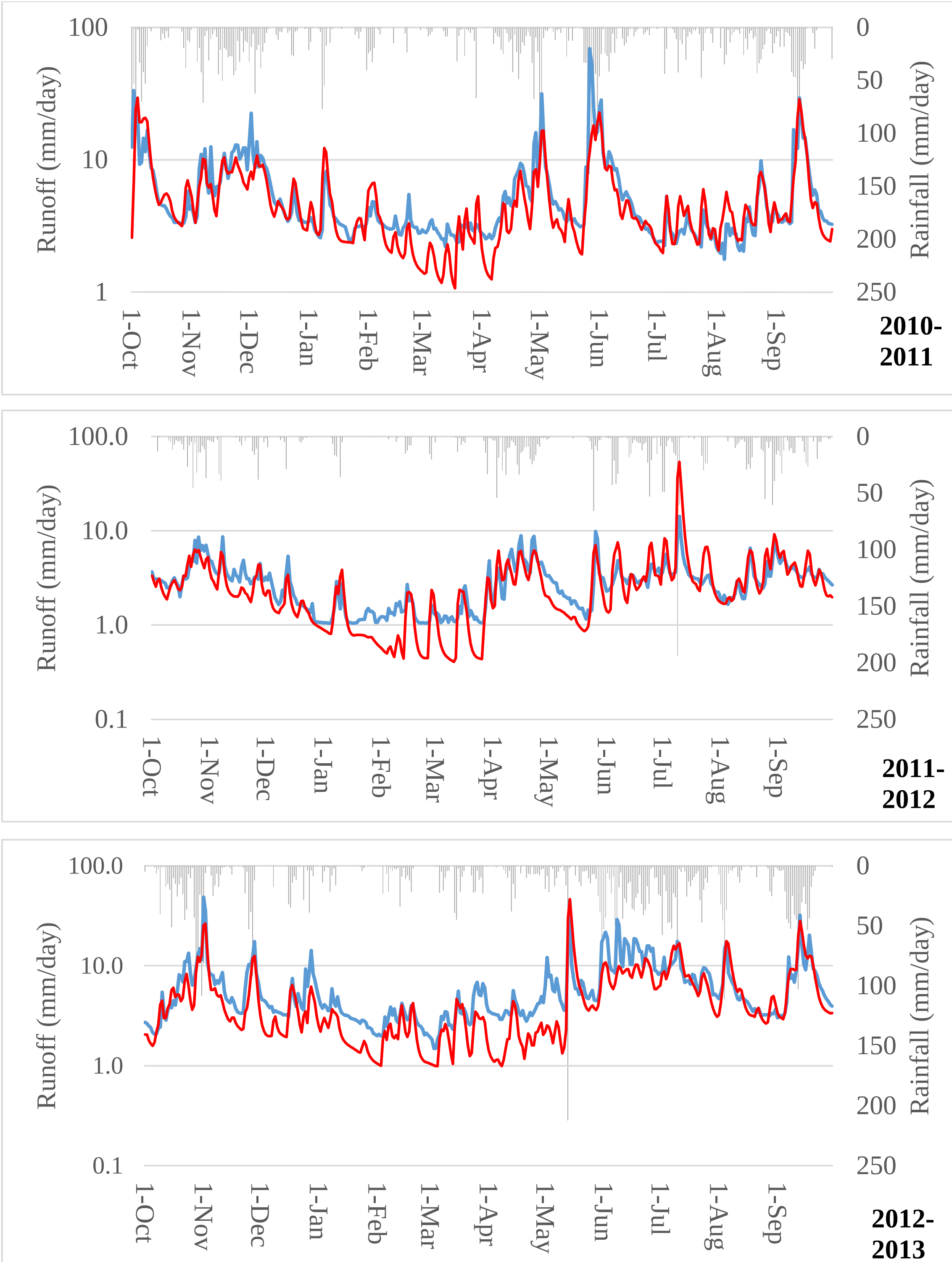


Figure 4-33 Performance of distributed Model-Validation period (3 sub divisions)

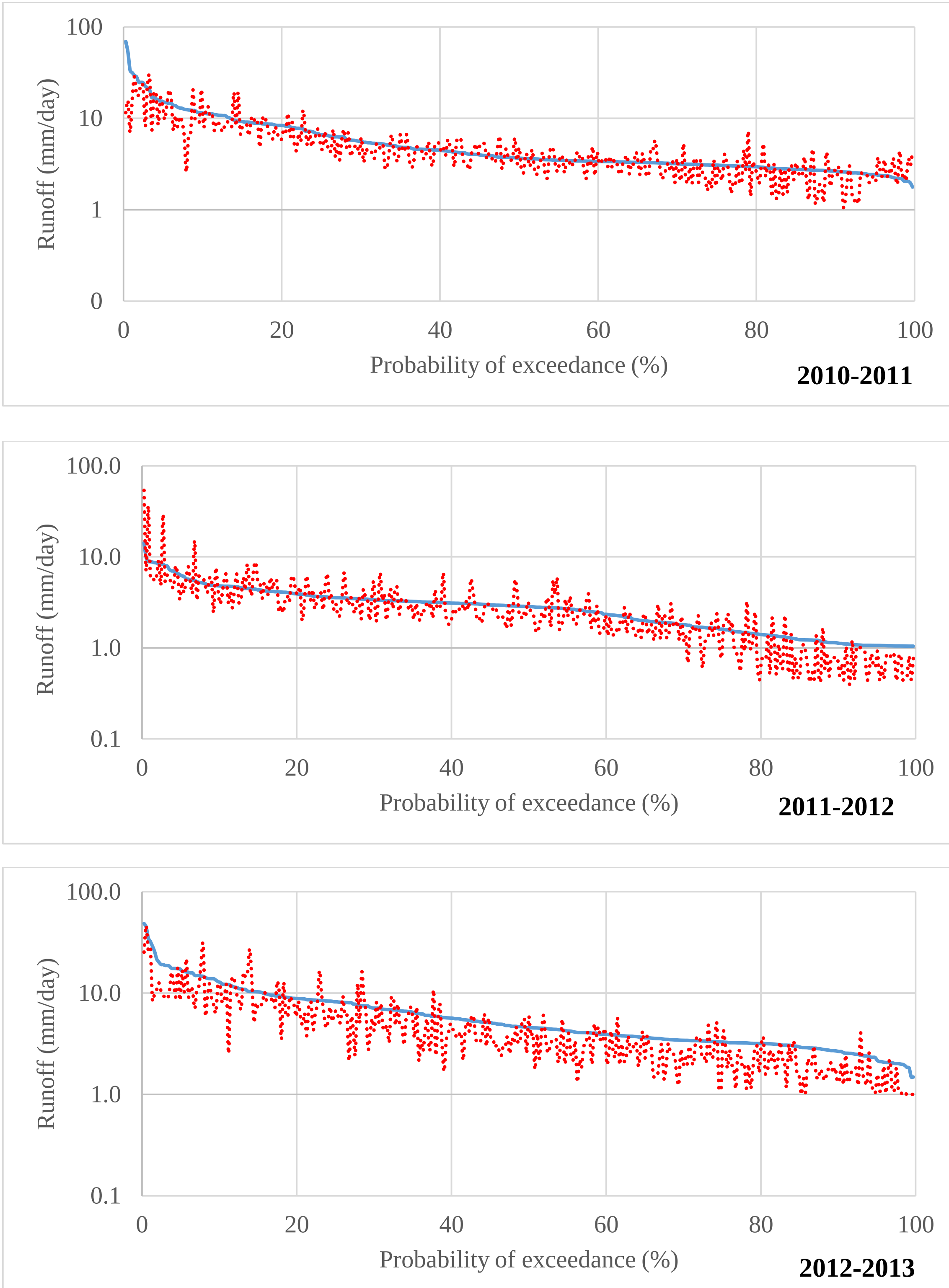


Figure 4-34 Flow duration curve of distributed model -Validation (3Sub divisions)

4.7.2 Six Sub Divisions

Performance of model for distributed model with six number of sub divisions during verification period assessed by statistical measure are shown in Table 4-17. The MRAE is 0.28 and Nash Sutcliff Coefficient is 0.52 for overall matching of flow duration curve. For high flow region of flow duration curve, the MRAE is 0.34 while for medium region of flow duration curve, the MRAE is 0.24. In low flow region of flow duration curve, the MRAE is found to be 0.34.

Table 4-17 Validation results of distributed model (6 sub divisions)

Glencorse-Gauging station	**Nash-Sutcliff**	**MRAE**	**Mass Balance Error %**	**Flow Duration Curve**					
				High		**Medium**		**Low**	
				Nash-Sutcliff	**MRAE**	**Nash-Sutcliff**	**MRAE**	**Nash-Sutcliff**	**MRAE**
Validation	0.52	0.28	17.8	-0.06	0.34	-0.14	0.24	-0.76	0.34

4.7.2.1 Matching Observed and Simulated Hydrograph

For distributed model with six sub divisions observed and simulated hydrographs in semi log scale for validation period is shown in Figure 4-35. Flow duration curve for each year is shown in Figure 4-36. Performance of model in each of the above three regions is given in Table 4-17.

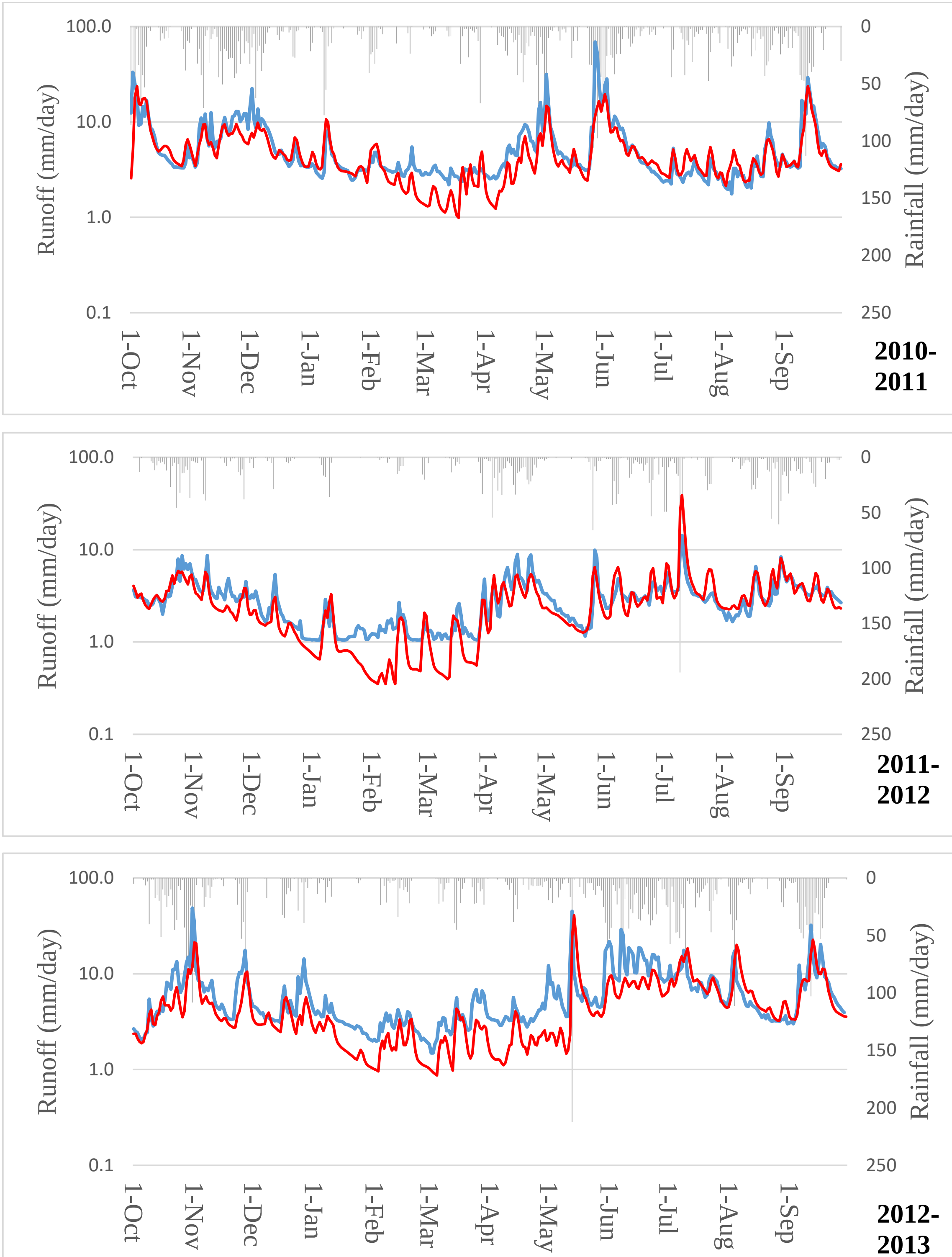


Figure 4-35 Performance of distributed Model-Validation period (6 sub divisions)

