POTENTIAL OF PARAMETER TRANSFERABILITY WITHIN A RIVER BASIN TO PREDICT DAILY STREAMFLOW IN UNGAUGED CATCHMENTS; CASE STUDY FOR UPPER NILWALA RIVER BASIN

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July 2020

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

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DECLARATION

I declare that this is my own work and this thesis does not incorporate without 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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The above candidate has carried out research for the Masters thesis under my supervision.

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Professor N.T.S.Wijesekera   Date

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ACKNOWLEDGEMENT

First and foremost, I am deeply indebted to my research supervisor Professor N.T.S. Wijesekera, Senior Professor Overall Program Director, UNESCO Madanjeet Singh Center for South Asia Water Management (UMCSAWM), the University of Moratuwa for his immense support throughout my study with his patience and knowledge. His challenging questions and constructive feedback were beneficial for me to remain on the correct path until the completion. Without his encouragement, motivation and continuous guidance, my thesis would not be a success.

Next, I would like to convey my thanks to the course coordinator Dr R.L.H.L. Rajapakse for extending all the necessary help and guidance throughout the postgraduate degree period. He was kind enough to provide help and support with his busy schedule. His sincere and consistent encouragement is greatly appreciated.

Further, I am grateful to the all-academic and non-academic staff of the University of Moratuwa for their guidance and support during this period. I should thank all my colleagues with whom I worked together, struggled together and solved the most critical issues together. They have supported me during my research period as well as during the lecture series.

I also extend my sincere thanks to my employer, National water supply and drainage board, Sri Lanka for inspiring me to develop my academic career.

Finally, I would like to convey my heartfelt gratitude and love to my husband, my family, and friends for providing me with the unfailing support and continuous encouragement throughout this achievement.

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ABSTRACT

Potential of Parameter Transferability within a River Basin to Predict Daily Streamflow in Ungauged Catchments; Case Study for Upper Nilwala River Basin

Water scarcity is being exacerbated by population growth, urbanization, industries and climate change amplifies the prevailing circumstances. Scarcity of water creates the necessity for sustainable water resource planning and management using reliable information and representative models. Since most catchments are ungauged, estimation of streamflow is a challenge faced by hydrologic engineers. Parameter transferability is being investigated by the researchers as a tool to address the issue. In that case, a process-based hydrologic model with daily temporal resolution generates more hydrologically acceptable, accurate catchment response model parameters by which information is provided for hydrological process-based management decisions. Among the many approaches, it is essential to investigate the potential of parameter transferability between sub-watersheds of a river basin to deliver small watersheds wise management decisions. The objective of this study is to evaluate the potential of parameter transferability between main catchment and sub-catchment to estimate daily streamflow by developing a HEC-HMS model for Pitabaddara and Urawa watershed in the Nilwala river basin.

HEC- HMS model was developed for Pitabaddara and Urawa watersheds by using topographical data and daily hydrologic data for water years from 2009/2010 to 2017/2018. Optimal model parameter sets were identified by semi-automatic optimization using Root Mean of Square Error as the objective function. Results were evaluated by selecting model performance criteria as, MRAE, sorted and unsorted FDC, annual water balance, streamflow hydrographs for total and high, intermediate and low flow regimes. Further, identified optimal parameter sets were verified through fully automatic model optimization. Then the sets of optimal parameters were transferred using temporal, spatial and spatiotemporal transfer schemes and model performance was assessed. Further, the potential of predicted streamflow for water resource management at various time resolutions such as annual, seasonal, monthly and daily was investigated.

Both models for Pitabaddara and Urawa calibrated with 3.2 mm/day and 4.36 mm/day RMSE values. However, surprisingly validation result was better in Urawa than calibration with a 3.25 mm/day error value for RMSE. There is an acceptable agreement in simulated and observed flow hydrographs except for extreme hydrological conditions such as drought and flood. Also model was not able to capture low flows at an acceptable level compared to high and intermediate flows due to the fewer number of parameter of selected one-layer precipitation loss model. Transformation of sub-catchment model parameters to the main catchment exhibits high performance than transferring of main catchment model parameters to sub-catchment. The spatial parameter transfer approach is the best way to predict streamflow in both catchments with regards to streamflow magnitude and its sequences and highly performed flow regime is intermediate flow with 95% and 82% of accuracy respectively for Pitabaddara and Urawa catchments. The spatial transfer scheme was capable of capturing streamflow for 84% and 88% of average accuracy level in Maha & Yala season at Pitabaddara. For Urawa catchment, the temporal transfer could provide an average of 91% and 71% when in predicting streamflow volume for Yala and Maha season respectively for seasonal water resource management. Also, the credibility of parameter transfers schemes, spatial, temporal and spatiotemporal is subjective to the objective of the application and temporal resolutions.

Key Words
parameter transferability, ungauged catchment, HEC HMS, Sri Lanka

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LIST OF ABBREVIATIONS

Abbreviation	Description
AWB	Annual Water Balance
AWBE	Annual Water Balance Error
CN	Curve Number
FDC	Flow Duration Curve
IDW	Inverse Distance Weighted
MRAE	Mean Ratio of Absolute Error
MSL	Mean Sea Level
RF	Rainfall Only
RMSE	Root Mean of Square Error
SCS	Soil Conservation Service
SF	Streamflow
WB	Water Balance
WMO	World Meteorological Organization

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1 INTRODUCTION

1.1 Hydrologic modelling for parameter transferability

Water scarcity is being exacerbated by population growth, urbanization, industrialization and climate change amplifies the prevailing circumstances. The scarcity of water creates the necessity for sustainable water resource planning and management using reliable information and representative models.

However, since most of the catchments are ungauged or poorly gauged and have incomplete runoff records (Mango, Melesse, McClain, Gann, & Setegn, 2011), there is a huge challenge in front of water resource planners, managers and decision-makers to carry out realistic streamflow estimations (Zelelew & Alfredsen, 2014). The use of models in ungauged catchments requires the determination of parameters using various methods. The usual method is to transfer parameters either from the works done for nearby watersheds or use material of similar work cited in other literature.

The literature discusses many methods used to transfer parameters between watersheds, including temporal or spatial or spatiotemporal schemes (Patil & Stieglitz, 2015; Kim & Kaluarachchi, 2008; Bárdossy, 2007; Samuel, Coulibaly, & Metcalfe, 2011a; Z. Zhang, Wagener, Reed, & Bhushan, 2008). Kim and Kaluarachchi (2008) identified different response mechanism of catchments that generates poor performance in parameter transferability. Patil and Stieglitz (2015) recommended having further research on the spatiotemporal parameter transfer method.

1.2 Process-based hydrologic model

Selection of the appropriate hydrological models over the hydrological application is one of the challenges faced by the hydrological community due to the unavailability of an exact guideline (Marshall, Nott, & Sharma, 2005). The usual hydrological modelling approach is chosen to take into account the complexity of the particular problem, the availability of data and the need to address the required precision (Chandra, Rao, András, Tian, & Chih-Ming, 2000). Process-based models are

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developed in the form of mathematical equations that include the hydrological process, precipitation, evaporation, infiltration, transpiration, etc. taking into account the principles of mass, momentum, energy, etc. to evaluate process control options (Chandra et al., 2000). On the other hand, lumped models are simpler, but conceptualizations are normally based on reality with less representative of the known physics. Development of process-based modelling has been initiated to minimize or overcome deficiencies such as the incapability to identify spatially distributed parameters which have a physical significance and requirement of an extensive hydrological record for calibration, encountered in lumped conceptual models (Abbott, Bathurst, Cunge, O'Connell, & Rasmussen, 1986).

1.3 Temporal resolution in streamflow modelling

Monthly and daily models contribute to a varied degree of simulation success. Hydro-meteorological data are usually collected at the daily temporal resolution, but more easily accessible data are at a monthly scale. When compared with monthly data, the processing of daily data is relatively easy because of the absence of aggregation effects on rainfall and streamflow over approximately 30days. Hence model outputs of daily scale accumulated to monthly values can be considered more reliable than monthly resolution outputs from a monthly (Hughes, 1995).

Xu and Singh (1998) state that hydrologic modelling using daily data improves estimates of hydrologic processes as evapotranspiration, interception, infiltration, and depression storage. Therefore, the daily model generates accurate model parameters at a finer resolution, which in turn depicts a more hydrologically acceptable and accurate catchment response.

1.4 Streamflow Transferability for Hydrologic modelling

The regionalization of hydrology has been progressive when the necessity of prediction of streamflow in an ungauged catchment is increasing among hydrologic communities. He, Bárdossy, and Zehe (2011) classified regionalization techniques into two types, (1) estimate parameters of streamflow statistics, flood quantiles (2) estimate

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parameters through a hydrological model simulating continuous flow or approximation continuous flow without a model.

Wijesekera (2013) carried out a study for the development of a mini-hydropower system using the head of Bopath Ella. Due to the unavailability of streamflow data at Bopath Ella gauged adjacent Deraniyagala catchment data were extrapolated to the ungauged catchment. Missing flow data of the catchment had been filled using a mathematical watershed model based on the Sugawara's Tank Model.

Potential of parameters transferability of wet and steep slope basins to wet and moderate slope basins was revealed by Hunukumbura, Tachikawa, and Shiiba (2012) by developing OHDIS-kwmss, distributed hydrological model for the Upper Kotmale basin in Sri Lanka, Illinois basin in the US, and the Mae Chaem basin in Thailand.

The best way to advance the efficiency of regionalization is by formulating the basic physical relationships between watershed model parameters and watersheds distinctive (Fernandez, Vogel, & Sankarasubramanian, 2000). Physic based models provide one of the best approaches to incorporate the aforesaid requirement to the hydrologic model (He et al., 2011).

Heuvelmans, Muys, and Feyen (2004) identified reasonable performance on transferring semi-distributed SWAT model parameters within the catchment and neighboring catchment. Further, studied depicts that special consideration is needed for simulation of low flows when transferring parameters to a region with different topography, soil and land use.

Nepal, Flügel, Krause, Fink, and Fischer (2017) carried out a study to assess the potential of spatial transferability of model parameters derived from J2000, process-based model to neighboring catchment, selecting two glaciated sub-watersheds of Koshi river basin in eastern Nepal. They concluded transferability of J2000 model parameter is viable for the Koshi river basin with similar topographic landscape features and noted underestimation of the peak flow of the model. Further, model output was within the range of the parameter uncertainty band.

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The regionalization process is intrinsically tangled with catchment attributes like physiographic information. Therefore, identification of best approaches for regionalization for the interested area is carrying out specific studies with a process-based hydrologic model (Razavi, Coulibaly, & Asce, 2012b).

1.5 Hydrologic modelling in the Nilwala river basin

Nilwala River is one of the several major rivers in the wet zone of Sri Lanka which regularly undergoes floods and water resource management issues. Wijesekera, Imbulana, and Neupane (2005) named Nilwala River as one of five rivers vulnerable to flooding. The steep gradient in the wet zone opening out into flood plains of the river noted for its flood hazard and the trend of increasing the food level has been identified by the studies.