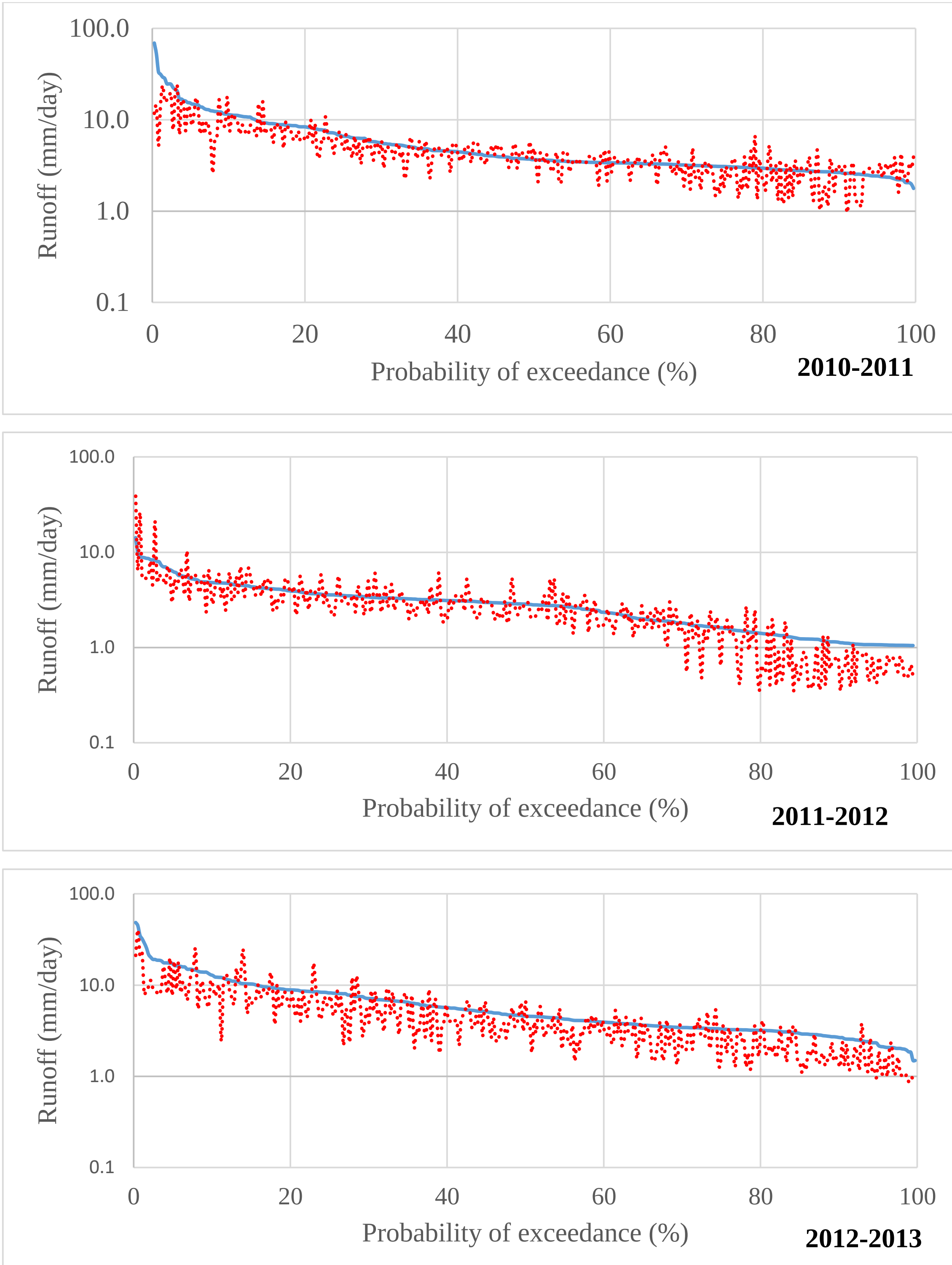


Figure 4-36 Flow duration curve of distributed model -Validation (6Sub divisions)

4.7.3 Nine Sub Divisions

Performance of model for distributed model with nine number of sub divisions during verification period assessed by statistical measure are shown in Table 4-18. The MRAE is 0.3 and Nash Sutcliff is 0.46 for overall matching of flow duration curve. For high flow region of flow duration curve, the MRAE is 0.36 while for medium region of flow duration curve, the MRAE is 0.27. In low flow region of flow duration curve, the MRAE is 0.34.

Table 4-18 Validation results of distributed model (9 sub divisions)

Glencorse-Gauging station	Nash-Sutcliff	MRAE	Mass Balance Error %	Flow Duration Curve					
				High		Medium		Low	
				Nash-Sutcliff	MRAE	Nash-Sutcliff	MRAE	Nash-Sutcliff	MRAE
Verification	0.46	0.30	22.25	-0.18	0.36	-0.43	0.27	-0.82	0.34

4.7.3.1 Matching Observed and Simulated Hydrograph

For distributed model with nine sub divisions observed and simulated hydrographs in semi log scale for validation period is shown in Figure 4-37. Flow duration curve for each year is shown in Figure 4-38. Performance of model in each of the above three regions is given in Table 4-18.

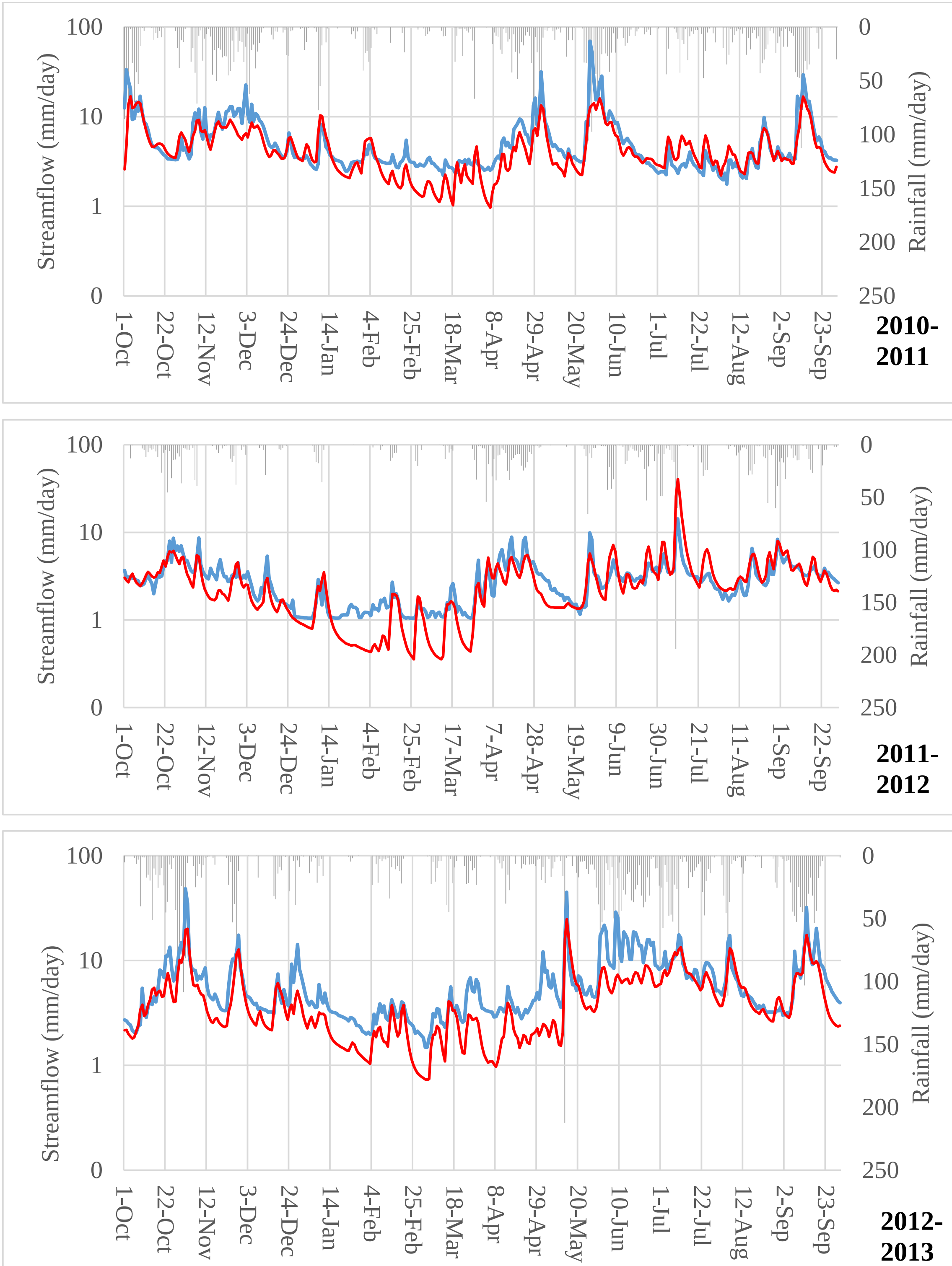


Figure 4-37 Performance of distributed Model-Validation period (9 Sub divisions)

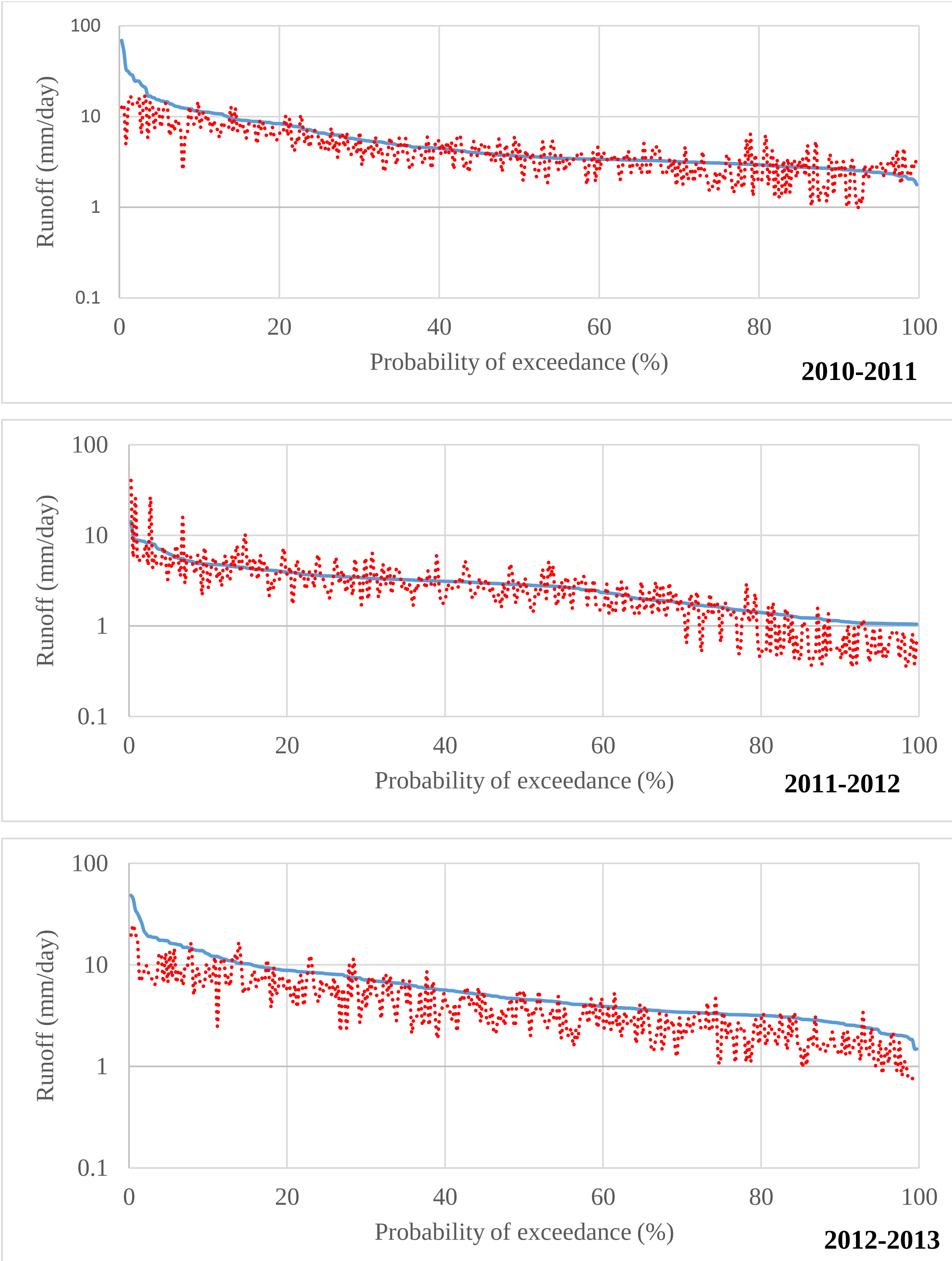


Figure 4-38 Flow duration curve of distributed model -Validation (9 Sub divisions)

4.7.4 Sixteen Sub Divisions

Performance of model for distributed model with sixteen number of sub divisions during verification period assessed by statistical measure are shown in Table 4-19. The MRAE is 0.3 and Nash Sutcliff is 0.51 for overall matching of flow duration curve. For high flow region of flow duration curve, the MRAE is 0.33 while for medium region of flow duration curve, the MRAE is 0.28. In low flow region of flow duration curve, the MRAE is 0.35.

Table 4-19 Validation results of distributed model (16 sub divisions)

Glencorse-Gauging station	**Nash-Sutcliff**	**MRAE**	**Mass Balance Error %**	**Flow Duration Curve**					
				High		**Medium**		**Low**	
				Nash-Sutcliff	**MRAE**	**Nash-Sutcliff**	**MRAE**	**Nash-Sutcliff**	**MRAE**
Calibration	0.51	0.30	9.80	0.00	0.33	-0.97	0.28	-1.18	0.35

4.7.4.1 Matching Observed and Simulated Hydrograph

For distributed model with sixteen number of sub divisions the observed and simulated hydrographs in semi log scale for calibration period is shown in Figure 4-39. Flow duration curve for each year is shown in Figure 4-40. Performance of model in each of the above three regions is given in Table 4-19.