Mungai, Ong, Kiteme, Elkaduwa, and Sakthivadive (2004) studied changes in total water yield in the Nilwala river basin considering the variation of annual runoff due to changes in land use and rainfall pattern.

Nevertheless, there is a lack of published studies carried out for the Nilwala basin to estimate daily streamflow in ungauged sub-watersheds for water resource planning and management.

1.6 Problem statement

In summary, the literature reveals the challenge faced by the hydrological community due to incapability to quantify streamflow in ungauged or poorly gauged catchments for sustainable water resource management and planning. Therefore, investigation of the potential of parameter transferability within a river basin to estimate streamflow in an ungauged catchment, deploying processed based hydrologic model parameters is a better solution to overcome the issue for a considerable extent.

Accordingly, the Nilwala river basin was selected due to the availability of data at finer resolution and lack of published studies, to derive reliable hydrological model

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parameters in finer (daily) resolution to represent more hydrologically acceptable and accurate catchment response.

Among many options for process-based hydrological models, HEC-HMS is one of popular hydrologic software being practiced by water engineers and it is freely available software with a high level of technical assistance. Therefore, HEC-HMS 4.3 was selected to assess the potential of parameter transferability within Nilwala river basin for daily streamflow estimation for sustainable water resource management and planning.

1.7 Objectives

1.7.1 Overall Objective

Evaluate the potential of the transferability of parameters between the main and sub-basin, developing a HEC-HMS model for Pitabaddara and Urawa watershed in Nilwala river basin to estimate daily streamflow for planning and sustainable management of water resources.

1.7.2 Specific Objectives

1. State of the art analysis of process-based hydrological models for parameter transferability
2. Preparation of meteorological data – the selection of the proper gauging station, data collection, data checking, and verification
3. Develop, calibrate and validate continuous HEC – HMS model for Pitabaddara and Urawa watersheds with calibration and verification
4. Transfer calibrated model parameters of the HEC-HMS model between Pitabaddara main watershed and Urawa sub-watershed.
5. Recommendation on the applicability of the transferability of the parameter in the HEC-HMS model to estimate river flows within an ungauged watershed for water resource management and planning.

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2 LITERATURE REVIEW

2.1 Hydrologic model

Devia, Ganasri, and Dwarakish (2015) define a hydrological model as " a set of equations that helps in the estimation of runoff as a function of various parameters used for describing watershed characteristics". The purpose of hydrologic modelling is to provide information to support decision making, water resource planning, management and designing. For aforesaid objectives, understanding of the variation of catchment yield in temporal and spatial, estimation of water availability concerning the relative contribution of individual catchments, estimation and prediction catchment response about natural and anthropogenic activities, etc. are involved (Vaze, Jordan, Beecham, Frost, & Summerell, 2011).

Generally, hydrological models are presented by the given formula (Singh, 2018).

$$O = f\,(I, P, t) + \varepsilon$$

Where,

O is an n × k matrix of hydrologic responses to be modeled

f is a collection of/ functional relationships

I is an n × m matrix of inputs

P is a vector of p parameters

t is time

ε is an n × k matrix of errors

n is the numbers of data points

k is the number of responses

m is the number of inputs

Responses "*O*" may be a range from a single number, for an instance a runoff volume, peak flow, to a continuous record of flow, soil water content, evaporation, etc. Model classification refers to the nature of "*f*". In general, "*I*" represents inputs, which are varying temporal and spatial whereas "*P*" denotes coefficients particular to a watershed, which estimated from correlations, observed data, etc. *ε*, represents the

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difference between what occurs, "*O*" and what the model predicts "*Op*" (A. Singh, 2018).

2.2 Type of hydrologic models

The Classification of the hydrological models depends on the model focus, model inputs and parameters, and physical model coverage (Devia et al., 2015). Sitterson et al. (2017) classify hydrological models to empirical, conceptual and physical (process) models based on the structure of the model and, lumped, semi-distributed and distributed based on the model's catchment area. Hydrological models can be broadly classified on various topics as shown in Table 2-1.

Table 2-1:Classification of hydrologic model

Source : (V. P. Singh, 1992)

Sr. No	Theme of modelling	Model type
1	Physical process representation	Conceptual or Physical based model
2	Input / outputs	Deterministic, Probabilistic, Stochastic
3	Geometry or spatial variables	Lumped or disbursed
4	Relationship between variables	Linear, non -linear, empirical or data-driven
5	Time of simulation	Continuous or event-based

Empirical models (data-driven model) use non-linear statistical relationships between inputs & outputs. The behavior of observation oriented is seeking to characterize system response from existing data and input accuracy is a key component to be concerned (Kokkonen, Koivusalo, & Karvonen, 2001). The simplicity of model facilitates to develop model easily for the ungauged watersheds, assigning physical and climatic representatives of the catchment to model parameters by regional analysis (Pechlivanidis, Jackson, Mcintyre, & Wheater, 2011a). However, Wheater (2002) states that dependency on available data causes to generating results lacking in the proper specification of assurance limits by the empirical model.

The conceptual rainfall-runoff model consists of basic components of typical hydrological processes which represent reservoirs. Those reservoirs recharge from

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rainfall, percolation, infiltration, etc. and emptied by runoff, evaporation, etc. (Devia et al., 2015). Conceptual models are popular among modelling community because of their easiness to use and calibration. These models are not appropriate where in detail catchment characteristics are required due to lack of physical meaning in governing equations and parameters (Sitterson et al., 2017).

The physical models are developed considering several physical laws like conservation of momentum, mass, and energy. Therefore, these models can model the physical process effectively (Ojha, Surampalli, & Bárdossy, 2017). A physical model developed cooperating time-based and spatial variation of the catchment and its logical structure creates a more realistic model through the connection between model parameter and physical catchment (Sitterson et al., 2017). Therefore, the process-based hydrologic model is a more suitable model for the derivation of the model parameters to evaluate parameter transferability as it generates accurate reliable catchment response model parameters.

Hydrologic models are classified as lumped and distributed according to their geometry or spatial inconsistency. Distributed runoff models represent the spatial heterogeneity to its inputs and parameters, separating the model process into small elements (Sitterson et al., 2017). Further, if the required accurate data input is available, reliable results can be obtained by a distributed model (Singh, 2018). The effect of land-use change and spatially variable input and output, movement of pollutant and sediment, and hydrological response at ungauged catchment are the summarized benefit of distributed models by Moradkhani and Sorooshian (2008). However, they noted estimation of excessive parameters initiate uncertainty within the distributed model itself.

Lumped hydrologic models are developed considering catchment as one unit, ignoring its spatial variability. Therefore, lump models are usually selected to simulate the streamflow just at the watershed outlet (Moradkhani & Sorooshian, 2008). Lumped hydrologic models synthesize and reflect the requirement of hydrologic communities in terms of water balance and water resources management by decreasing parameters to essential few (Todini, 1988).

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Hydrologic models are classified into an event and continuous based on the time of the simulation. The basin response to an individual rainfall event such as peak, time to peak, and detention is modelled by event hydrologic modelling. In converse, hydrologic continuous process model hydrologic processes and phenomena over a longer period (Chu & Steinman, 2009). In other words, event-based hydrologic models generate output for a specific period, such as flood whilst continuous hydrologic model produces a continuous output (Devia et al., 2015).

Continuous hydrologic models reflect hydrologic processes such as evapotranspiration, canopy intercept, depression storage, percolation, shallow subsurface flow, etc. which are neglected in single event hydrologic models such as a flood. Examination of the entire spectrum of streamflow is essential to identify stream stability for water resource management (Mcenroe & Ph, 2010). According to the literature review process based lumped continuous hydrologic model is appropriate to identify the model parameter for water resource management.

2.3 Parameter transferability

Estimation of streamflow to an acceptable degree is important for planning, designing and managing water resources. The initial way to accomplish the prescribed requirement is the use of observed meteorological and streamflow data to understand the hydrological process of a watershed. However, the challenge of ungauged catchments that are genuinely ungauged or poorly gauged has been identified by hydrologic communities. As a result, hydrologist developed models and techniques which do not require the long term series of meteorological and hydrological measurements. Among them, one option is transferring of hydrologic model parameters of a measured catchment to ungauged catchment by regionalization (Loukas & Vasiliades, 2014).

Razavi, Coulibaly, and Asce (2012a) classified continuous streamflow regionalization into two categories as a rainfall-runoff model by which model parameters are used as tools to transfer hydrological information and hydrologic model-independent method such as transfer streamflow directly through data-driven methods. Furthermore, they presented specific classification as shown in Table 2-2, depending on the techniques

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used for extrapolating hydrological model parameters in the hydrologic model-dependent regionalization.

Table 2-2:Classification of extrapolation of hydrological model parameter

	Category	Studies
a	Arithmetic mean method	Merz and Blöschl, 2004 ; Oudin, Andréassian, Perrin, Michel, and Le Moine, 2008
b	spatial proximity (spatial distance) approach	Merz and Blöschl, 2004; Oudin et al., 2008; Parajka, Merz, and Blöschl, 2005; Li, Zhang, Chiew, and Xu, 2009
c	physical similarity approach	Oudin et al., 2008; Samaniego, Bárdossy, and Kumar, 2010; Samuel et al., 2011
d	scaling relationships	Croke, Merritt, and Jakeman, 2004; Schreider, Jakeman, Gallant, and Merritt, 2002
e	regression-based methods (linear and nonlinear)	Merz and Blöschl, 2004; Parajka et al., 2005; Oudin et al., 2008; Cheng, Ko, Yuan, Ge, and Zhang, 2006; Mohamoud, 2008
f	hydrological similarity approach	Masih, Uhlenbrook, Maskey, and Ahmad, 2010

Shrestha et al. (2007) developed a physically-based distributed BTOPMC model to study the potential of spatial and temporal parameter transferability to the Southern part of Nepal. They identified that the model performance is satisfactory for the estimation of seasonal, annual water availability in the catchment and other water budget-related studies. However, this study revealed model limitations as to capture the recession of baseflow and incapability imitate seasonal bulges in respective hydrographs.

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Gan and Burges (2006) used the Sacramento model (SAC-SMA) to assess model parameter transferability in the South-Eastern United States by rescaling model parameters obtained from soil properties. The modeled hydrographs were atrociously bad for the simulate low, intermediate and peak flows concluding rescaling was not productive.

Gumindoga, Rwasoka, Nhapi, and Dube (2017) developed the HEC-HMS model to Upper Manyame watershed, Zimbabwe to model runoff in an ungauged catchment, transferring the model parameter by the proxy catchment approach. In their study, optimal sets of parameters of gauged micro-catchments have been transferred successfully to six ungauged catchments. Accordingly, they conclude the application of HEC-HMS model parameters for simulation of continuous streamflow in a complex watershed with many micro-catchments and channel reaches, deploying parameter transferability approach.

The challenge of input data, meteorological and physiographic data can overcome through electing a hydrological model with easy setup, least input figures with adequate accuracy. HEC HMS is one of the models which satisfy the above criteria (Majidi & Shahedi, 2012). Therefore, the HEC HMS process-based model has been widely chosen for parameter transferability (Gumindoga et al., 2017; Wałęga, 2013; Meresa, 2019)

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2.4 Model Selection

The selection of a suitable model is subjective to the intention of the study. For that ten criteria were identified following the purposes of the study, estimation of daily streamflow using a lumped process-based hydrologic model for sustainable water resource management and planning. A list of criteria is shown below.

Criteria 1 - Model application

Criteria 2 - Model application for parameter transferability in the world

Criteria 3 - Model application for parameter transferability in Sri Lanka

Criteria 4 - Dissociation of the simulation period

Criteria 5 - Physical process representation

Criteria 6 - Representation of geometry or spatial variation

Criteria 7 - Model accessibility

Criteria 8 - Temporal resolution

Criteria 9 - Data requirement

Criteria 10 - Technical support for the modeler

Shortlisted seven models, J2000, SLURP, SWAT, TOPMODEL/BTOPMC, MIKE 11/NAM, TANK, HEC-HMS were evaluated assigning marks for the satisfaction of the requirement as the state in Table 2-4 and then classified the models into three class as High, Medium, Low. Classification of seven models to the three classes is shown in Table 2-3. Accordingly, SWAT, MIKE 11/NAM and HEC-HMS were in class High and HEC-HMS was selected for the study.

Criteria 2 & 3 depicted low category (Table 2-3) for all shortlisted seven models and from a different point of view, it was one of the gaps to be filled by researchers.

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Table 2-3: Model Selection

Criteria	J2000	SLURP	SWAT	TOPMODEL/ BTOPMC	MIKE 11/ NAM	TANK	HEC HMS
Criteria 1 : Model application	Medium (2)	Medium (2)	High (3)	High (3)	High (3)	High (3)	High (3)
Criteria 2 : Model application for parameter transferability in the world	Low (1)	Low (1)	Low (1)	Low (1)	Low (1)	Low (1)	Low (1)
Criteria 3: Model application for parameter transferability in Sri Lanka	Low (1)	Low (1)	Low (1)	Low (1)	Low (1)	Medium (2)	Low (1)
Criteria 4: Dissociation of the simulation period	High (3)	High (3)	High (3)	High (3)	High (3)	Medium (2)	High (3)
Criteria 5: Physical process representation	High (3)	Medium (2)	High (3)	High (3)	High (3)	Medium (2)	High (3)
Criteria 6 : Representation of geometry or spatial variation	Low (1)	Low (1)	High (3)	Low (1)	High (3)	Medium (2)	High (3)
Criteria 7: Model accessibility	High (3)	Low (1)	High (3)	Medium (2)	Low (1)	High (3)	High (3)
Criteria 8: Temporal resolution	High (3)	High (3)	High (3)	High (3)	High (3)	High (3)	High (3)
Criteria 9 : Data requirement	Low (1)	Low (1)	Medium (2)	Low (1)	High (3)	High (3)	High (3)
Criteria 10: Technical support for modeler	High (3)	High (3)	High (3)	Low (1)	High (3)	Low (1)	High (3)
Average weight	0.7	0.6	0.8	0.6	0.8	0.7	0.9
Classified Class	Medium	Low	High	Low	High	Medium	High
Reference	(Nepal et al., 2017), (Shrestha et al., 2007), (Van Der Linde & Woo, 2003), (Heuvelmans et al., 2004), (Garcia, Folton, & Oudin, 2017), (Oudin, Andréassian, Mathevet, Perrin, & Michel, 2006), (Samuel, Coulibaly, & Metcalfe, 2011b), (Wu, Liu, Cai, Li, & Jiang, 2017), (Wickramaarachchi, Ishidaira, & Wijayaratna, 2012), (Devia et al., 2015), (Supriya & Krishnaveni, 2016)						

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Table 2-4: Judgements for model selection

Criteria		High	Medium	Low
Criteria 1	Model application	Model applications in Sri Lanka	Model applications in Asian region	Model applications in other regions
Criteria 2	Model application for parameter transferability	Parameter transferability applications in all around the world	Parameter transferability applications in part of the world	Parameter transferability applications only for specific countries
Criteria 3	Model application for parameter transferability in Sri Lanka	More than 5 applications	Less than 5 applications	No applications
Criteria 4	Dissociation of simulation period	Continuous and event based modelling	Continuous based modelling	Event based modelling
Criteria 5	Physical process representation	Physics based model	Conceptual model	Empirical model
Criteria 6	Representation of geometry or spatial variation	Lumped and distributed model	Lumped model	Distributed model
Criteria 7	Model accessibility	Freely available model	Freely available only for education purpose	Fully commercial model
Criteria 8	Temporal resolution	sub daily, daily models	Monthly models	Annual model
Criteria 9	Data requirement	Model runs with limited data availability	Model runs with moderate data availability	Model runs with high data availability
Criteria 10	Technical support for modeler	User guides and manuals are freely available	User guides and manuals are commercially available	None availability of manuals and guides

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2.5 Data, data checking, and estimation of missing data

2.5.1 Data length and Quality

The quality and adequacy of the data length used governs obtaining the optimal parameter set in the calibration process. Data applied to the model should be representative to capture real hydrologic processes of the catchment. However, Soroosh Sorooshian, Gupta, and Fulton (1983) emphasized rather than the use of longer data length to increase catchment representativeness, attention should be paid to the information confined in data and the methodology for the extracting that information to achieve the objective. In addition to that, obtaining lengthy data series leads to cost for data acquisition, increases the computational burden in obtaining optimal model parameters and also challenges in a data-sparse situation. Therefore, requisite precision in parameters, computational restraints and incurred cost for obtaining data should be compromised to accomplish the quality of the data (Gupta & Sorooshian, 1985).

There is a declining tendency in the numbers of gauging stations to capture hydro-meteorological data due to inadequate funding, lack of attention and appreciation for the long-term data and development of water infrastructure (Zelelew & Alfredsen, 2014). However, there are some systematic errors contains in data that is uncorrectable and that negatively influence in model calibration. As well the inconsistencies of the data quality and quantity of data end up resulting non-optimal set of parameters in hydrologic modelling (Burges, 2011). Nevertheless, Chaplot, Saleh, and Jaynes (2005) express those models are capable to compensate input errors within a reasonable degree by fine-tuning their parameter values.

Literature reveals that HEC-HMS model has been developed with five to ten years' series of hydrologic data and results has implied their better performance in simulating streamflow (Tassew, Belete, & Miegal, 2019; Gyawali & Watkins, 2013; Gumindoga, Rwasoka, Nhapi, & Dube, 2017b; Singh & Jain, 2015).

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2.5.2 Fill missing data

Encountered missing data in the input data series is one of the major limitations in hydrologic modelling. Obtaining continuous data serious with the temporal and spatial variability is difficult. Though filling data by mean values are used as a traditional method, a trend of application of regression method can observe in past decades (Lo Presti, Barca, & Passarella, 2010). Silva, Dayawansa, and Ratnasiri (2007) have identified climatic zone wise methods for missing streamflow estimation in Sri Lanka. Accordingly, they recommend the inverse distance method as the most suitable method for low country stations while the normal ratio method has been recommended for mid-country and upcountry intermediate zone. In addition to that, the arithmetic mean method performed better in the upcountry wet zone and for the mid-country wet zone, the areal precipitation ratio method has been suggested.

2.5.3 Aerial averaging of rainfall

Thiessen polygon method (Chow, Maidment, & Mays, 1988) has been applied in many hydrologic studies to calculate average rainfall for the catchment because of its capability for representing precipitation data from unevenly distributed gauging stations (Brassel & Reif, 1979). Table 2-5 shows the applications of the HEC-HMS model deploying the Thiessen polygon method as rainfall areal averaging method for the various catchments over the world.

Table 2-5: Applications of Thiessen Polygon method in HEC-HMS

Reference	Modelled Catchment
(Gebre, 2015)	The upper Blue Nile River Basin, Ethiopian Highlands
(Supriya & Krishnaveni, 2016)	Chinnar and Anaivari odai sub-basins, India
(Tassew et al., 2019)	Gilgel Abay catchment, Upper Blue Nile Basin, Ethiopia
(Wicher, 2016)	Kävlinge River Basin, Sweden
(Kanchanamala, Herath, & Nandalal, 2016)	Kalu Ganga River, Sri Lanka

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Reference	Modelled Catchment
(Kamali, Mousavi, & Abbaspor, 2012)	Gorganroud River Basin in Iran
(Silva, Weerakoon, & Herath, 2014)	Kelani River basin, Sri Lanka
(Nandalal & Ratmayake, 2010)	Kalu-Ganga River, Sri Lanka
(Zema, Labate, Martino, & Zimbone, 2017)	Mésima Torrent (Southern Italy)

2.6 Streamflow threshold identification

Identification of streamflow regimes as high, medium and low is a challenge faced by water managers, and the research community and also it is essential for sustainable water infrastructure engineering and management in the concerned watersheds. High streamflow creates flood whereas low flow is necessary to maintain the river environment. Intermediate flow is more important when planning infrastructure to sustain water resources (Ali, Bajracharyar, & Raut, 2017).

The streamflow threshold value for high, intermediate and low flow has been defined in varies studies, researches and projects respective to the objects such as water extraction, water power statistics, climate variability, etc. (Wijesekera, 2018).

2.7 Model warm-up

Hong and Jonathan (2014) expresses the importance of state variables such as consist of soil moisture, retain water storage near the surface and underground, etc. for the reliable performance of the hydrologic model. Further, they explain one of the approaches to overcome the challenges of estimating state variables as warming up the soil and stream state variables. Initialization of important model variable or reaching of dynamic equilibrium of important processes can be achieved by model warm-up in the hydrologic model by letting the model work long enough period before the simulation period (Daggupati et al., 2015).

The use of too short warm-up periods results in a biased simulated hydrologic response, especially when the initial year's prevailing uncertainty in the characterization of the initiate sate rather than model and parameter uncertainty (Huard

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& Mailhot, 2008). However, Daggupati et al. (2015) have expressed that recommendation of model developers for a warm-up for a hydrological model, as two to three years and for sediment and nutrient-related processes as five to ten years. Johnston and Pilgrim (1976) found that the warm-up period needs to be long enough to generate the first runoff for stores (interception, upper soil, drainage, etc.) to fill at a threshold value. One year of the warm-up period has been recommended by Berthet, Andréassian, Perrin, and Javelle (2009) for lumped continuous hydrologic models by modelling 178 catchments.