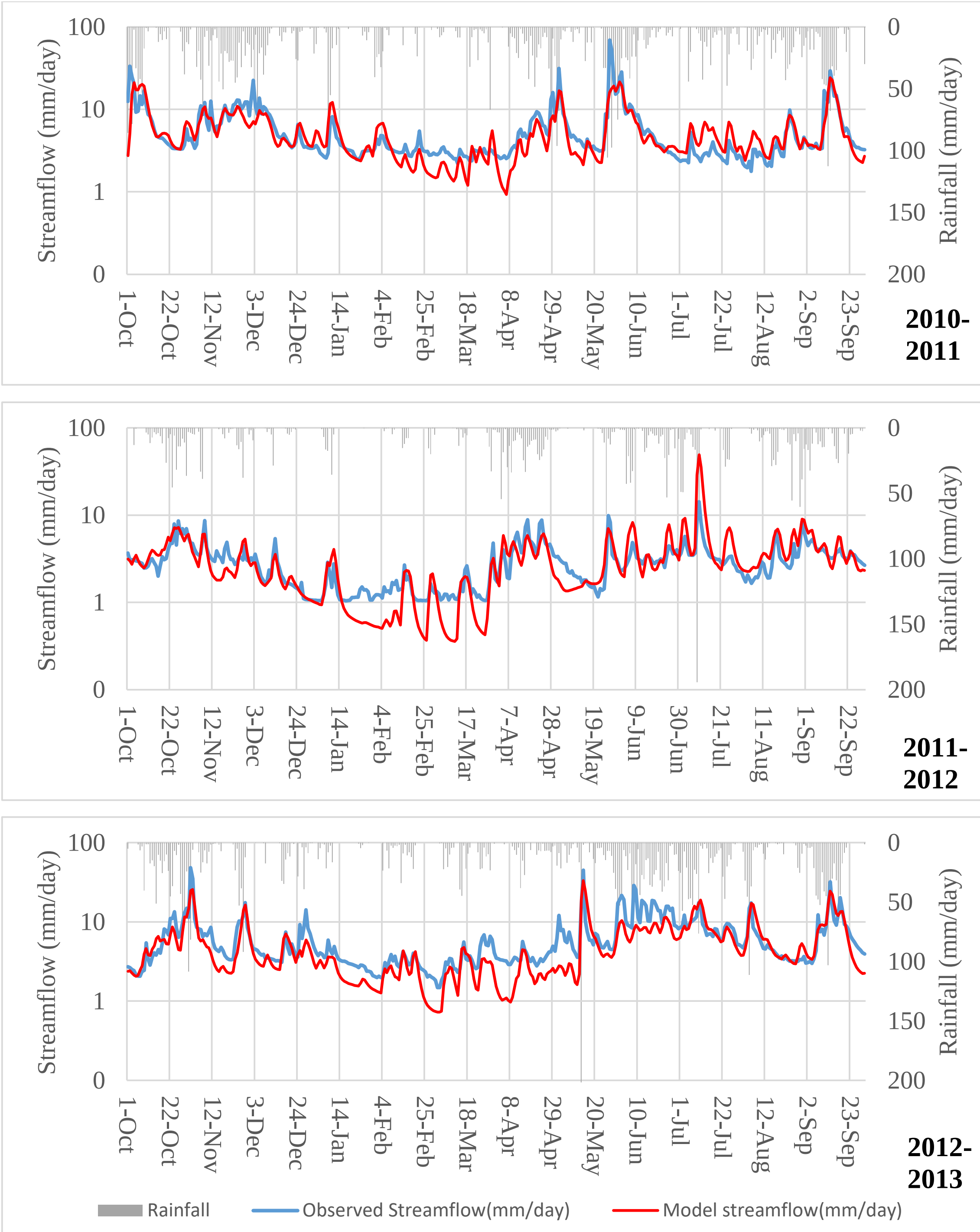


Figure 4-39 Performance of distributed Model-Validation period (16 Sub divisions)

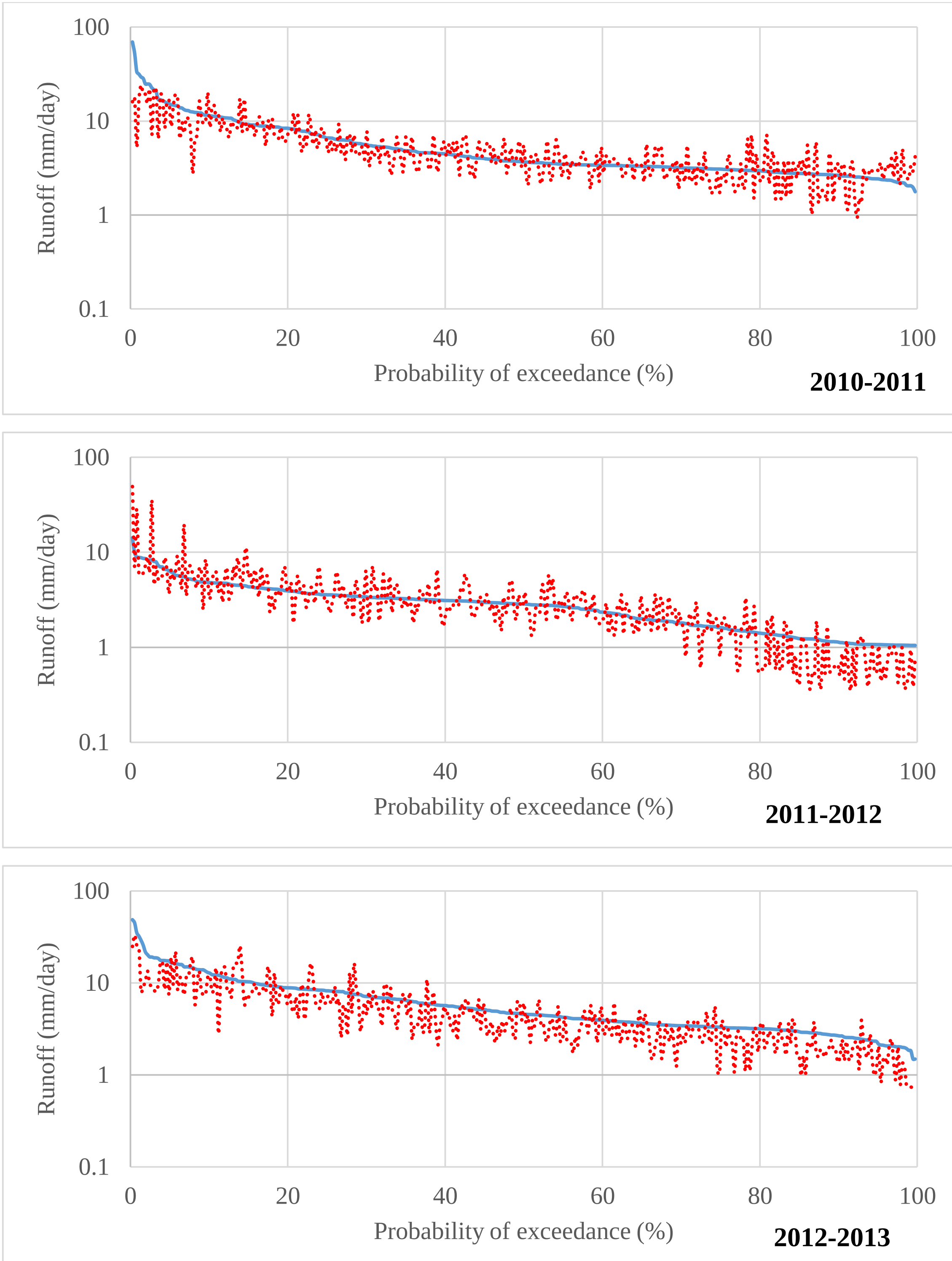


Figure 4-40 Flow duration curve of distributed model -Validation (16 Sub divisions)

4.8 Comparison of Distributed Model Performance

Values of objective function of distributed model for different numbers of sub division along with NASH and Percent Error in Volume is given in Table 4-20. Results of model performance for overall matching as well as in high, medium and low flow regions are also listed. It can be seen from results that model performance started improving initially when shifting toward distributed modelling as compared to that of lumped one up to a certain number of sub divisions after which model performance started decreasing. When looking at the statistical performance measures for both calibration and verification period in Table 4-20, the distributed model with 6 numbers of sub division gives the best performance. Although model with nine number of sub divisions showed better model performance with 0.26 and 0.30 value of MRAE for calibration and verification, the other statistical measures are not showing good performance. Variation of MRAE and NASH with number of sub divisions and lumped one for comparison purpose during calibration period is shown graphically in Figure 4-41 while during validation period is shown in Figure 4-42.

Table 4-20 Summary of distributed model performance

Sub divisions	Glencorse-Gauging station	Nash-Sutcliff	MRAE	Mass Balance Error %	Flow Duration curve					
					High		Medium		Low	
					Nash-Sutcliff	MRAE	Nash-Sutcliff	MRAE	Nash-Sutcliff	MRAE
3	Calibration	0.64	0.29	-0.58	0.43	0.34	-1.03	0.27	-0.53	0.29
3	Verification	0.48	0.29	13.83	-1.11	0.34	-0.57	0.27	-0.82	0.33
6	Calibration	0.63	0.28	2.40	0.37	0.33	-0.52	0.26	-0.49	0.30
6	Verification	0.52	0.28	17.80	-0.06	0.34	-0.14	0.24	-0.76	0.34
9	Calibration	0.62	0.26	12.50	0.32	0.29	-0.09	0.23	-0.18	0.30
9	Verification	0.46	0.30	22.25	-0.18	0.36	-0.43	0.27	-0.82	0.34
16	Calibration	0.62	0.30	-1.70	0.37	0.32	-0.74	0.29	-0.57	0.33
16	Verification	0.51	0.30	9.80	0.00	0.33	-0.97	0.28	-1.18	0.35

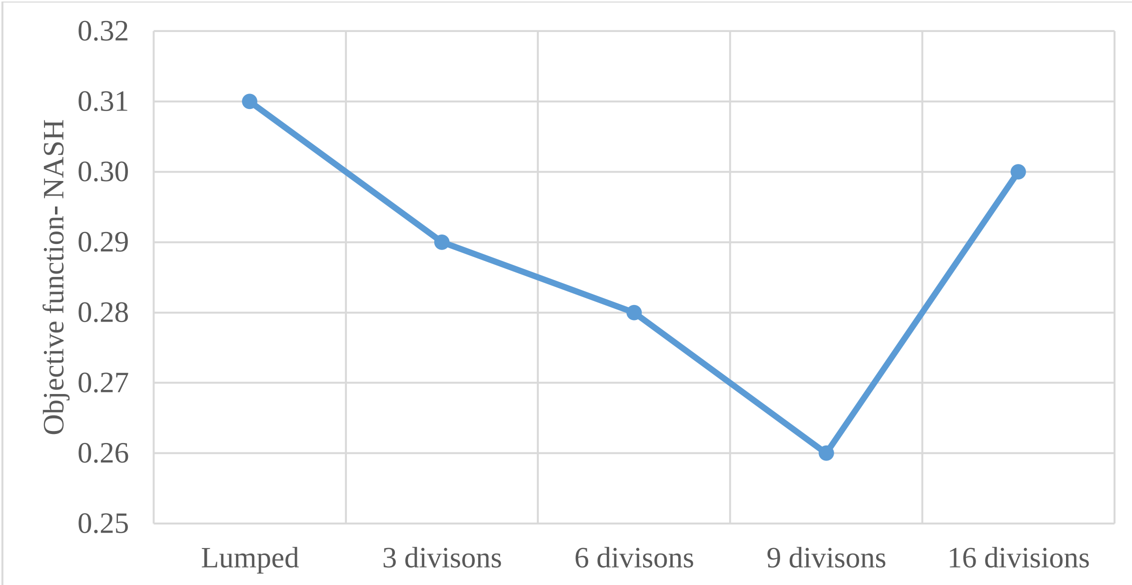


Figure 4-41 MRAE variation for lumped and distributed model- (Calibration period)

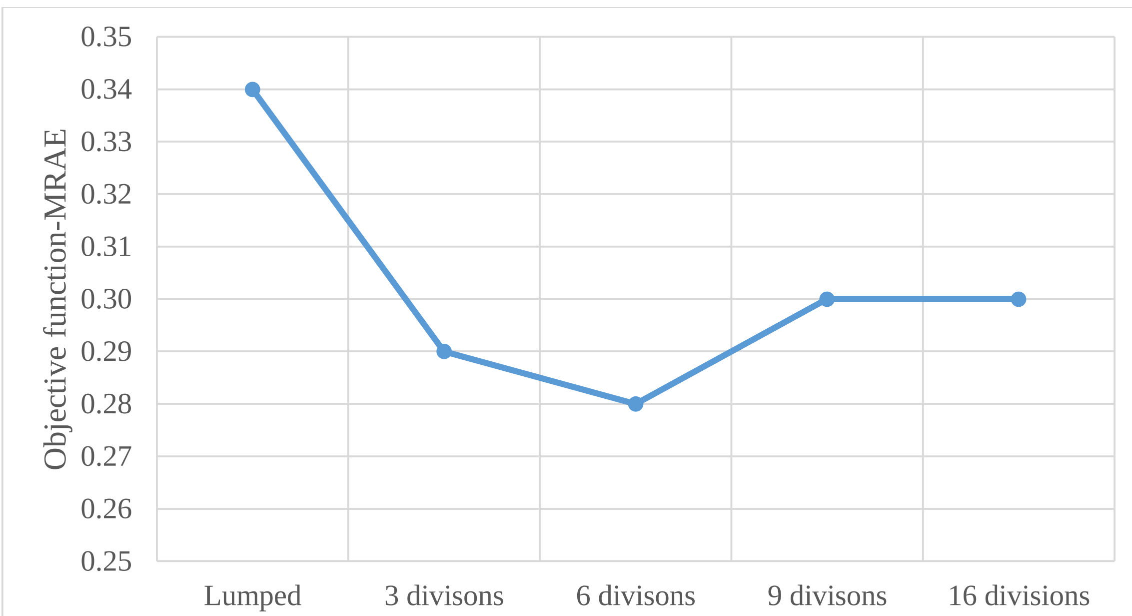


Figure 4-42 MRAE variation for lumped and distributed model- (Validation period)

Variation of objective function for lumped and distributed model revealed 6 numbers of sub divisions to be the optimum number of sub divisions for which model gives the best performance when compared with the lumped one. Therefore, 6 numbers of sub divisions were selected as the optimum sub divisions and was compared with lumped model performance to investigate catchment scale effect.

Statistical measures for assessing model performance of optimum number of sub division i.e. six number with lumped model for comparison purposes is shown in Table 4-21. Model performance improved for both calibration and verification period when compared with lumped one. Value of objective function MRAE reduced from 0.31 to 0.28 for calibration period while 0.34 to 0.28 for validation period by moving toward distributed modelling as compared to lumped one. Major improvement can be seen in low and medium flow region while model performance in high flow region got reduced in distributed model. Percent error in volume reduced from 2.9% to 2.4% for calibration period whereas it increased from 14.8% to 17.8% during the verification period for distributed model with 6 number of sub divisions as compared to lumped model.

Table 4-21 Comparison of lumped and distributed model performance

Model	**Glencorse-Gauging station**	**Nash-Sutcliff**	**MRAE**	**Mass Balance Error %**	**Flow Duration Curve**					
					High		**Medium**		**Low**	
					Nash-Sutcliff	**MRAE**	**Nash-Sutcliff**	**MRAE**	**Nash-Sutcliff**	**MRAE**
Lumped	Calibration	0.7	0.31	2.9	0.51	0.27	-0.84	0.31	-0.71	0.36
	Verification	0.57	0.34	14.8	0.09	0.34	-0.56	0.31	-2.00	0.42
6 divisions	Calibration	0.63	0.28	2.4	0.37	0.33	-0.52	0.26	-0.49	0.30
	Verification	0.52	0.28	17.8	-0.06	0.34	-0.14	0.24	-0.76	0.34

5 DISCUSSION

5.1 Data and Data Period

5.1.1 Selection of Data Period

Glencorse catchment was selected for this study based on the availability of precipitation and streamflow data. Survey was carried out to identify the areas where data of recent past years were available from Irrigation and Meteorological Departments. There were some areas where although sufficient data was available but either it was not of the recent past or was in manual form. It is necessary to simulate the model for recent data as catchment may have experienced some major land use changes or changes in precipitation trends due to which previous data remains no longer reliable. Therefore, Glencorse catchment in Kelani river basin was selected as data of recent past from 2006/2007 to 2008/2009 and 2010/2011 to 2012/2013 was available in digital form with minimum amount of missing data. Therefore, 6-year data period was selected and existence of extreme conditions within data period was checked. Data period covers both wet and dry season. On analyzing, it was observed that 2011/2012 was the driest year in selected data period while 2010/2011 and 2013/2014 were wet years.

5.1.2 Data Errors

Visual observation as well as different statistical checks were carried out on the entire data set in order to check the consistency and homogeneity of data. Average annual rainfall and streamflow for each year is given in Table 3-4. It can be observed that both streamflow and rainfall experiences a sudden decrease in 2011/2012 as compared to other years which was marked as an abnormal year. Further, although rainfall in 2010/2011 is slightly more than 2012/2013, the streamflow had increased by 200 mm. There were several points in data set where streamflow was non responsiveness to rainfall. Those points were taken out for scrutiny and were analyzed in detail. This reveals minor inconsistencies in data.

5.2 Loss and Baseflow Method Option Analysis

Selection of appropriate method for simulating precipitation loss and baseflow plays an important role in accurate estimation. Among nine different loss methods available in HEC-HMS for simulating precipitation loss, only Deficit and constant rate method and Soil Moisture Accounting method can be used for continuous hydrological modelling. Same is the case with baseflow methods. Some available methods for simulating baseflow in HEC-HMS can be used only in conjunction with some other loss models such as linear reservoir model can be used only for simulating baseflow when Soil Moisture Accounting is used as a loss model. Two Options with different loss and baseflow method for simulation were used for this study. In Option-1, Deficit and constant loss model was selected as loss model while recession method was selected as baseflow model while in Option-2, Soil Moisture Accounting was selected as loss model with linear reservoir as baseflow model. Model performance of both Options in calibration and validation period are discussed in Section 5.2.1.

5.2.1 Model Performance in Calibration

5.2.1.1 Statistical Goodness of Measure

Value of objective function MRAE along with other two statistical goodness of measures, NASH and Percent Error in Volume for calibration phase is given in Table 4-11. Value of MRAE reduced from 0.38 to 0.31 when Option-2 was used for simulation as compared to Option-1. Value of NASH for overall flow also increased from 0.67 to 0.70 for calibration phase. Percent Error in Volume also showed improvement in calibration phase by shifting toward Option-2 with value reducing from 4.62 to 2.90%. Value of statistical goodness of measures for different categories of flow based on their probability of occurrence, i.e. high, medium and low, are also listed in Table 4-11. Significant improvement can be observed in low flow region where MRAE value reduced from 0.57 to 0.36 whereas in high and medium region, it also showed slight improvement. Percent Error in Volume of each year for Option-1 with simulated and observed runoff coefficient is listed in Table 4-3 while for Option-2, it is in Table 4-6. Highest mass balance error for Option-1 can be observed in 2006/2007 while for Option-2 it is in 2007/2008.

5.2.1.2 Behavior of Simulated Hydrograph

Simulated hydrograph of Option-1 for each year is shown in Figure 4-5 and of Option-2, in Figure 4-8. Significant variation can be observed in simulated hydrograph behavior especially in low flow regions. It can be seen that Option-1 is highly underestimating simulated flow especially during periods where there is no rainfall for long duration. In other regions of flow duration curve, there is no significant difference.

5.2.2 Model Performance in Validation

5.2.2.1 Statistical Goodness of Measure

Value of objective function MRAE along with other two statistical goodness of measures, NASH and Percent Error in Volume for validation phase is given in Table 4-11. Value of MRAE reduced from 0.40 to 0.34 when Option-2 was used for simulation as compared to Option-1. Value of NASH for overall flow also increased from 0.42 to 0.57 for calibration phase. Percent Error in Volume does not show improvement in validation phase by shifting toward Option-2 with value increasing from 11.0% to 14.8 %. Value of statistical goodness of measures for different categories of flow based on their probability of occurrence, i.e. high, medium and low, are also listed in Table 4-11. Significant improvement can be observed in low flow region where MRAE value reduced from 0.53 to 0.41. It also showed good improvement in medium region of flow duration curve where MRAE reduced from 0.37 to 0.30 whereas in high region, it also showed slight improvement by shifting toward Option-2. Percent Error in Volume of each year for Option-1 with simulated and observed runoff coefficient is listed in Table 4-8 while for Option-2, it is presented in Table 4-10. Highest mass balance error for Option-1 can be observed in 2010/2011 while for Option-2 it is in 2012/2013.

5.2.2.2 Behavior of Simulated Hydrograph

Simulated hydrograph of Option-1 for each year is shown in Figure 4-11 and of Option-2, in Figure 4-14. Similar to calibration period, significant variation can be observed in simulated hydrograph behavior especially in low flow regions. It can be seen that Option-1 is highly underestimating simulated flow especially during periods where there is no rainfall for long duration.

5.2.3 Selection of Best Option

Objective function value and hydrograph matching were used as an evaluation criterion for selection of best Option. Objective function value and simulated hydrograph behavior of both Options for calibration and validation phase as discussed in Chapter 5.2.1 and Chapter 5.2.2 resulted in selection of Soil Moisture Accounting as loss model while linear reservoir is selected as baseflow model

Deficit and constant method is unable to represent the real situation as specifying a constant loss rate for entire period of simulation is far from reality as loss rate is dependent on climate condition and antecedent moisture condition. On the other hand, Soil Moisture Accounting takes consideration of all these factors and is capable of simulating both wet and dry conditions which is most likely case in continuous simulation. Movement of water in and above the soil are represented by using five layers in this method. This model estimates the surface runoff, groundwater flow, loss due to evapotranspiration and deep percolation for entire basin. Since our study period is of 6 years consisting of both wet and dry periods with extreme events, Soil Moisture Accounting method for simulating losses is the best possible option.

Baseflow falls rapidly to a lower level for disturbed catchments about 40 % faster than un disturbed catchments (Buytaert et al. 2004). Results showed human induced land use changes and physical characteristics like soils have a strong impact on water resources.

Project area for this research can be classified as an undisturbed catchment with soil having high retention capacity recognized from the behavior shown by outflow hydrograph. Glencorse catchment has a strong baseflow component. The baseflow can be estimated roughly around 45 m^3/sec from outflow hydrograph making around 48% of the annual observed flow. Keeping in view of the nature of soil and baseflow share in streamflow, linear reservoir model for simulating baseflow is the most appropriate method used in conjunction with Soil Moisture Accounting especially for continuous simulation as this combination will allow to preserve mass balance and both loss and baseflow rate can be designed for continuous simulation. Simulation of streamflow of areas having soil with high retention capacity can be achieved only by using linear reservoir model used in combination with Soil Moisture Accounting because it gives the freedom to store water in different layers of soil and draining rate can be specified by the user in order to match the real situation as compared to recession method which does not conserve mass balance and is more appropriate for shorter duration periods; i.e. mainly for events for watersheds where the volume and timing of the baseflow is strongly influenced by the precipitation event itself. Hence, recession method is more suitable for event based simulation or can be used in continuous simulation where main objective is flood management. Since present study is aimed to water resource management, i.e. over all matching of flow, therefore the recession method is not suitable.

5.3 Analysis of Catchment Scale Effect

Comparison of Options resulted in selection of Option-2 as the best Option based on the model performance evaluation. In order to investigate the effect of catchment scale on model performance, the pre-calibrated lumped model was divided into different number of sub divisions. Glencorse catchment was divided into 3, 6, 9 and 16 numbers of subdivisions, respectively. Soil Moisture Accounting and linear reservoir models were used for simulating precipitation loss and baseflow while Clark method was used for transformation. Routing was carried out through lag method.

5.3.1 Calibration Period Results

Value of statistical goodness of measures used for assessing model performance during calibration phase for different number of sub divisions is given in Table 4-20. Model showed good improvement for smaller number of sub divisions during calibration phase. It can be observed that when sub divisions were increased from nine then model performance started decreasing. Major improvement can be seen in high flow region where MRAE reduced from 0.37 to 0.32 when shifted toward nine sub divisions as compared to that of six sub divisions. Value of MRAE reduced from 0.32 to 0.29 on moving toward 3 sub divisions from the lumped one. Improvement in model performance during calibration phase continued up to nine number of sub divisions, after which decrease in model performance can be observed.

5.3.2 Validation Period Results

Objective function MRAE and other two statistical goodness of measures used showed good improvement in validation phase by shifting toward distributed modelling as compared to lumped one but only up to certain number of sub divisions after which model performance started decreasing. Value of statistical goodness of measures used for assessing model performance during validation phase for different number of sub divisions is given in Table 4-20. Value of MRAE increased from 0.28 to 0.30 when shifted toward six to nine sub divisions. Percent Error in Volume also increased from 17.80% to 22.25% on moving toward six to nine sub divisions. NASH also showed a declining behavior with value decreasing from 0.52 to 0.46 during validation phase.

5.3.3 Comparison of Lumped and Distributed Model Performance

Optimum number of sub division was found based on the model performance assessed through objective function value. Variation of objective function value and NASH with different number of sub divisions are shown in Figure 4-36 and Figure 4-37. Number of sub divisions were stopped at sixteen due to increase in model uncertainty with exponential increase in number of parameters and limitation of system power. Distributed model with six number of sub divisions was selected as optimum model layout based on the model performance. Comparison of lumped model with distributed model with six number of sub divisions carried out showed improvement in model performance by shifting toward distributed modelling. Value of objective function MRAE along with other two statistical goodness of measures, NASH and Percent Error in Volume for lumped and optimum distributed model for comparison purpose is given in Table 4-21. Value of MRAE reduced from 0.31 to 0.28 for calibration period and 0.34 to 0.28 for validation phase. Other statistical goodness of measure used, NASH reduced from 0.70 to 0.63 in calibration and 0.57 to 0.52 for validation phase. Major improvement can be observed in low flow region where MRAE reduced from 0.36 to 0.30 in calibration and 0.42 to 0.34 in validation period when compared with lumped model performance.

Moving toward distributed model results in improvement of model performance but high resolution data accompanied with efficient systems are required.

6 CONCLUSIONS

1. HEC-HMS lumped model for two different loss and baseflow models was successfully calibrated and validated for Glencorse watershed.

2. Sensitivity analysis carried out showed impervious area (%) and recession constant to be the most sensitive parameters when deficit and constant method was used as loss and recession method as baseflow method while Groundwater1 coefficient and Groundwater1 percolation parameter to be the most sensitive parameters when Soil Moisture Accounting was used in combination with linear reservoir method for simulating streamflow.

3. Model performance was improved by shifting toward Option-2 (Soil Moisture Accounting (SMA) and Linear reservoir methods as loss and baseflow method) for overall flow and especially in low flow region as compared to Option-1 (Deficit and Constant Method as loss and Recession as baseflow method). Value of objective function MRAE reduced from 0.38 to 0.31 and 0.40 to 0.34 for calibration and verification period respectively while MRAE value reduced from 0.57 to 0.36 and 0.53 to 0.41 for low flows.

4. Soil Moisture Accounting loss method and Linear reservoir baseflow method used in combination with Clark unit hydrograph transformation method was selected as the best combination for simulating streamflow in HEC-HMS.

5. Number of sub divisions improved model performance only up to a certain number after which model performance started decreasing. Six number of sub divisions were identified as the optimum number of sub divisions based on the model performance evaluation.

6. Model performance improved by shifting toward distributed modelling with 6 number of sub divisions as compared to the lumped model with MRAE value for overall flow decreasing from 0.31 to 0.28 for calibration period and 0.34 to 0.28 for validation period.

7 RECOMMENDATIONS

1. Developed lumped and distributed models can be used for water resource management in project area and elsewhere with similar hydrologic characteristics.

2. It is necessary to select the most appropriate method among the different methods available in software for simulating precipitation loss and baseflow in accordance with overall objective of the study.

3. It is essential to consider that watersheds with soils having high retention capacity can be modelled better by using Linear reservoir as baseflow method while Recession method is more suitable for watersheds where the volume and timing of the baseflow is strongly influenced by the precipitation event itself.

4. Automatic parameter optimization should be used but with adequate cauion for optimum calibration of distributed models.

5. Moving toward distributed modelling can increase model performance as compared to the lumped model but it is necessary to have high resolution data and efficient computer systems. Therefore, hydrologic aspects as well as data and resource availability should be considered prior to decision making.

8 REFERENCES

Akbari, S., & Singh, R. (2012). Hydrological modelling of catchments using MIKE SHE. In *2012 International Conference on Advances in Engineering, Science and Management (ICAESM)* (pp. 335–340).

Bisri, M., Limantara, L. M., Prasetyorini, L., & Chasanawati, D. (2017). Application of the Kineros model for predicting the effect of land use on the surface run-off Case study in Brantas sub-watershed, Klojen District, Malang City, East Java Province of Indonesia. *Journal of Water and Land Development*, *35*(1). https://doi.org/10.1515/jwld-2017-0062

Bobba, A. G., Singh, V. P., & Bengtsson, L. (2000). Application of environmental models to different hydrological systems. *Ecological Modelling*, *125*(1), 15–49. https://doi.org/10.1016/S0304-3800(99)00175-1

Buytaert, W., De Bièvre, B., Wyseure, G., & Deckers, J. (2004). The use of the linear reservoir concept to quantify the impact of changes in land use on the hydrology of catchments in the Andes. *Hydrology and Earth System Sciences*, *8*(1), 108–114. https://doi.org/10.5194/hess-8-108-2004

Canfield, H. E., & Goodrich, D. C. (2003). Studies of Scale and Processes in Hydrologic Modeling on the Lucky Hills Watershed. *ResearchGate*. Retrieved from https://www.researchgate.net/publication/255585422_Studies_of_Scale_and_Processes_in_Hydrologic_Modeling_on_the_Lucky_Hills_Watershed

Cheng, S. (2010). The best relationship between lumped hydrograph parameters and urbanized factors. *Natural Hazards*, *56*(3), 853–867. https://doi.org/10.1007/s11069-010-9596-4

Chow, V., Maidment, D., & Mays, L. (1988). *Applied Hydrology* (1 edition). New York: McGraw-Hill Science/Engineering/Math.