Variation of the model warmup period over initial wetness and precipitation has been identified by Kim, Kwon, and Han (2018) from the study done for a catchment at southwestern England using two conceptual models, HYMOD and IHACRES.

Literature reveals many HEC-HMS based hydrologic models which have been developed with a one-year warm-up period for various region and performance of that models were reliable (Plesca et al., 2012; Razmkhah, Saghafian, Ali, & Radmanesh, 2016; Razmkhah, 2018).

2.8 Model Optimization

2.8.1 Model calibration

The process of selection of model parameter for the hydrologic model by which closely simulate hydrological behavior of the catchment is called as model calibration (Wagener, Wheater, & Gupta, 2004; Moore & Doherty, 2005). Sorooshian and Gupta (1995) classify model parameters into two types as physical parameters and process parameters. Physical parameters represent usually measurable catchment characteristics. But there are some physical characteristics such as hydrologic conductivity, porosity which can be estimated by the theoretical approach and difficult to measure in practice. Process parameters represent catchment characters which are normally cannot be measured. Therefore, the calibration process involves minimizing the uncertainty of parameter estimation in the model.

The calibration process is done either manual or automatic (Pechlivanidis et al., 2011a). HEC-HMS has pre-defined hard constraints which limit optimized physical

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parameter within the reasonable intervals, as well as values within those constraints, do not cause numeric instabilities or error in computations. Further, HEC-HMS allows users to define soft constraints by which limit the range of value specific to the relevant catchments.

Juraj and Slobodan (2004) stated their approach to optimize the HEC-HMS model. The first model was calibrated manually to determine the soft limits to ensure that physically meaningful initial parameters are used. Then the model has been tuned up within pre-identified soft limit by automatic calibration. Singh and Jain (2015) and Gyawali and Watkins (2013) recommended a combination of manual and auto calibration for HEC-HMS model optimization.

Sorooshian and Gupta (1995) described four major elements which include classic automatic parameter assessment. Those are selected objective function, the optimization algorithm, their termination criteria, and the calibration data. The finding of those values optimizing the numerical value of the objective function is noted as the purpose of calibration.

Researchers have presented many views on selecting the calibration and validation period for hydrologic modelling. Gan, Dlamini, and Biftu (1997) suggest having both dry and wet periods within the calibration and validation data series and further state that it ensures the range of conditions in which the model is targeted to be performed. Nevertheless, the limitation of monitoring data availability challenges over this proposal (Arnold, Moriasi, Gassman, & White, 2012).

2.8.2 Objective Function

The adaptation of the developed model to the specific watershed is done through parameter estimation. The parameter can be projected directly or indirectly from field measurements. Moreover, according to the previous hydrologic studies and researches, some parameters have been identified which can only be estimated with the comparison of calculated result with observed data (streamflow). Even for aforesaid directly or indirectly estimated parameters embrace uncertainty which needs some adjustment to optimize the model. Therefore, the necessity of the quantitative measure

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for the goodness-of-fit between the modelled flow and measured flow is filled by objective functions (Scharffenberg, Bartles, Brauer, Fleming, & Karlovits, 2018). The selection of objective function for any model is a subjective decision that affects both the value of model parameters and the performance of the model. Usually, the objective function is selected for the intended purpose of the study (Diskin & Simon, 1977).

HEC-HMS program has deterministic and stochastic objective functions to minimize or maximize the selected objective functions depending on its error computation structure. There are fourteen objective functions for the minimization goal maximizing goodness-of-fit. Maximization goal can be utilized in two different ways. One is maximizing element properties such as flow volume, reservoir stage, etc. and the other one is maximizing goodness-of-fit statics (Scharffenberg et al., 2018).

According to the literature review, the mostly applied objective functions in HEC-HMS model studies were Nash Sutcliffe coefficient, Root Mean Square Error, The Peak Weighted Root Mean Square Function (Meenu, Rehana, & Mujumdar, 2012; U. Kim & Kaluarachchi, 2008; Singh & Jain, 2015; Verma, Jha, & Mahana, 2010; Gyawali & Watkins, 2013; Verma et al., 2010; Razmkhah et al., 2016; Rathod, Borse, & Manekar, 2015)

1. Nash Sutcliffe efficiency coefficient (NSE)

$$NSE = 1 - \frac{\sum_{i=1}^{N}(Q_c - Q_O)^2}{\sum_{i=1}^{N}(Q_O - \bar{Q}_O)^2} \qquad \text{Equation 2-1}$$

   Where Q_C is calculated streamflow, Q_O is observed streamflow and $\bar{Q}_O$ is the mean of observed streamflow. The optimum value for NSE is 1 and it ranges from -∞ to 1.0

2. Root Mean Square Error (RMSE)

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(Q_C - Q_o)^2} \qquad \text{Equation 2-2}$$

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Where Q_C is calculated streamflow and Q_O is observed streamflow. The optimum value of RMSE is zero and its upper limit is infinity.

3. The Peak Weighted Root Mean Square Error (PWRMSE)

$$\text{PWRMSE} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(Q_C - Q_o)^2 \, X \, \frac{(Q_o + Q_{ave})}{2Q_{ave}}} \qquad \text{Equation 2-3}$$

Where Q_C is calculated streamflow, Q_O is observed streamflow and Q_{ave} is average streamflow

The HEC-HMS model output depicts the value of the objective function at the end of each iteration by a graph. Juraj and Slobodan (2004) state that a monotonically decreasing coordinates of objective function graph suggest that a global minimum of the objective function was found during the optimization.

2.8.3 Optimization algorithm

Optimized model parameters for the selected objective function are identified through search algorithms. There are two inbuilt search methods presented in the HEC-HMS model for model optimization as deterministic and stochastic methods. Markov Chain Monte Carlo is the available stochastic method. In deterministic methods, the model provides two options as the univariate method and the simplex method (Nelder and Mead). In univariate method model allows to optimize only one parameter at one time and while the simplex method uses downhill simplex to optimized all parameter in concurrently (Scharffenberg et al., 2018).

2.8.4 Model performance evaluation

Developed hydrologic models are optimized by the objective function which has been selected based on the objective of the study (Diskin & Simon, 1977). Nevertheless, model results obtained through an optimized objective function would not be able to satisfy all the expected criteria. There are various types of evaluation criteria applied by different researchers for their HEC-HMS model performance evaluation.

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Legates and Jr (1999) and Moriasi et al. (2007) recommended to include the following three components in evaluation model efficiency as the requirement.

1. One dimensionless statics
2. One absolute error-index statistic
3. One graphical technique

2.8.5 Model verification

Validation of the model's strength, the capability to represent the hydrologic response of the model and detention of bias calibrated parameters are the main aims of the model verification (Gupta, Beven, & Wagener, 2005). Model verification is carried out in different approaches. Bathurst, Ewen, Parkin, O'Connell, and Cooper (2004) present 4 tests with an extension to the Ewen and Parkin (1996) view and listed follows.

1. Simple split sample test
2. Different split sample test
3. Proxy catchment test
4. Different proxy catchment test

Among various tests, the simple split sample test is mostly being practised by the hydrologic community. In this approach, the data series is divided into two or more parts. One part is used for model calibration and other parts for model validation to verify the satisfaction of the model prediction (Pechlivanidis, Jackson, Mcintyre, & Wheater, 2011b).

Literature reveals, the sample-split method as a widely practiced test for validation in HEC-HMS hydrologic models. Wallner, Haberlandt, and Dietrich (2012) for Aller-Leine river, Germany; Meenu, Rehana, and Mujumdar (2012) for Tunga–Bhadra river basin, India; Plesca et al. (2012) for San Francisco catchment; Fleming and Neary (2004) for Cumberland River basin; Weragoda (1998) for Nilwala & Gin river basin in Sri Lanka, have applied HEC-HMS model with sample-split validation method.

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2.9 HEC-HMS model structure

2.9.1 Basin model

2.9.1.1 Canopy Method

The canopy method is applied to account for the precipitation intercept by the plants. On another hand, it is an indicator of the existence of plants in the landscape. The impact of the canopy is essential for the continuous simulation application in rainfall-runoff modelling (Scharffenberg et al., 2018).

The first contribution of precipitation is for the canopy interception. When canopy storage is filled, excess precipitation is obtainable for infiltration. Potential evapotranspiration is first satisfied with the available canopy storage and then from surface storage. When that amount is not adequate for the potential evapotranspiration, finally water removed from the upper soil profile storage (Scharffenberg et al., 2018).

Three types of canopy methods have been provided in the HEC-HMS model as Gridded Simple Canopy, Simple Canopy, and Dynamic Canopy. The suitable model was selected evaluating subjective criteria as shown in Table 2-6.

Table 2-6: Selection of canopy model

Criteria	Dynamic canopy	Simple canopy
Criteria 1: Model Parsimonious	Medium (2)	High (3)
Criteria 2: Long term Streamflow Simulation	High (3)	High (3)
Criteria 3: Simple Representation of Plant Canopy	Low (1)	High (3)
Average weight	2	3
Reference	(Wicher, 2016), (Sok & Oeurng, 2016), (Ahbari, Stour, Agoumi, & Serhir, 2018), (Singh & Jain, 2015), (International Sava River Basin Commission, 2017), (Scharffenberg et al., 2018), (Mcenroe & Ph, 2010)	

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2.9.1.2 Surface method

The surface method represents the precipitation which may accumulate in surface depression storage. A Surface stream is generated once the precipitation rate exceeds the infiltration rate and the surface storage is filled. Generally, the application of the surface model is more suitable and effective in continuous streamflow simulation applications. Simple Surface and Gridded Simple Model is available in HEC HMS 4.3.

2.9.1.3 Precipitation loss model

Infiltration losses are evaluated by precipitation loss models. HEC-HMS 4.3 program categorizes all the land and water in the catchment as either directly connected impervious layer or previous layer. In the former part, water directly contributes to the precipitation runoff, without water losses in infiltration, evaporation or any other processes. Water in the latter category is subjected to losses and alternative models such as Initial and Constant rate loss model, Deficit and Constant rate loss model, SCS Curve number loss method, Green and Ampt loss model, Soil Moisture Accounting model, are provided to assess the cumulative losses. Among those models, The deficit and Constant rate loss model and Soil Moisture Accounting Model is suited for continuous streamflow simulation (Feldman, 2000).

Data availability and accessibility of the data is one of the major challenges in model and parameter selection. Soil Moisture Accounting model is not preferred for the simulation in many river basins in the Sri Lankan context, because it requires a high number of parameters (Halwatura & Najim, 2013). The appropriate model for precipitation loss process was selected evaluating subjective criteria as shown in Table 2-7.

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Table 2-7: Selection of precipitation loss model

Criteria	Deficit and Constant	Exponential	Green and Ampt	Initial and Constant	SCS curve number	Smith Parlange	Soil Moisture Accounting
Criteria 1 : Model Maturity	High (3)	Medium (2)	Medium (2)	High (3)	High (3)	Medium (2)	High (3)
Criteria 2: Easy to set up and use	High (3)	Low (1)	Medium (2)	High (3)	High (3)	Low (1)	Low (1)
Criteria 3 : Model Parsimonious	High (3)	Medium (2)	Low (1)	High (3)	High (3)	Low (1)	Low (1)
Criteria 4 : Long term Simulation	High (3)	Low (1)	Low (1)	Low (1)	Low (1)	Low (1)	High (3)
Average weight	3	1.5	1.5	2.5	2.5	1.25	2
Reference	(Scharffenberg, Bartles, Brauer, Fleming, & Karlovits, 2018), (Feldman, 2000), Halwatura & Najim (2013), International Sava River Basin Commission (2017), (Meenu et al., 2012),						

Therefore, the Deficit and Constant Rate model was selected to simulate the infiltration process. International Sava River Basin Commission (2017) used the Deficit and Constant rate model to simulate streamflow of the Sava River which is located in Southeastern Europe. Halwatura and Najim (2013) recommended the Deficit and Constant Rate loss method as the best loss model with Snyder unit hydrograph as a transformation method to simulate streamflow in Aththanagalu Oya basin.

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2.9.1.4 **Transform Model**

HEC-HMS program provides seven direct rainfall-runoff models as Clark unit hydrograph, Kinematic Wave, ModClark, SCS unit hydrograph, User-specified S-Graph, User Specified unit hydrograph. All models are lumped model except the ModClark model (Scharffenberg et al., 2018). Those models are applied for event-based models and coupling the model with continuous loss model allows for continuous flow simulations. Thus, event hydrologic modelling facilitates to drive fine-scale parameters to understand the detailed hydrologic process and those can be applied for coarse-scale continuous modelling (Chu & Steinman, 2009).

The Transform model for the study was selected evaluating subjective criteria for the objective. Evaluation of criteria is shown in Table 2-8. Accordingly, the SCS unit hydrograph was selected as the appropriate model for this study with respected selected criteria.

Table 2-8: Selection of Transform model

Criteria	Clark unit hydrograph	Kinematic wave	Modclark	Snyder unit hydrograph	User-specified s graph	User-specified unit hydrograph	SCS unit hydrograph
Criteria 1: Easy to set up and use	Medium (2)	Low (1)	High (3)	Medium (2)	Low (1)	Low (1)	High (3)
Criteria 2: Model Parsimonious	High (3)	Low (1)	High (3)	High (3)	Low (1)	Low (1)	High (3)
Criteria 3: Lumped model	High (3)	Low (1)	Low (1)	High (3)	High (3)	High (3)	High (3)
Criteria 4 : Applicability for different environment	High (3)	Low (1)	Medium (2)	High (3)	Medium (2)	Medium (2)	High (3)
Average weight	2.75	1	2.25	2.75	1.75	1.75	3
Reference	(Scharffenberg et al., 2018), (Feldman, 2000), (Asadi & Boustani, 2013), (Zema et al., 2017), (Sardoii, Rostami, Sigaroudi, & Taheri, 2012), (Chu & Steinman, 2009), (Supriya & Krishnaveni, 2016), (Jayadeepa, 2016), (Weragoda, 1998)						

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2.9.1.5 Baseflow Model

HEC-HMS has five alternative models for baseflow as Bounded recession, Constant monthly, linear reservoir, Nonlinear Boussinesq and Recession. The linear-reservoir baseflow model is applied in combination with the continuous soil- moisture accounting (SMA) model (Scharffenberg et al., 2018). Negligence of the baseflow component in hydrologic modelling has caused under or over simulations of streamflow (Mcenroe & Ph, 2010; Gumindoga et al., 2017). The suitable baseflow model was selected evaluating subjective criteria as shown in Table 2-9. Accordingly, the Recession model was selected as the baseflow model.

Table 2-9: Selection of Baseflow model

Criteria	Bounded Recession	Constant Monthly	Linear Reservoir	Nonlinear Boussinesq	Recession
Criteria 1: Long term streamflow simulation	Low (1)	Low (1)	Low (1)	High (3)	High (3)
Criteria 2: Model Parsimonious	High (3)	High (3)	Low (1)	Medium (2)	High (3)
Average weight	2	2	1	2.5	3
Reference	(Scharffenberg et al., 2018), (Feldman, 2000), (Silva et al., 2014), (Verma et al., 2010), (Chu & Steinman, 2009), (Nandalal & Ratmayake, 2010), (International Sava River Basin Commission, 2017), (Singh & Jain, 2015)				

2.9.1.6 Routing model

Reach of the stream or river is performed by a routing method in the HEC-HMS model. Nevertheless, in the case of lump model total catchment behaves as one unit and routing model is not applicable (Scharffenberg et al., 2018).

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3 METHODOLOGY

A comprehensive methodology flow chart is given in Figure 3-1. One of the major challenges faced by water resource managers and engineers in term of sustainable planning and management of water resources was identified through field exposure and literature review. Accordingly, objective and specific objectives were established which are to be covered under the study. The Literature review was carried out to identify reliable approaches to solve the identified problem. After an evaluation of subjective criteria and reviewing the state-of-art, an appropriate model and project area were selected. Accordingly, HEC-HMS model was designated for the study and Urawa and Pitabaddara watersheds of Upper Nilwala river basin were selected as the project area.

After identifying data required for model development precipitation, streamflow and evaporation data were obtained. Collected raw data were checked for consistency using the double mass curve, visual data check, annual water balance, etc. to verify the accuracy of the data for the application.

Metro-hydrological data were split into two parts for model calibration and model validation. Model parameters were identified and initiated with the aid of literature. Initial model parameters were optimized using the objective function (RMSE) with manual, automatic and semi-automatic optimization method using Univariate Gradient and Nelder and Mead search algorithms. Addition to the objective function model performance criteria, sorted and unsorted flow duration curves, streamflow hydrograph, annual water balance, etc. were established to extract the best set of model parameters. Finally, semi-automatic optimization with Nelder and Mead search algorithm was concluded as the best optimization approach and it was verified by developing model assigning model parameters with the set of optimal parameters and optimizing through the fully automatic approach. Then calibrated parameters were validated through model verification. Once the performance evaluation criteria were poor in the validation, calibration process was repeated changing parameters and also tried it with the changes in calibration data years. This procedure was carried out for both Pitabaddara and Urawa watersheds.

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After that recognized optimal set of parameters for both catchments were transferred between two catchments cooperating temporal, spatial and Spatio-temporal variations with the concept of donor catchment is gauged and receiver catchment is ungauged. Also, parameters transferability from the main catchment to sub-catchment and vice-versa was assessed. Derived subjective performance criteria were used for performance assessment. Finally, according to the results, conclusions and recommendations were made for the objective of this study.

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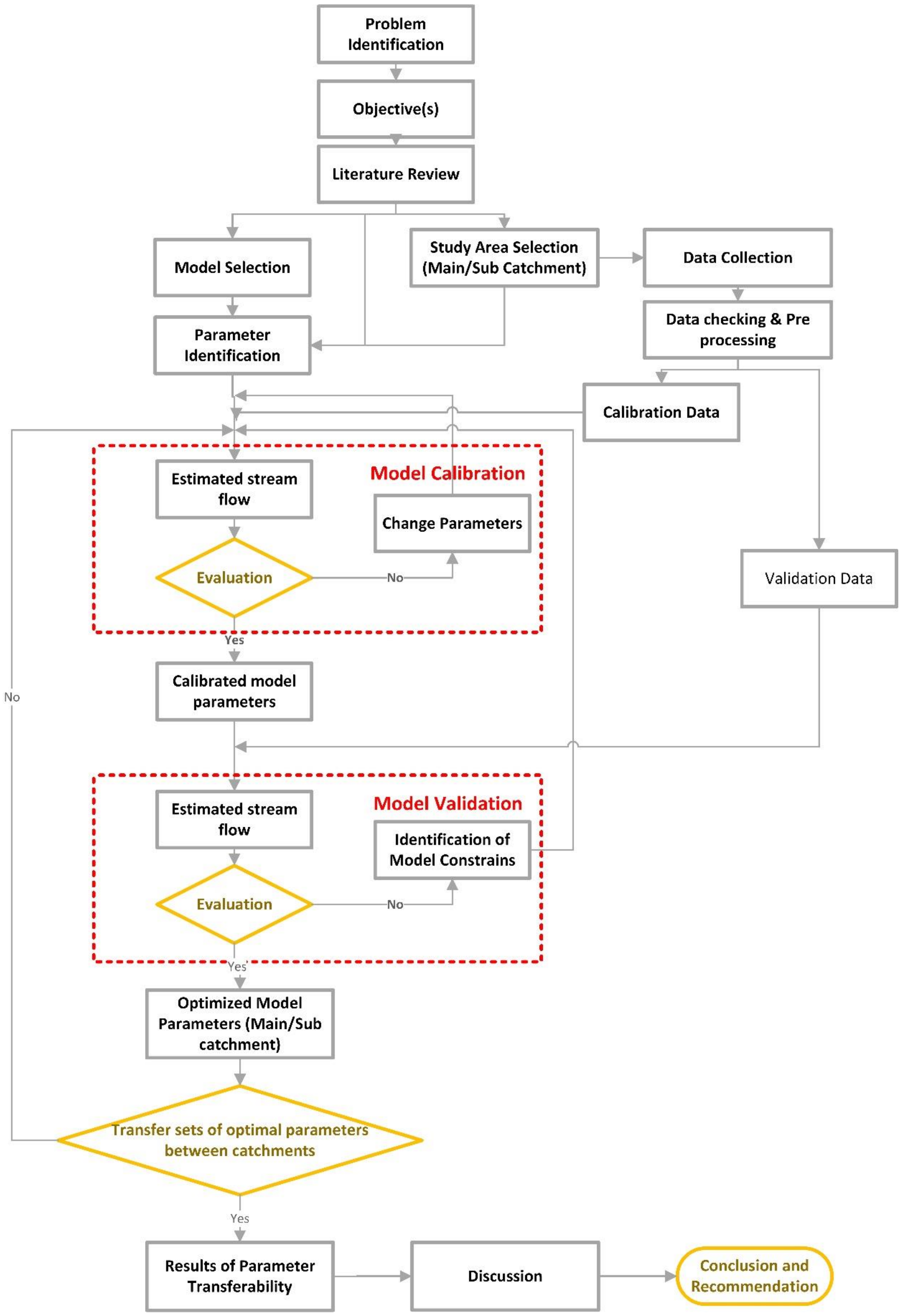

Figure 3-1: Methodology flow chart

4 DATA AND DATA CHECKING

4.1 Data collection

Streamflow, rainfall, and evaporation data were collected as hydro-meteorological data for the model development. Data were obtained from the Irrigation Department, Department of Meteorology and Survey Department and more details such as resolution, duration, and source of each data are provided in Table 4-1.