Chu, X., & Steinman, A. (2009). Event and Continuous Hydrologic Modeling with HEC-HMS. *Journal of Irrigation and Drainage Engineering*, *135*(1), 119–124. https://doi.org/10.1061/(ASCE)0733-9437(2009)135:1(119)

Costa, M. H., Botta, A., & Cardille, J. A. (2003). Effects of large-scale changes in land cover on the discharge of the Tocantins River, Southeastern Amazonia. *Journal of Hydrology*, *283*(1–4), 206–217. https://doi.org/10.1016/S0022-1694(03)00267-1

Cunderlik, J., & Simonovic, S. (2004). Calibration, Verification and Sensitivity Analysis of the HEC-HMS Hydrologic Model. *Water Resources Research Report*. Retrieved from http://ir.lib.uwo.ca/wrrr/11

Daofeng, L., Ying, T., Changming, L., & Fanghua, H. (2004). Impact of land-cover and climate changes on runoff of the source regions of the Yellow River. *Journal of Geographical Sciences*, *14*(3), 330–338. https://doi.org/10.1007/BF02837414

De Silva, M. M. G. T., Weerakoon, S. B., & Herath, S. (2014). Modeling of Event and Continuous Flow Hydrographs with HEC–HMS: Case Study in the Kelani River Basin, Sri Lanka. *Journal of Hydrologic Engineering*, *19*(4), 800–806. https://doi.org/10.1061/(ASCE)HE.1943-5584.0000846

Diskin, M. H., & Simon, E. (1977). A procedure for the selection of objective functions for hydrologic simulation models. *Journal of Hydrology*, *34*(1–2), 129–149. https://doi.org/10.1016/0022-1694(77)90066-X

Elfert, S., & Bormann, H. (2010). Simulated impact of past and possible future land use changes on the hydrological response of the Northern German lowland “Hunte” catchment. *Journal of Hydrology*, *383*(3–4), 245–255. https://doi.org/10.1016/j.jhydrol.2009.12.040

Eriyagama, N., & Smakhtin, V. (2010). Observed and projected climatic changes, their impacts and adaptation options for Sri Lanka: a review. *International Water Management Institute, Conference Papers*.

Faurès, J.-M., Goodrich, D. C., Woolhiser, D. A., & Sorooshian, S. (1995). Impact of small-scale spatial rainfall variability on runoff modeling. *Journal of Hydrology*, *173*(1–4), 309–326. https://doi.org/10.1016/0022-1694(95)02704-S

Felipe, G., & Baquero, M. (n.d.). DIAGNOSTIC EVALUATION OF WATERSHED MODELS. *ResearchGate*. Retrieved from https://www.researchgate.net/publication/265011220_DIAGNOSTIC_EVALUATION_OF_WATERSHED_MODELS

Gibson S. A., Pak J. H., & Fleming M. J. (n.d.). Modeling Watershed and Riverine Sediment Processes with HEC-HMS and HEC-RAS. *Watershed Management 2010*. https://doi.org/10.1061/41143(394)120

Green, I. R. A., & Stephenson, D. (1986). Criteria for comparison of single event models. *Hydrological Sciences Journal*, *31*(3), 395–411. https://doi.org/10.1080/02626668609491056

Guinot, V., Cappelaere, B., Delenne, C., & Ruelland, D. (2011). Towards improved criteria for hydrological model calibration: theoretical analysis of distance- and weak form-based functions. *Journal of Hydrology*, *401*(1–2), 1–13. https://doi.org/10.1016/j.jhydrol.2011.02.004

Hafezparast, M. (2013). A Conceptual Rainfall-Runoff Model Using the Auto Calibrated NAM Models in the Sarisoo River. *Journal of Waste Water Treatment & Analysis*, *04*(01). https://doi.org/10.4172/2157-7587.1000148

Halwatura, D., & Najim, M. M. M. (2013). Application of the HEC-HMS model for runoff simulation in a tropical catchment. *Environmental Modelling & Software*, *46*, 155–162. https://doi.org/10.1016/j.envsoft.2013.03.006

Helton, J. C., & Davis, F. J. (2002). Illustration of Sampling-Based Methods for Uncertainty and Sensitivity Analysis. *Risk Analysis*, *22*(3), 591–622. https://doi.org/10.1111/0272-4332.00041

Himesh, Rao, & Mahajan. (n.d.). *CALIBRATION AND VALIDATION OF WATER QUALITY MODEL (Cae 1 River)*.

Jiang, L., Chen, Y., & Wang, H. (2015). Urban flood simulation based on the SWMM model. *Proceedings of the International Association of Hydrological Sciences*, *368*, 186–191. https://doi.org/10.5194/piahs-368-186-2015

Kanchanamala, D. P. H. M., Herath, H. M. H. K., & Nandalal, K. D. W. (2016a). Impact of Catchment Scale on Rainfall Runoff Modeling: Kalu Ganga River Catchment upto Ratnapura. *Engineer: Journal of the Institution of Engineers, Sri Lanka*, *49*(2), 1. https://doi.org/10.4038/engineer.v49i2.7003

Kanchanamala, D. P. H. M., Herath, H. M. H. K., & Nandalal, K. D. W. (2016b). Impact of Catchment Scale on Rainfall Runoff Modeling: Kalu Ganga River Catchment upto Ratnapura. *Engineer: Journal of the Institution of Engineers, Sri Lanka*, *49*(2), 1. https://doi.org/10.4038/engineer.v49i2.7003

Krause, P., Boyle, D. P., & Bäse, F. (2005). Comparison of different efficiency criteria for hydrological model assessment. *Advances in Geosciences*, *5*, 89–97. https://doi.org/10.5194/adgeo-5-89-2005

Krysanova, V., Bronstert, A., & MüLler-Wohlfeil, D.-I. (1999). Modelling river discharge for large drainage basins: from lumped to distributed approach. *Hydrological Sciences Journal*, *44*(2), 313–331. https://doi.org/10.1080/02626669909492224

Legates, D. R., & McCabe, G. J. (1999). Evaluating the use of "goodness-of-fit" Measures in hydrologic and hydroclimatic model validation. *Water Resources Research*, *35*(1), 233–241. https://doi.org/10.1029/1998WR900018

Madsen, H. (2000). Automatic calibration of a conceptual rainfall–runoff model using multiple objectives. *Journal of Hydrology*, *235*(3–4), 276–288. https://doi.org/10.1016/S0022-1694(00)00279-1

McCuen, R. H. (1973). The role of sensitivity analysis in hydrologic modeling. *Journal of Hydrology*, *18*(1), 37–53. https://doi.org/10.1016/0022-1694(73)90024-3

Nandalal, H. K., & Ratmayake, U. R. (2016). Event Based Modeling of a Watershed Using HEC-HMS. *Engineer: Journal of the Institution of Engineers, Sri Lanka*, *43*(2), 28. https://doi.org/10.4038/engineer.v43i2.6979

Ondieki, C. M. (1997). [No Title]. *Environmental Monitoring and Assessment*, *45*(3), 285–299. https://doi.org/10.1023/A:1005751331595

Pechlivanidis, I., Jackson, B., McIntyre, N., & Wheater, H. (2011). Catchment scale hydrological modelling: A review of model types, calibration approaches and uncertainty analysis methods in the context of recent developments in technology and applications. *ResearchGate*, *13*(3), 193–214.

Perera, K. R. J., & Wijesekera, N. T. S. (2016). Identification of the Spatial Variability of Runoff Coefficients of Three Wet Zone Watersheds of Sri Lanka. *Engineer: Journal of the Institution of Engineers, Sri Lanka*, *44*(3), 1. https://doi.org/10.4038/engineer.v44i3.6960

Rathod, P., Borse, K., & Manekar, V. (2015a). Simulation of Rainfall -Runoff Process Using HEC-HMS.

Rathod, P., Borse, K., & Manekar, V. L. (2015b). Simulation of Rainfall -Runoff Process Using HEC-HMS. In *ResearchGate*. Retrieved from https://www.researchgate.net/publication/291274149_Simulation_of_Rainfall_-Runoff_Process_Using_HEC-HMS

Razmkhah, H. (2016). Comparing performance of different loss methods in rainfall-runoff modeling. *Water Resources*, *43*(1), 207–224. https://doi.org/10.1134/S0097807816120058

Reed, S., Koren, V., Smith, M., Zhang, Z., Moreda, F., Seo, D.-J., & DMIP Participants, and. (2004). Overall distributed model intercomparison project results. *Journal of Hydrology*, *298*(1–4), 27–60. https://doi.org/10.1016/j.jhydrol.2004.03.031

Roy, D. D., Begam, S., Ghosh, S., & Jana, S. (2013). Calibration and validation of HEC-HMS model for a river basin in eastern India. *ResearchGate*, *8*(1), 40–56.

Rulin, O., Liliang, R., Weiming, C., & Zhongbo, Y. (2008). Application of hydrological models in a snowmelt region of Aksu River Basin. *Water Science and Engineering*, *1*(4), 1–13. https://doi.org/10.3882/j.issn.1674-2370.2008.04.001

S. B. Weerakoon, M. M. G. T. De Silva, & Srikantha Herath. (2014). Modeling of Event and Continuous Flow Hydrographs with HEC–HMS: Case Study in the Kelani River Basin, Sri Lanka. https://doi.org/10.1061/(ASCE)HE.1943-5584.0000846

Sardoii, E. R., Rostami, N., Sigaroudi, S. K., & Taheri, S. (2012). Calibration of loss estimation methods in HEC-HMS for simulation of surface runoff (case study: Amirkabir dam watershed, Iran). *ResearchGate*, *6*(1), 343–348.

Sarkar, A., & Kumar, R. (2012). Artificial Neural Networks for Event Based Rainfall-Runoff Modeling. *Journal of Water Resource and Protection*, *04*(10), 891. https://doi.org/10.4236/jwarp.2012.410105

Singh, W. R., & Jain, M. K. (2015). Continuous Hydrological Modeling using Soil Moisture Accounting Algorithm in Vamsadhara River Basin, India. *Journal of Water Resource and Hydraulic Engineering*, *4*(4), 398–408. https://doi.org/10.5963/JWRHE0404011

Sudheer, K. P., Chaubey, I., Garg, V., & Migliaccio, K. W. (2007). Impact of time-scale of the calibration objective function on the performance of watershed models. *Hydrological Processes*, *21*(25), 3409–3419. https://doi.org/10.1002/hyp.6555

Tang, W. Y., Kassim, A. H. M., & Abubakar, S. H. (1996). Comparative studies of various missing data treatment methods - Malaysian experience. *Atmospheric Research*, *42*(1–4), 247–262. https://doi.org/10.1016/0169-8095(95)00067-4

Tramblay, Y., Bouvier, C., Martin, C., Didon-Lescot, J.-F., Todorovik, D., & Domergue, J.-M. (2010). Assessment of initial soil moisture conditions for event-based rainfall–runoff modelling. *Journal of Hydrology*, *387*(3–4), 176–187. https://doi.org/10.1016/j.jhydrol.2010.04.006

USACE 2000. (n.d.). *United States Army Corps of Engineers, Hydrologic Engineering Centre (USACE 2000), Technical Reference Manual, Davis, California* (No. CPD-74B).

Valent, P., Szolgay, J., & Riverso, C. (2012). Assessment of The Uncertainties of a Conceptual Hydrologic Model By Using Artificially Generated Flows. *Slovak Journal of Civil Engineering*, *(4)*, 35. https://doi.org/10.2478/v10189-012-0020-9

Wagener, T., & Kollat, J. (2007). Numerical and visual evaluation of hydrological and environmental models using the Monte Carlo analysis toolbox. *Environmental Modelling & Software*, *22*(7), 1021–1033. https://doi.org/10.1016/j.envsoft.2006.06.017

Wheater, H. S. (2002). Progress in and prospects for fluvial flood modelling. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and*

Engineering Sciences, *360*(1796), 1409–1431. https://doi.org/10.1098/rsta.2002.1007

Wood, E. F., Sivapalan, M., Beven, K., & Band, L. (1988). Effects of spatial variability and scale with implications to hydrologic modeling. *Journal of Hydrology*, *102*(1–4), 29–47. https://doi.org/10.1016/0022-1694(88)90090-X

Zhang, H. L., Wang, Y. J., Wang, Y. Q., Li, D. X., & Wang, X. K. (2013). The effect of watershed scale on HEC-HMS calibrated parameters: a case study in the Clear Creek watershed in Iowa, USA. *Hydrology and Earth System Sciences Discussions*, *10*(1), 965–998. https://doi.org/10.5194/hessd-10-965-2013