Pitabaddara & Urawa sub-watersheds in the Nilwala River basin were selected for this study due to the availability of daily rainfall and streamflow data and acceptable limit of continuation of the data. Five rainfall gauging stations, namely Anningkanda, Dampahala, Urawa Rotumba, Hulanduwa, and Derangala were selected for Pitabaddara watershed and Dampahala and Urawa Rotumba rainfall stations were selected for Urawa watershed. Pan evaporation data were obtained from Kottawa station.

Table 4-1: Data resolution and sources

Data type	Temporal/spatial resolution	Data period	Data source
Rainfall	Daily	October 2018 to September 2018	Irrigation Department D Department of Meteorology
Streamflow	Daily		Irrigation Department
Evaporation	Daily		Department of Meteorology
Topographic	1:50,000		Survey Department
Contour	1:50,000		Survey Department
Land use	1:50,000		Survey Department

4.2 Compliance gauging configuration to standards

Streamflow and rainfall Gauging stations were selected following presented guidelines in the World Meteorological Organization standards (WMO, 1975) with the consideration of spatial distribution and other identified researches as shown in Table 4-2.

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Table 4-2: Distribution of rainfall and streamflow gauging stations

Gauging Station	Stations at each watershed		Station Density (km2/station)		WMO Standards (km2/station)	Kodippili (2019) (km2/station)
	Pitabaddara	Urawa	Pitabaddara	Urawa		
Rainfall	Hulandawa Anningkanda Dampahala Urawa-Rotumba Derangala	Urawa-Rotumba Dampahala	58.3	26.3	575	175
Streamflow	Pitabaddara	Urawa	291.3	52.7	1875	
Evaporation	Kottawa	Kottawa	291.3	52.7		

4.3 Selection of data period

10 years from water year 2008/09 to water year 2017/18 was selected for the study. Among all the year's water year 2016/17 was the water year with the highest rainfall as 289mm/day. As well as August and September in water year 2015/16 and 2017/18 and February and March in water year 2008/09 and 2015/16 have been recorded for extreme droughts within the catchment. Data had a very low percentage of missing data as shown in Table 4-3.

Table 4-3: Percentage of missing data of rainfall and streamflow data

Data Type	Station	Missing Data	
		No. of Missing Data	Missing Data
Rainfall	Dampahala Tea Factory	61	1.7%
	Derangala Hill	273	7.5%
	Anningkanda	0	0.0%
	Hulandawa	182	5.0%
	Urawa Rotumba	1	0.0%
River Discharge	Pitabeddara	0	0.0%
	Urawa	19	0.5%

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4.4 Precipitation Areal Averaging

As described in 2.5.3, Thiessen polygon method (Chow et al., 1988) is one of the widely practised rainfall averaging method in HEC –HMS model development. Therefore, developed Thiessen polygons for the Pitabaddra watershed are shown in Figure 4-1 and Thiessen average weights for Pitabaddra watershed are in Table 4-4.

Table 4-4: Thiessen weight for Pitabaddara watershed

Rainfall Station	Thiessen Weight
Hulanduwa	0.09
Derangala	0.25
Urawa Rotumba	0.36
Anningkanda	0.17
Dampahala	0.13

Similarly, Figure 4-2 shows developed Thiessen polygons for Urawa watershed and respective Thiessen average weights are shown in Table 4-5.

Table 4-5: Thiessen weight for Urawa watershed

Rainfall Station	Thiessen Weight
Urawa Rotumba	0.24
Dampahala	0.76

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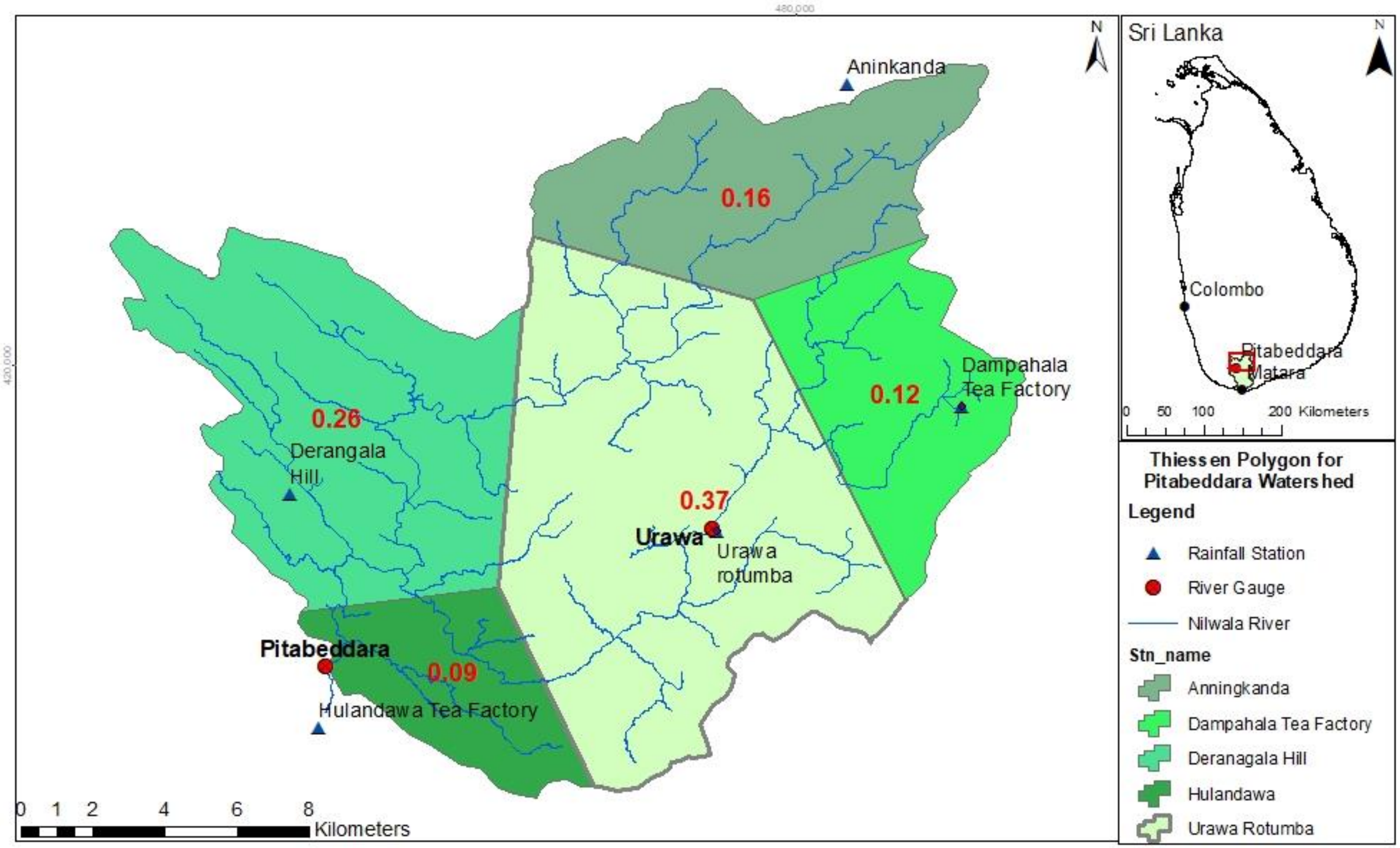

Figure 4-1 : Thiessen polygon map - Pitabaddara Catchment

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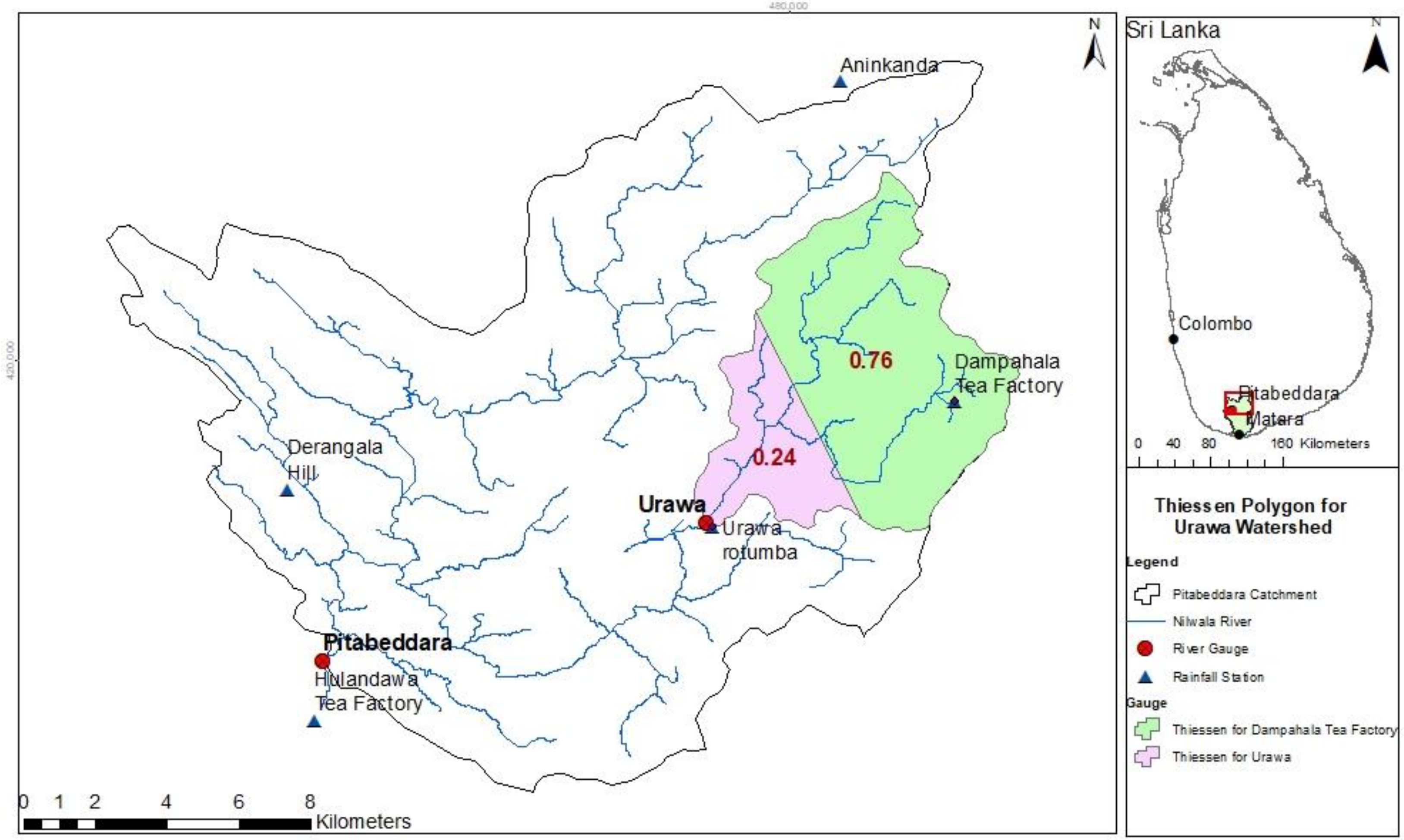

Figure 4-2: Thiessen polygon map - Urawa Catchment

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4.5 Annual Water Balance

4.5.1 Annual Water Balance at Pitabaddara

An annual water balance (AWB) assessment was performed to compare the annual flow, precipitation, evaporation and annual rainfall-runoff coefficient in the Pitabaddara watershed. Conversion factor 0.8 was used to obtain evaporation from pan evaporation (Ponrajah, 1984). Following Table 4-6 and Figure 4-3 illustrate the annual water balance for Pitabaddara catchment.