APPENDIX A: STREAMFLOW RESPONSE WITH RAINFALL

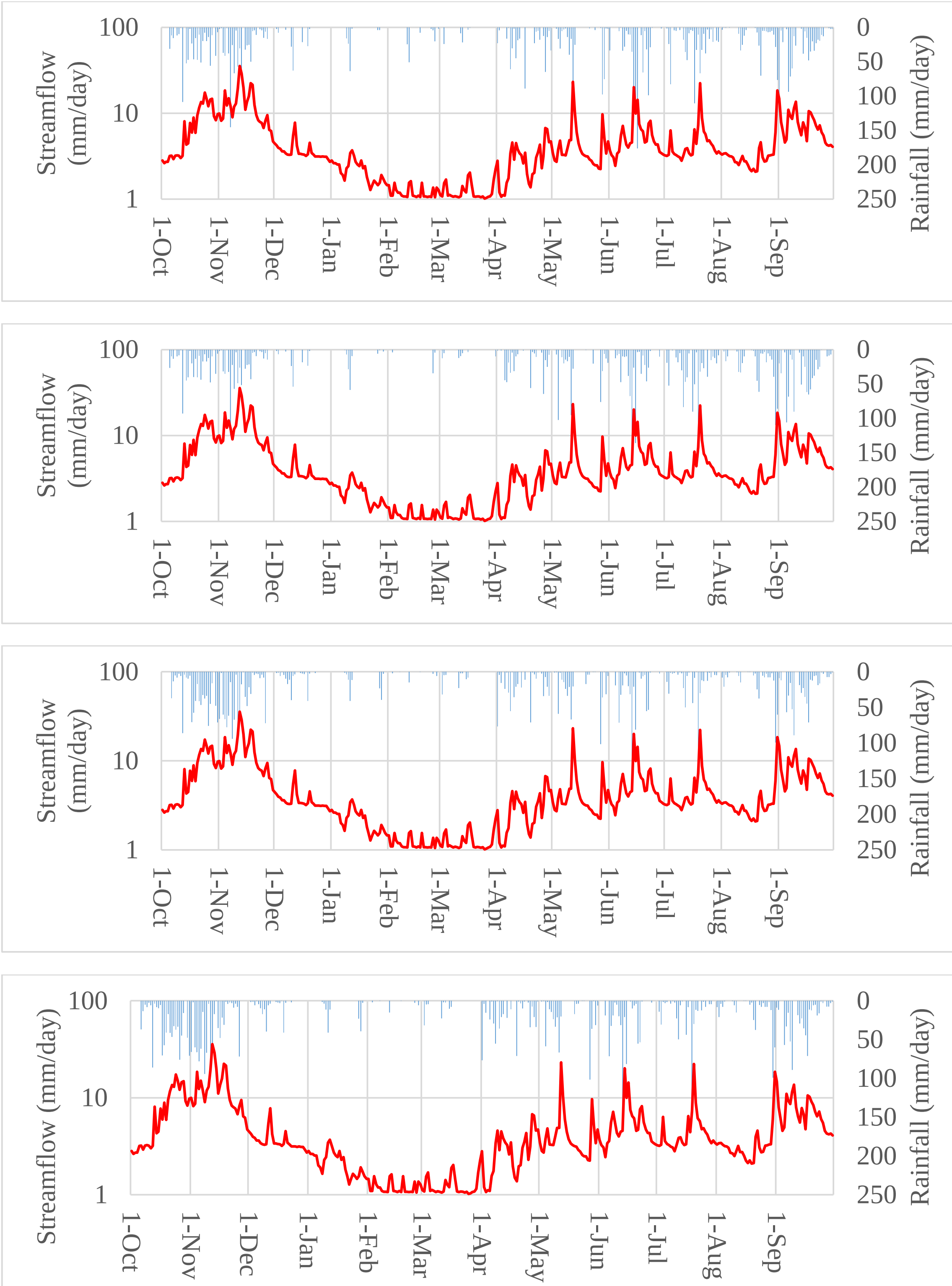


Figure 8-1 Streamflow response of Glencorse with rainfall in 2006/2007

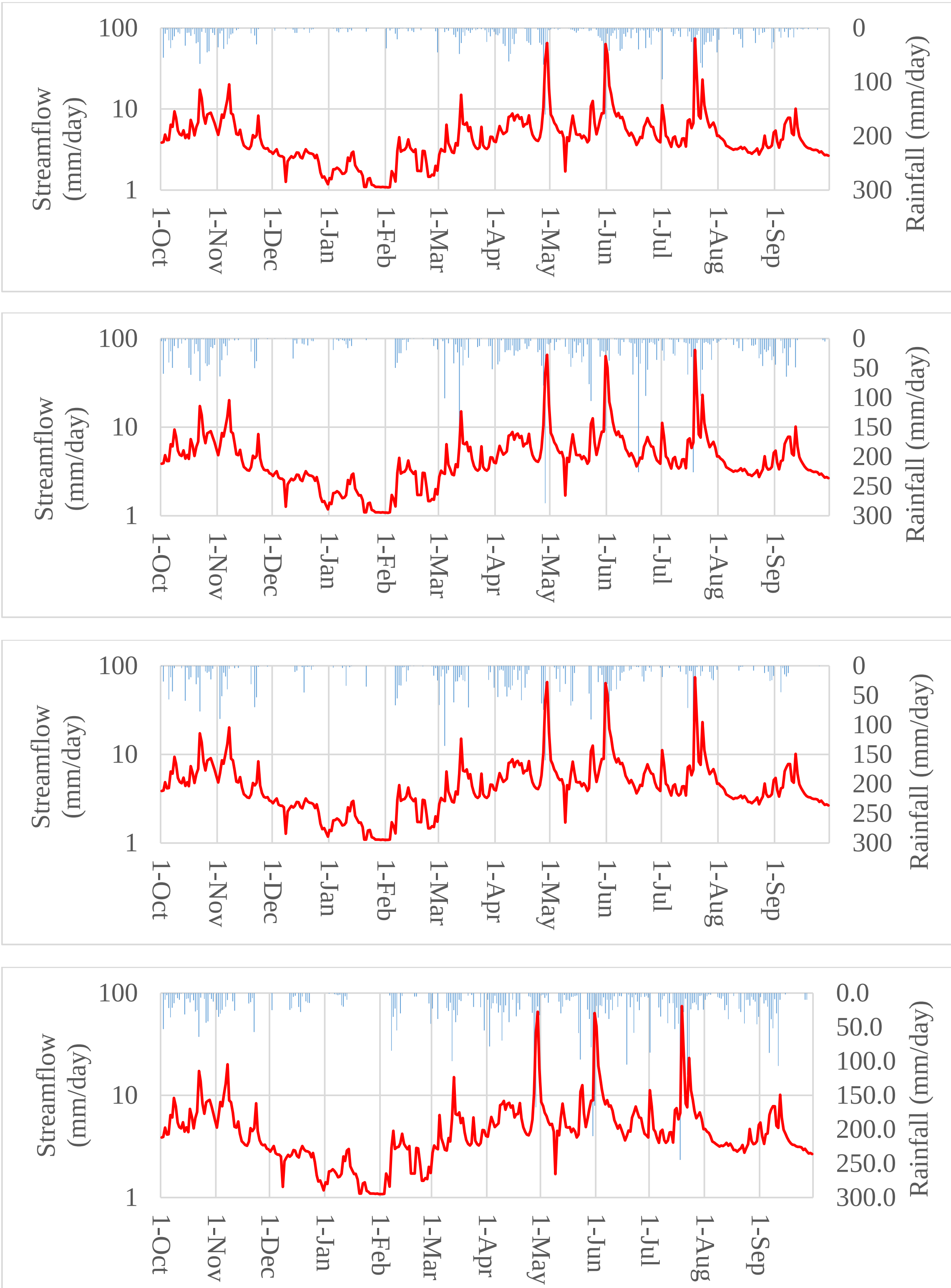


Figure 8-2 Streamflow response of Glencorse with rainfall in 2007/200

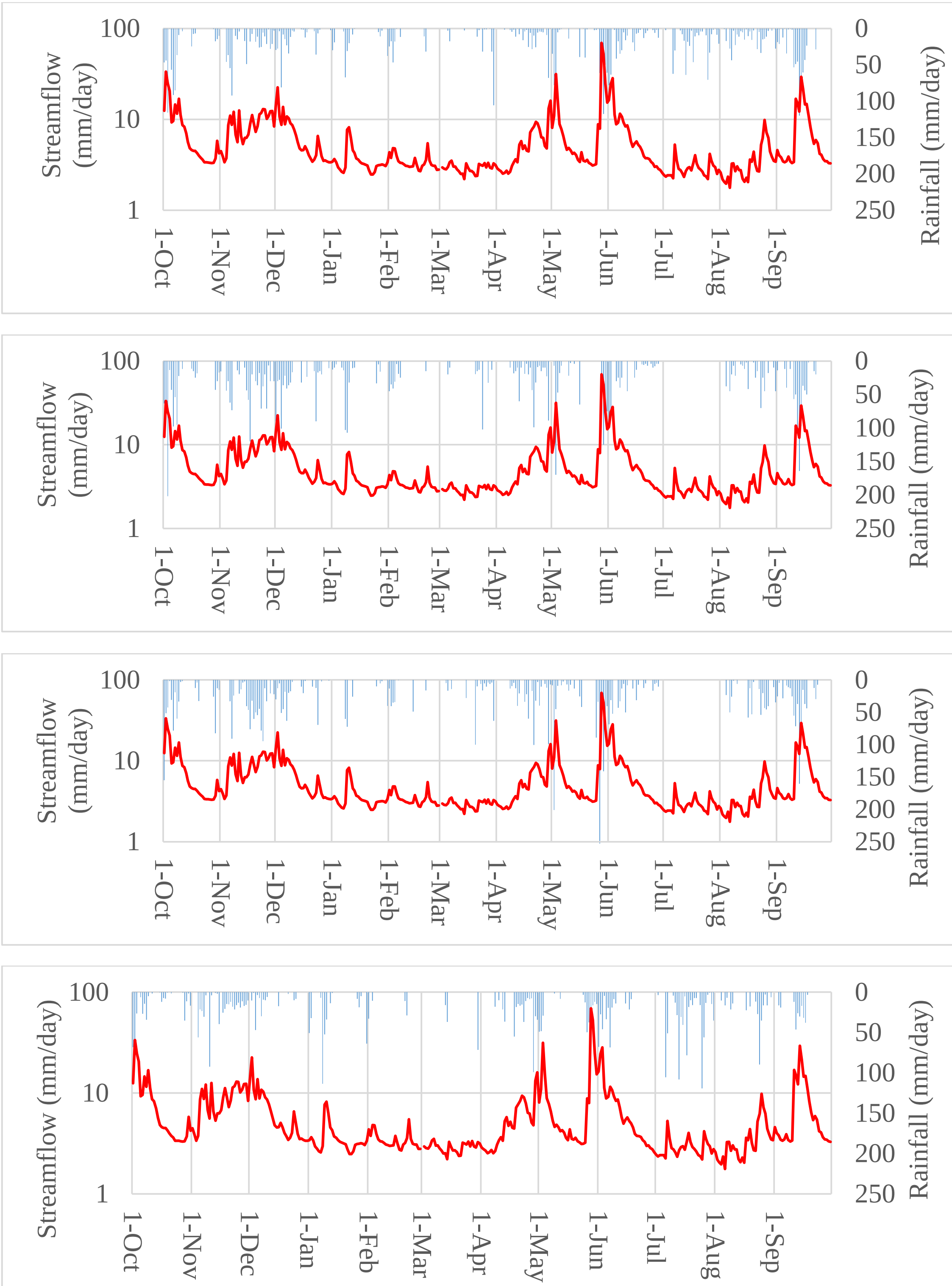


Figure 8-3 Streamflow response of Glencorse with rainfall in 2010/2011

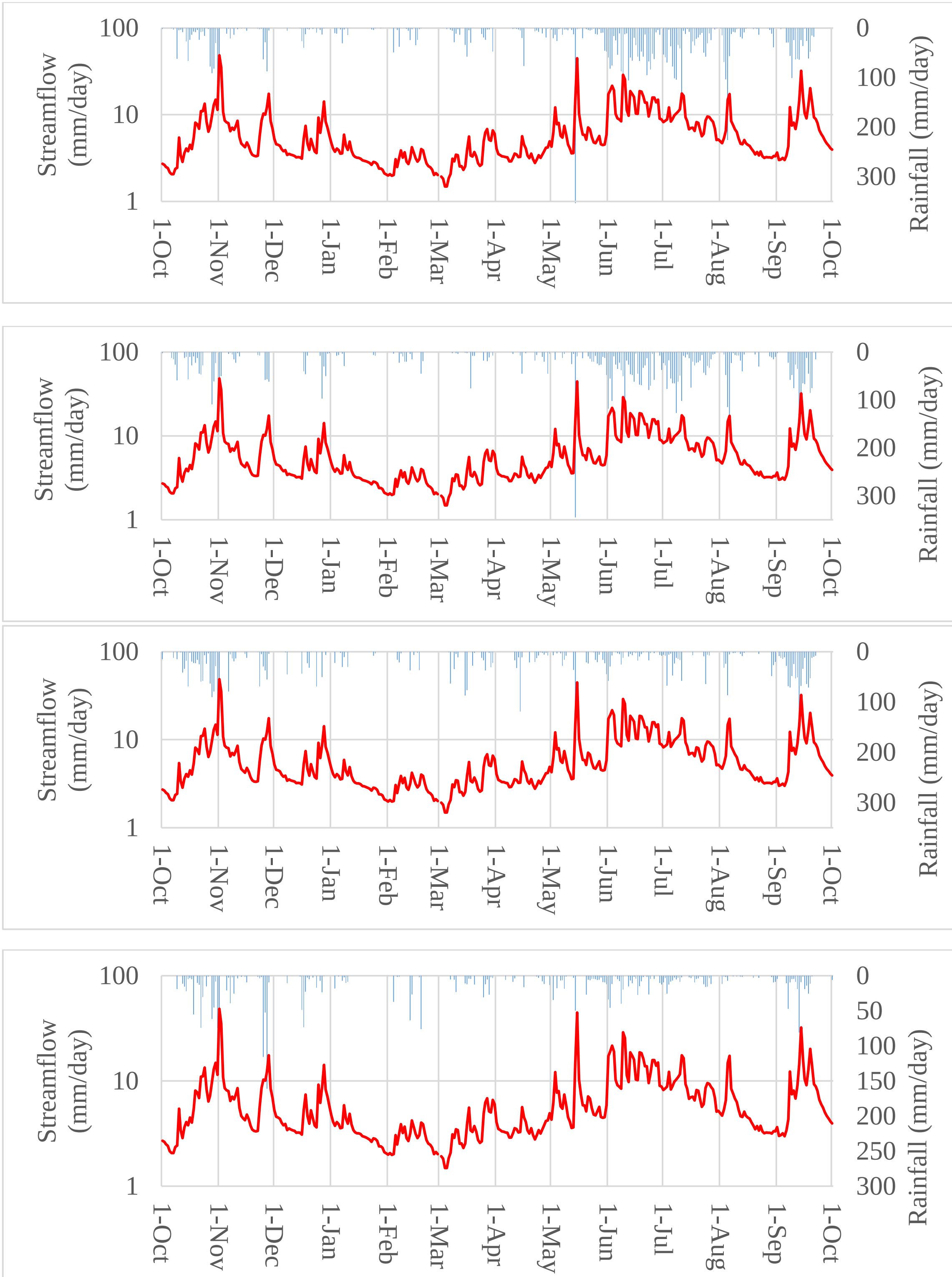


Figure 8-4 Streamflow response of Glencorse with rainfall in 2012/2013

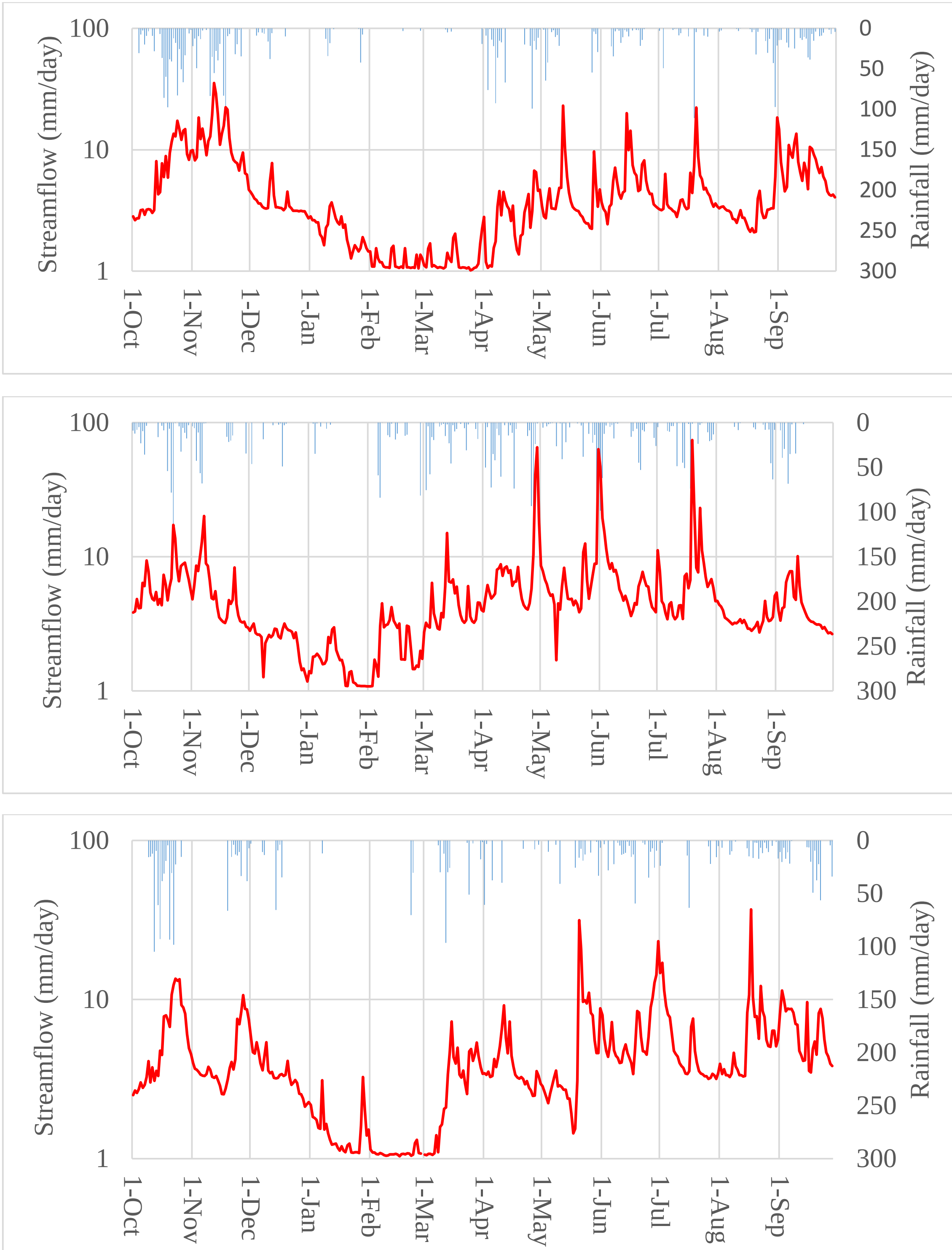


Figure 8-5 Streamflow response with Hanwella rainfall gauging (Calibration period)

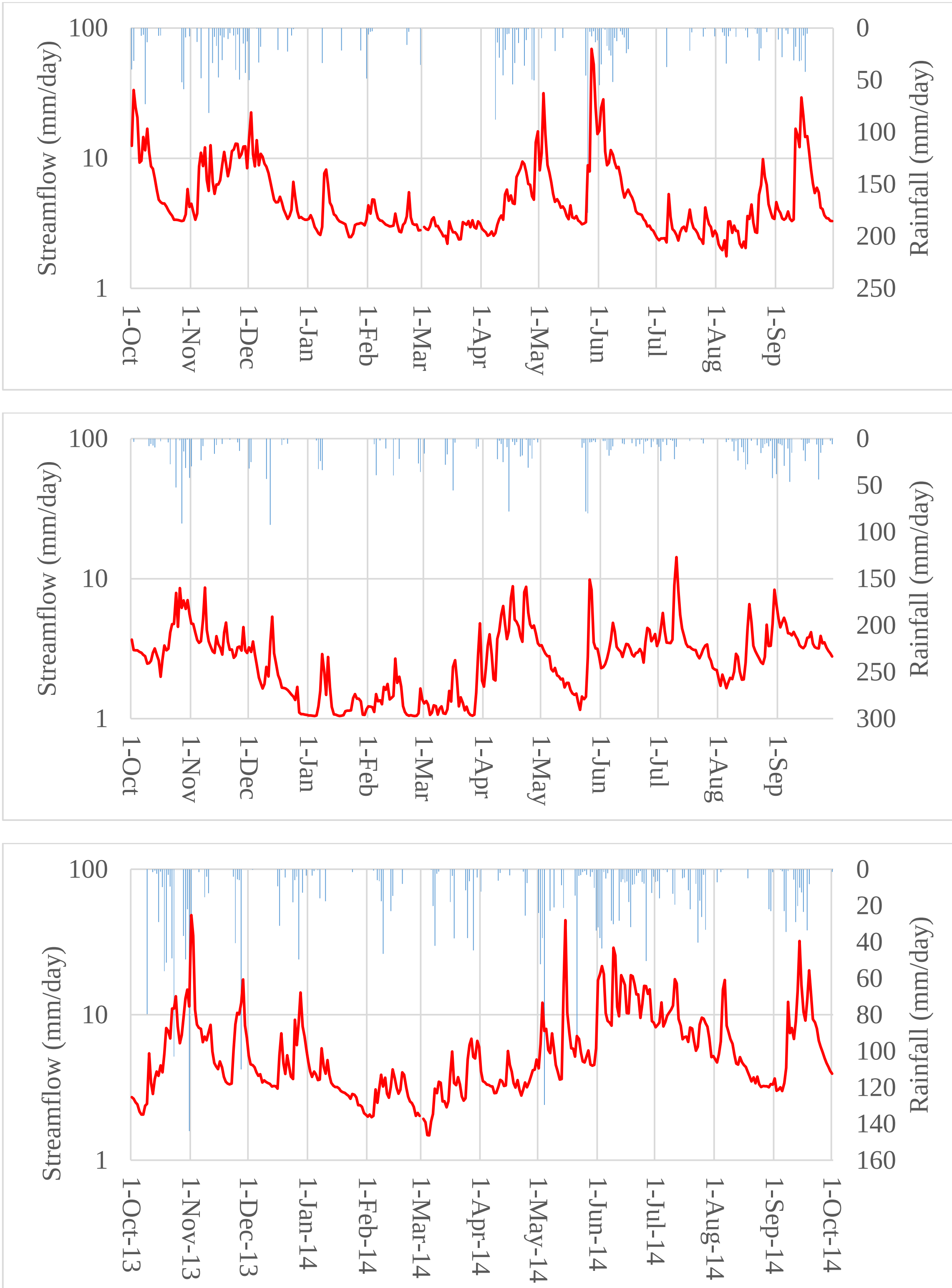


Figure 8-6 Streamflow response with Hanwella rainfall gauging (Validation period)