Table 4-6: Annual water balance at Pitabaddara

Water Year	Annual Rainfall - Thiessen Method (mm/year)	Observed Annual Streamflow (mm/year)	Evaporation (mm/year)	Annual Water Balance (mm/year)	Annual Runoff Coefficient
2008/09	2756	1823	930	933	0.7
2009/10	2666	1710	867	956	0.6
2010/11	3370	2542	878	828	0.7
2011/12	2488	1436	867	1052	0.6
2012/13	3367	2274	835	1093	0.7
2013/14	2778	1425	788	1353	0.5
2014/15	3444	2101	704	1343	0.6
2015/16	2698	1808	722	890	0.7
2016/17	2767	1651	755	1116	0.6
2017/18	3482	2023	721	1459	0.6
Average	2982	1879	807	1103	0.6

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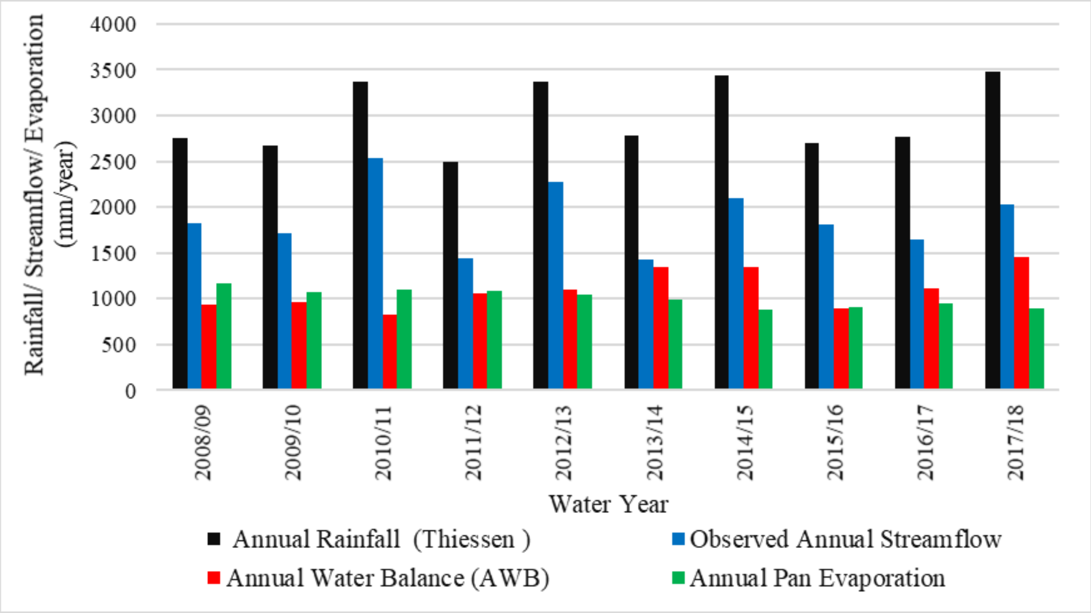

Figure 4-3: Annual water balance at Pitabaddara

4.5.1.1 Variation of annual runoff coefficients and evaporation of Pitabaddara

The annual runoff coefficient varies from 0.5 to 0.7 throughout the past 10 years and the average runoff coefficient is 0.6. Minimum annual runoff coefficient, 0.5 is reported for the 2013/14 water year. However, it could observe that streamflow at Pitabaddra in year 2013/14 is very low compared to streamflow with a similar volume of precipitation. Runoff coefficient derived for the Nilwala river basin from annual rainfall and streamflow was verified with the value recommended by literature (Elkaduwa & Sakthivadivel, 1999). A further comparison was done with the runoff coefficient given in the Hydrological Annuals prepared by the Hydrology Division of Irrigation Department, Sri Lanka.

The decline of annual evaporation is observed from 2008/09 to 2014/15 as shown in Figure 4-4 and minimum evaporation value is reported for the year 2014/15. The maximum evaporation has been recorded in the year 20018/09.

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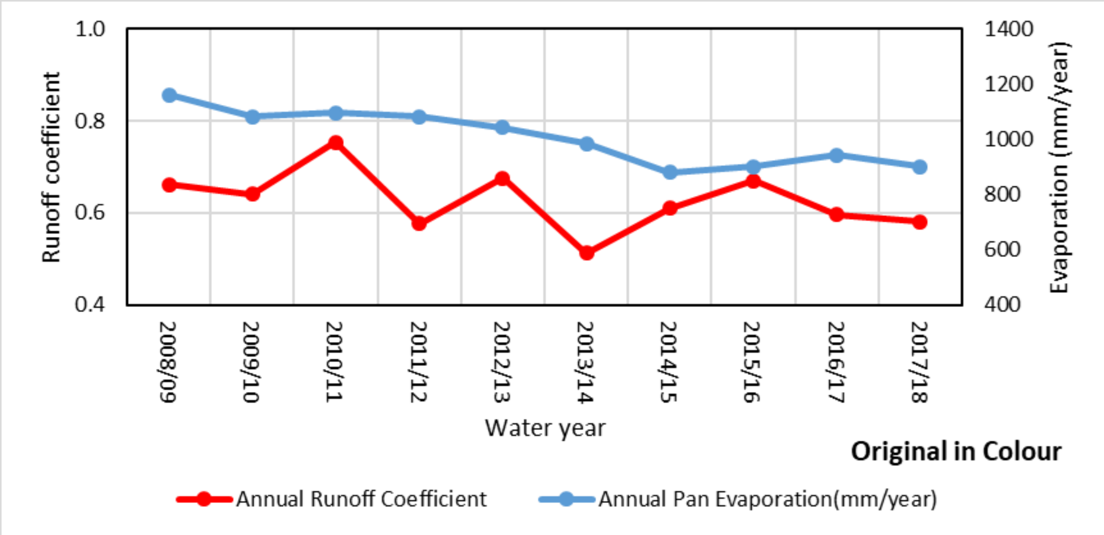

Figure 4-4: Variation of Annual Evaporation and Runoff Coefficient in Pitabaddara Watershed

4.5.1.2 Variation of annual rainfall and streamflow of Pitabaddara

Annual streamflow to annual rainfall presented the comparatively acceptable pattern as shown in Figure 4-5. High rainfalls were recorded in water year 2010/11, 2012/13, 2014/15 and 2017/18 where rainfall is greater than 3000 mm/year. However, the 2010/11 annual discharge showed the highest discharge and was a deviation from the annual discharge compared to other years with similar rainfall. The highest streamflow, 2542 mm/year could be seen in water year 2010/2011 for annual rainfall 3370 mm/year.

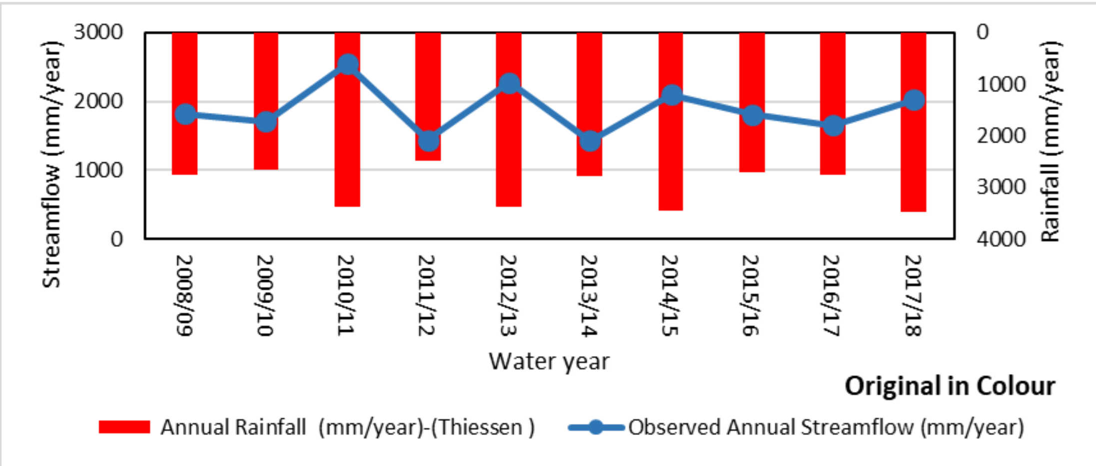

Figure 4-5: Variation of Annual Rainfall and Streamflow of Pitabaddara

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4.5.2 Annual Water Balance at Urawa

The AWB for Urawa catchment is shown in Table 4-7 and Figure 4-6. The reported streamflow in year 2016/17 was lower than streamflow with similar rainfall quantity such as water year2012/13 and 2017/18.