APPENDIX B: DOUBLE MASS CURVES

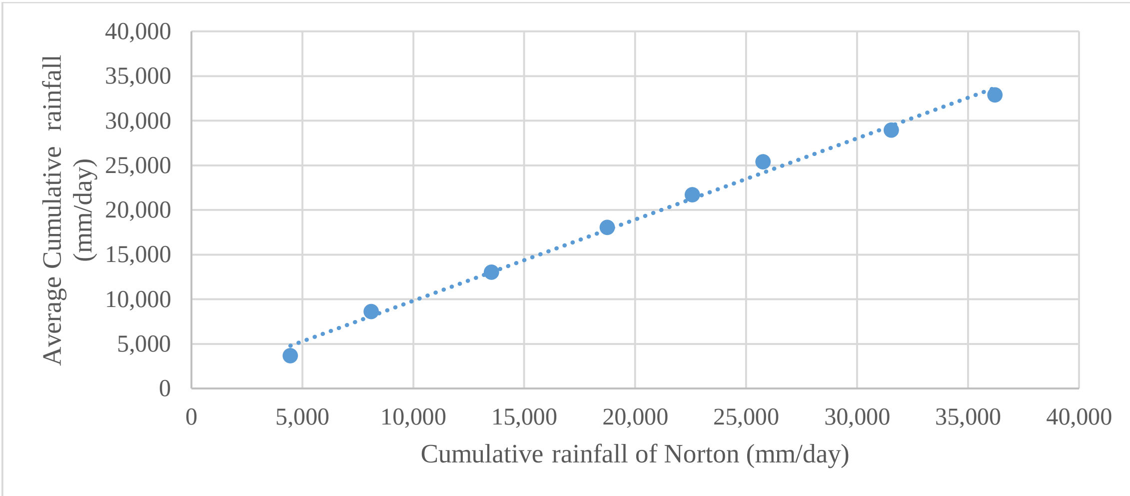


Figure 8-8 Double mass curve - Norton Bridge

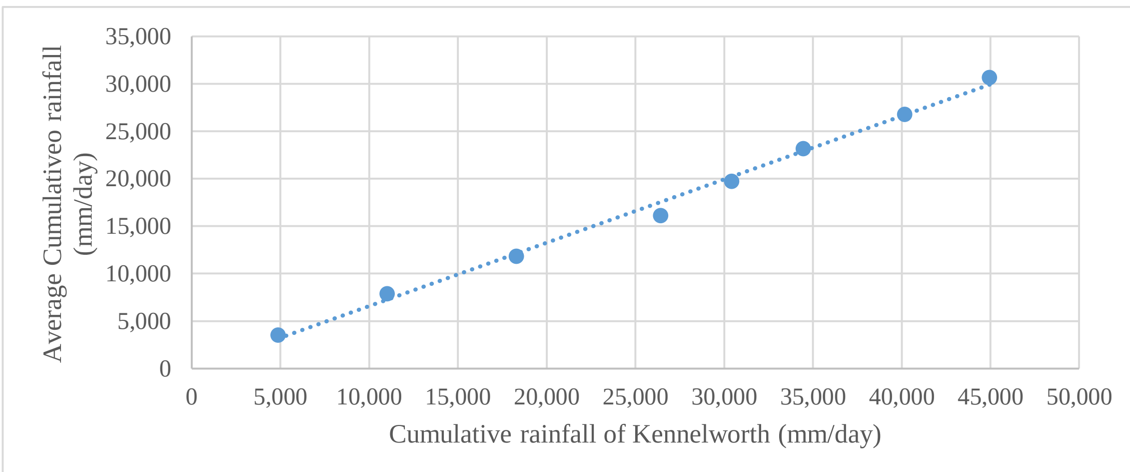


Figure 8-9 Double mass curve - Kennel worth

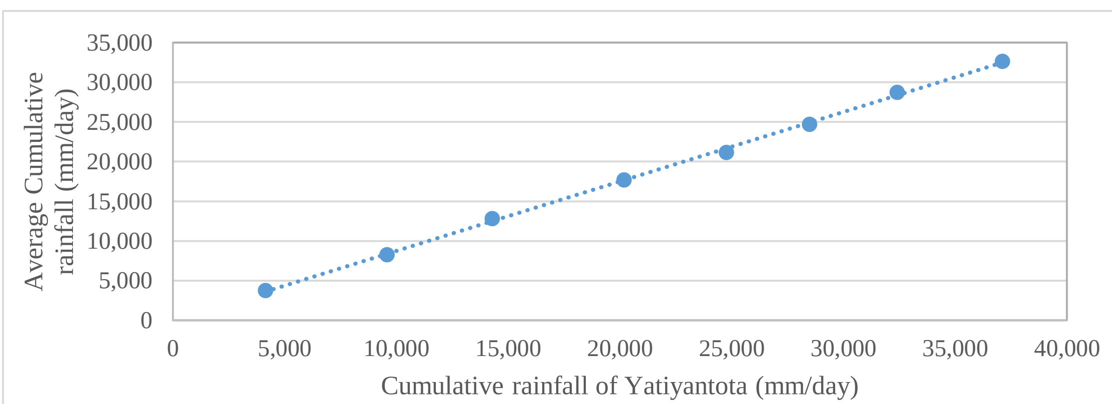


Figure 8-7 Double mass curve - Yatiyantota

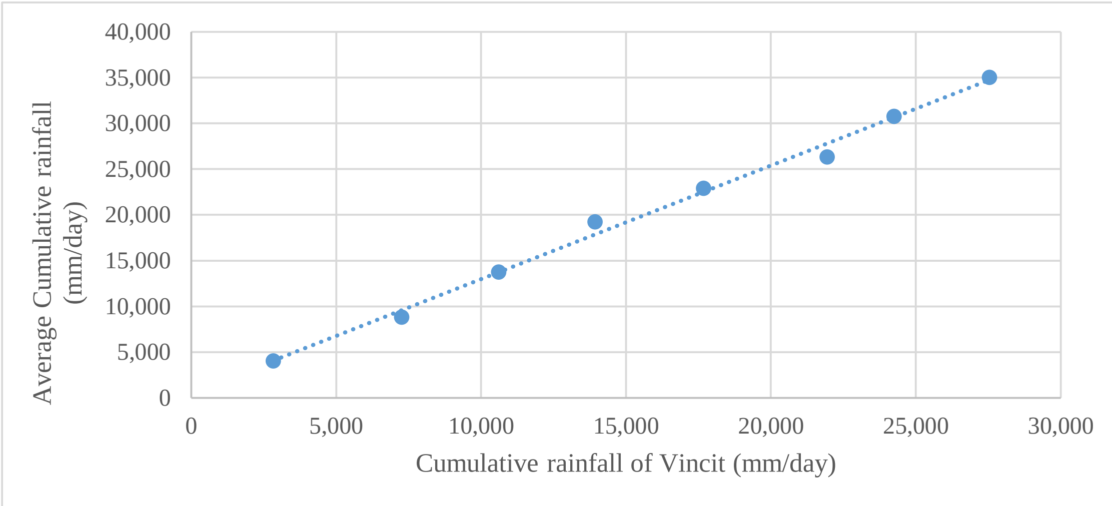


Figure 8-10 Double mass curve-Vincit

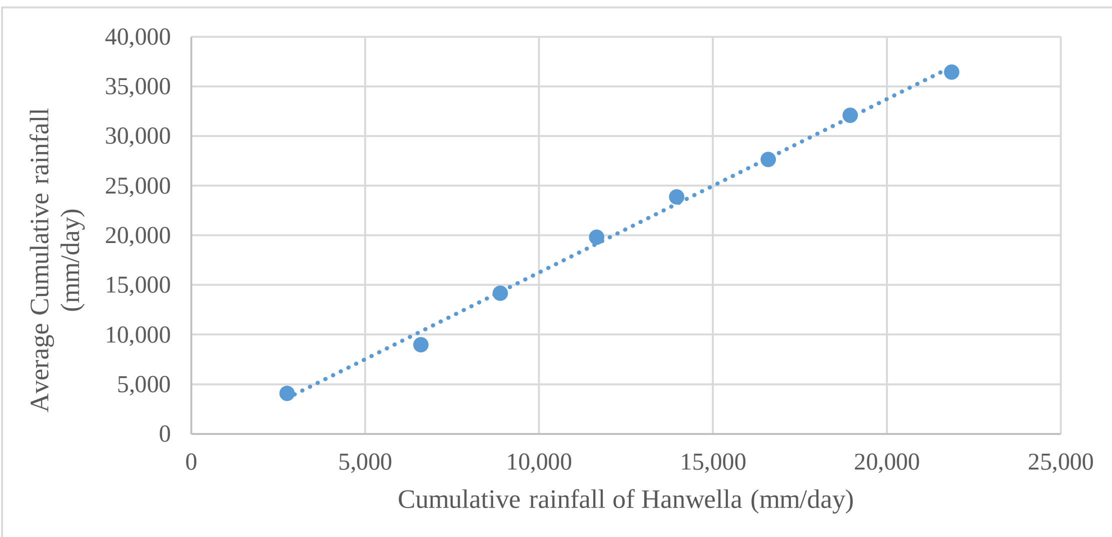


Figure 8-11 Double mass curve-Hanwella

APPENDIX C: BASEFLOW AND DIRECT RUNOFF FROM OPTION-1 AND OPTION-2

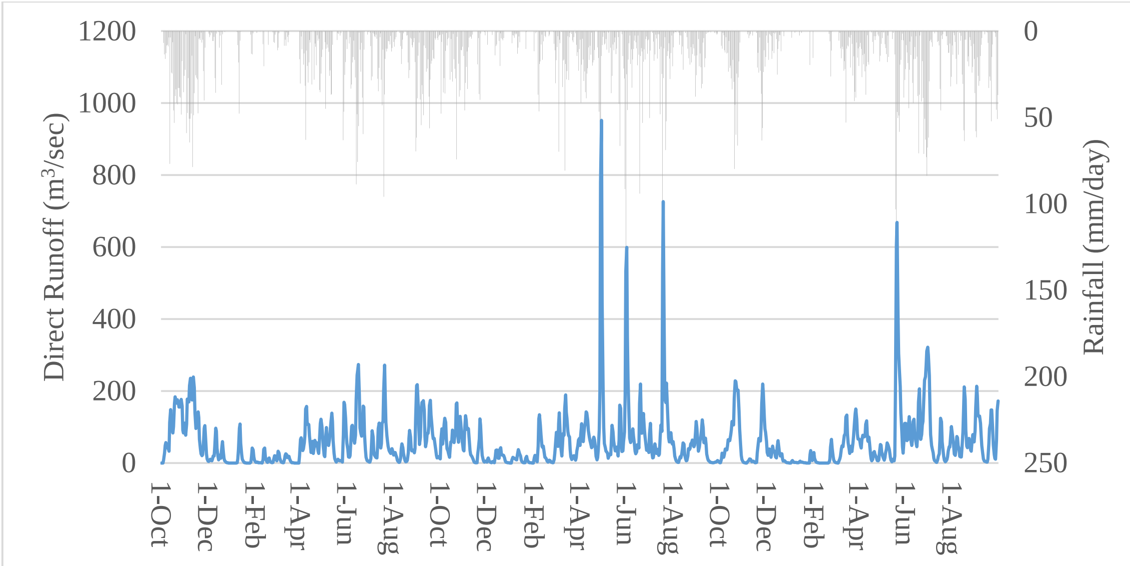


Figure 8-12 Direct runoff from Deficit and Constant method (Calibration period)

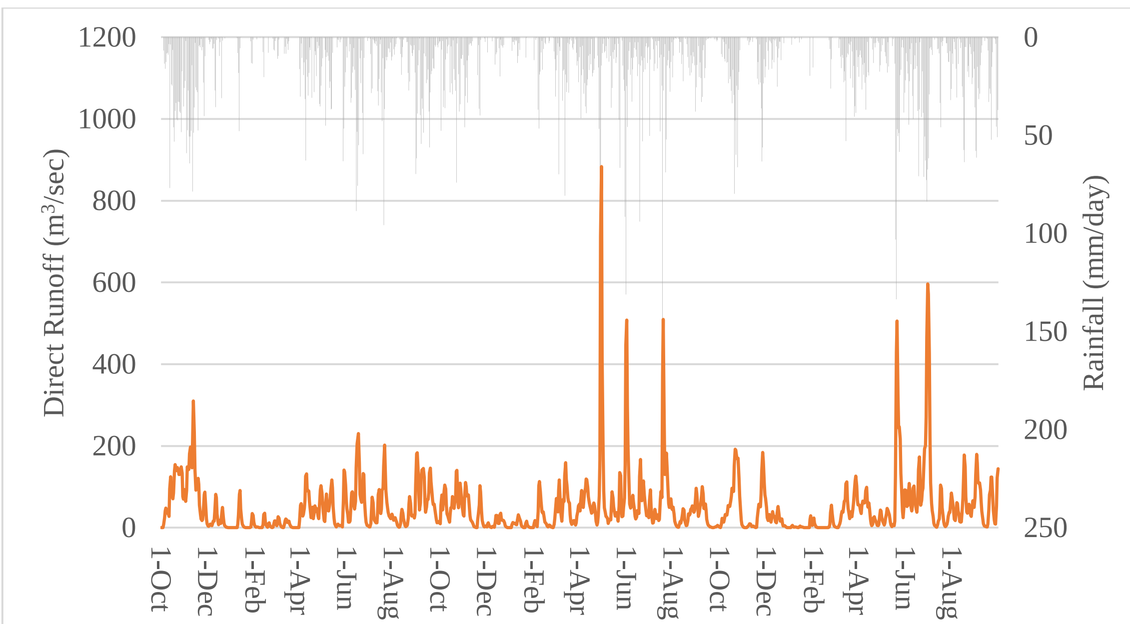


Figure 8-13 Direct runoff from SMA loss method (Calibration period)

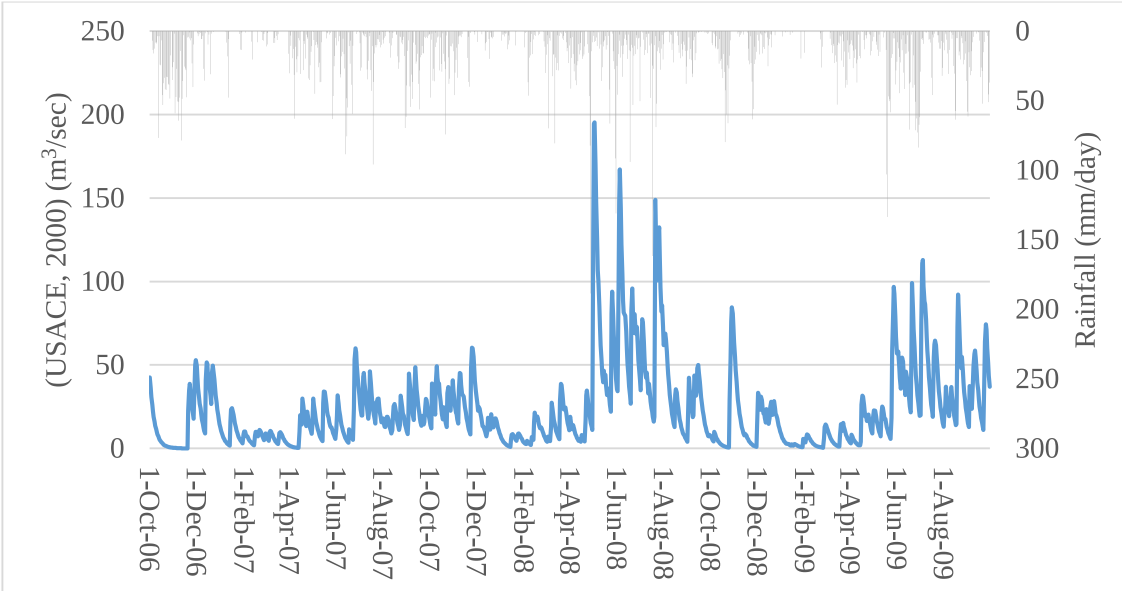


Figure 8-14 Baseflow simulated from Linear reservoir method (Calibration period)

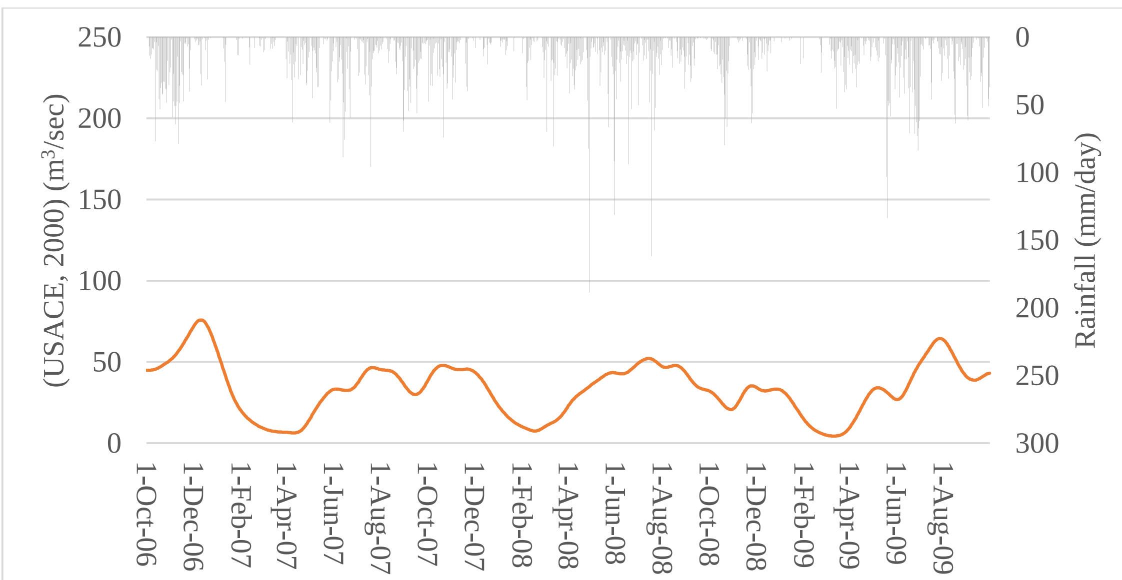


Figure 8-15 Baseflow simulated from Recession method (Calibration period)

APPENDIX D: DISTRIBUTED MODEL THIESSEN WEIGHT

Table 8-1 Thiessen weight of sub basins (3 divisions)

Name of sub basin	Area (km^2)	Thiessen weight			
		Norton	Kennel worth	Yatiyantota	Vincit
Subdivison-1	403.60	0.898	0.101		
Subdivison-2	691.10		0.065	0.524	0.409
Subdivison-3	409.92	0.246	0.228	0.275	0.248

Table 8-2 Thiessen weight of sub basins (6 divisions)

Name of sub basin	Area (km^2)	Thiessen weight			
		Norton	Kennel worth	Yatiyantota	Vincit
Subdivison-1	403.6	0.898	0.101		
Subdivison-2	227.6	0.391	0.364	0.243	
Subdivison-3	225.0		0.201	0.784	0.013
Subdivison-4	323.3			0.566	0.433
Subdivison-5	142.7			0.020	0.979
Subdivison-6	182.2	0.100	0.059	0.315	0.558

Table 8-3 Thiessen weight of sub basins (9 divisions)

Name of sub basin	Area (km^2)	Thiessen weight			
		Norton	Kennel worth	Yatiyantota	Vincit
Subdivison-1	209.70	0.880	0.110		
Subdivison-2	193.92	0.910	0.080		
Subdivison-3	227.60	0.391	0.364	0.243	
Subdivison-4	137.40		0.274	0.707	0.017
Subdivison-5	87.57		0.087	0.904	0.007
Subdivison-6	323.33			0.566	0.433
Subdivison-7	59.84			0.048	0.951
Subdivison-8	82.89				1.000
Subdivison-9	182.2	0.066	0.059	0.315	0.558

Table 8-4 Thiessen weight of sub basins (16 divisions)

Name of sub basin	Area (km^2)	Thiessen weight			
		Norton	Kennel worth	Yatiyantota	Vincit
Subdivison-1	209.7	0.880	0.120		
Subdivison-2	193.9	0.920	0.080		
Subdivison-3	110.1	0.740	0.260		
Subdivison-4	42.1		0.840	0.160	
Subdivison-5	62.5		0.600	0.400	
Subdivison-6	87.5		0.090	0.910	
Subdivison-7	96.4			0.800	0.20
Subdivison-8	226.9			0.470	0.53
Subdivison-9	27.0				1.00
Subdivison-10	87.6				1.00
Subdivison-11	32.7			0.080	0.92
Subdivison-12	74.8			0.970	0.03
Subdivison-13	61.0			0.350	0.65
Subdivison-14	48.5				1.00
Subdivison-15	75.3	0.090	0.260	0.645	
Subdivison-16	68.2	0.177	0.158	0.527	0.136