Table 4-7: Annual Water Balance at Urawa

Water Year	Annual Rainfall - Thiessen Method (mm/year)	Observed Annual Streamflow (mm/year)	Evaporation (mm/year)	Annual Water Balance (mm/year)	Annual Runoff Coefficient
2008/2009	2525	1586	930	939	0.6
2009/2010	1968	1295	867	673	0.7
2010/2011	2968	1838	878	1130	0.6
2011/2012	2097	1062	867	1035	0.5
2012/2013	2715	1707	835	1008	0.6
2013/2014	2029	990	788	1039	0.5
2014/2015	2624	1422	704	1202	0.5
2015/2016	2253	1470	722	783	0.7
2016/2017	2772	1121	755	1651	0.4
2017/2018	2848	1793	721	1055	0.6
Average	2480	1428	807	1052	0.6

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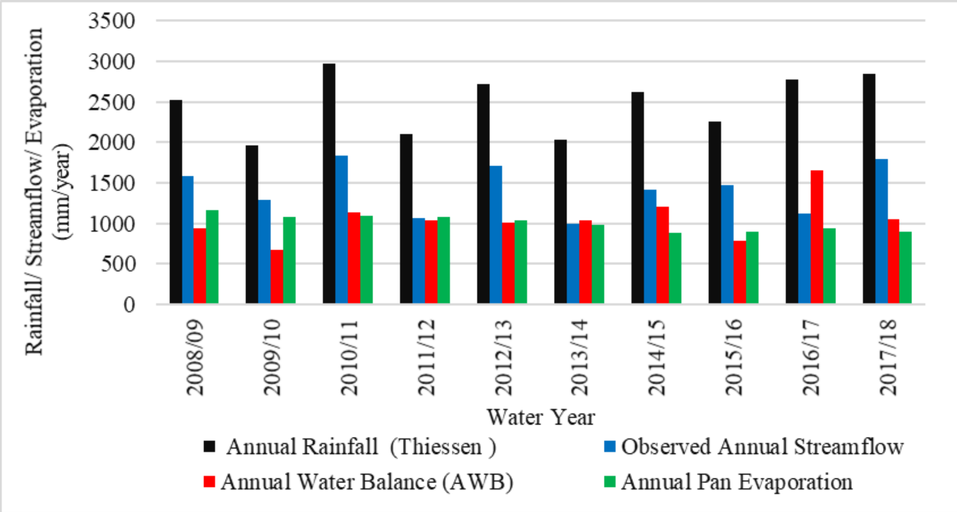

Figure 4-6: Annual Water Balance at Urawa

4.5.2.1 Variation of annual runoff coefficients and evaporation of Urawa

The annual rainfall-runoff coefficient varied from 0.4 to 0.7 where average runoff was recorded as 0.6. Runoff coefficient value complies with the values given in the literature as prescribed under above 4.5.1.1. Nevertheless, minimum value 0.4 could be seen as shown in Figure 4-7 for water year 2016/17 which has an unexpected reduction in annual streamflow.

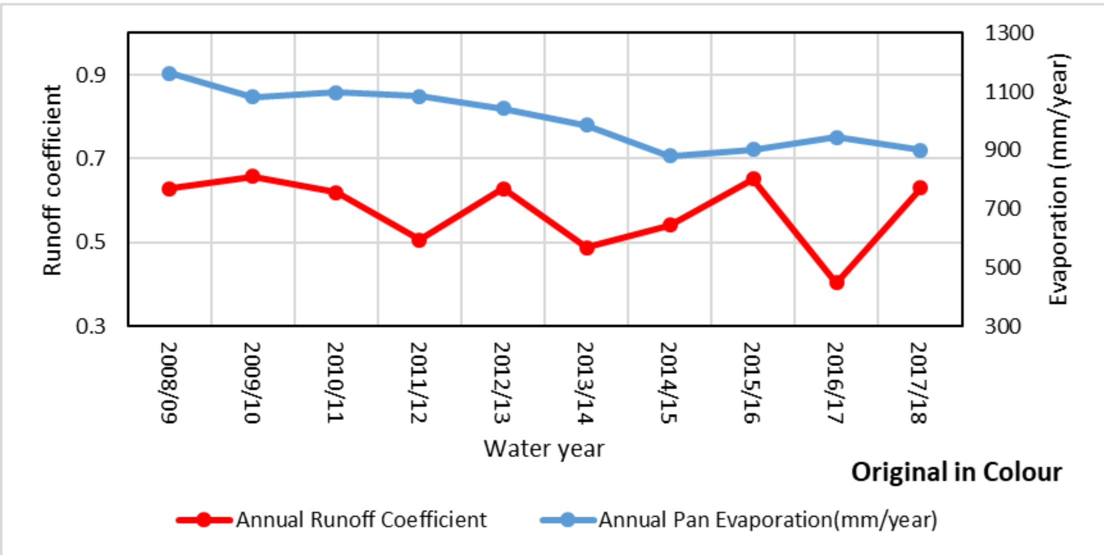

Figure 4-7: Variation of Annual Evaporation and Runoff Coefficient in Urawa Watershed

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4.5.2.2 Variation of annual rainfall and streamflow at Urawa

The pattern of annual streamflow concerning the annual rainfall was acceptable except for the year 2016/2017 as depicts in Figure 4-8. Annual rainfall had increased by 519 mm from year 2015/16 to 2016/17 where annual streamflow had reduced by 349 mm which was an unexpected situation. The highest streamflow of 1838 mm/year was observed for the highest rainfall in 2010/11.

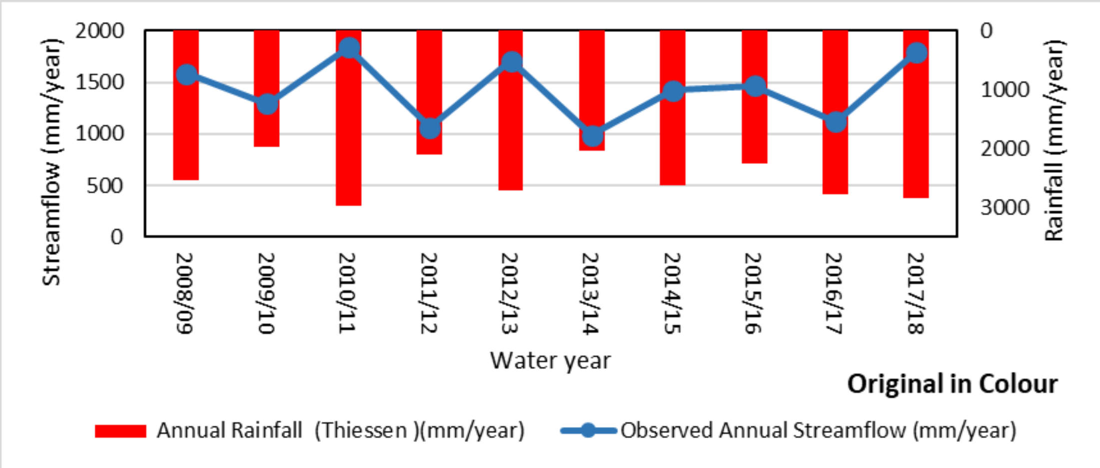

Figure 4-8: Variation of Annual Rainfall and Streamflow in Urawa Watershed

4.6 Consistency Check

The double mass curve was applied for this study to check the consistency of hydrological data, precipitation, streamflow and evaporation by the comparison of pertinent hydrological data of one station against the summation of data of other stations in the project area.

Consistency of the data is shown by the relation of these two variables. A fixed-rate of two variable denotes the consistency of variable and it is shown by a straight line in graphically. Breaks of the line depict inconsistencies of the presented hydrological data series (Searcy, Hardison, & Langbein, 1960). These inconsistencies depict whether interested hydrological data have undergone significant changes over the selected time series due to anthropogenic activities, changes of gauging station, climatic changes, and occurrence of observational error, etc. (Gao et al., 2017).

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Following Figure 4-9 shows a double mass curve plot for the rainfall gauging stations and accordingly, there is no significant difference in precipitation data series for the considered 10-year period.

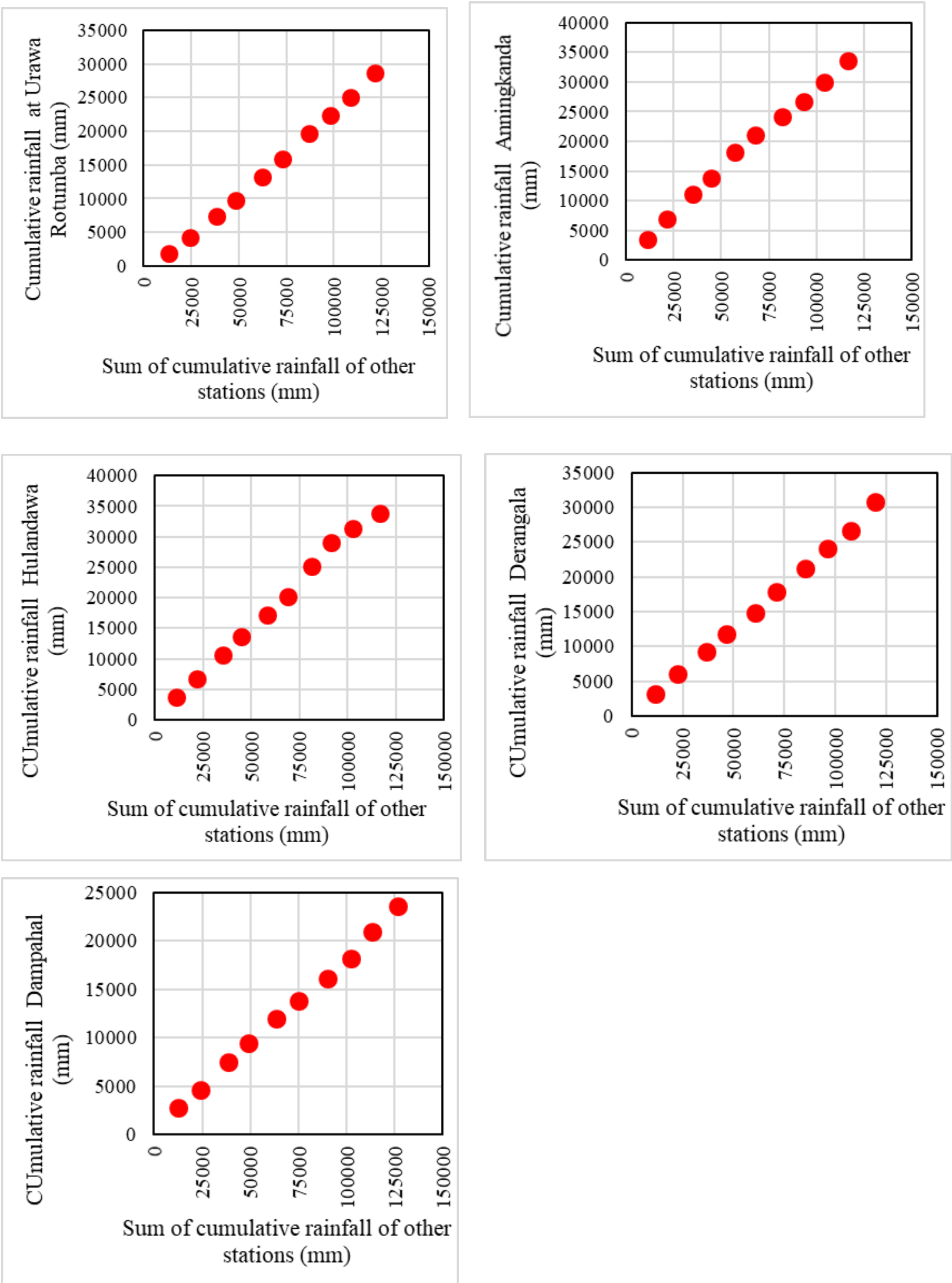

Figure 4-9: Double Mass Curve for Rainfall Stations

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According to the graphical representation of a double mass curve for the rainfall, streamflow and evaporation data as shown in Figure 4-10, there is no significant inconsistency in rainfall, streamflow and evaporation data within the selected period.

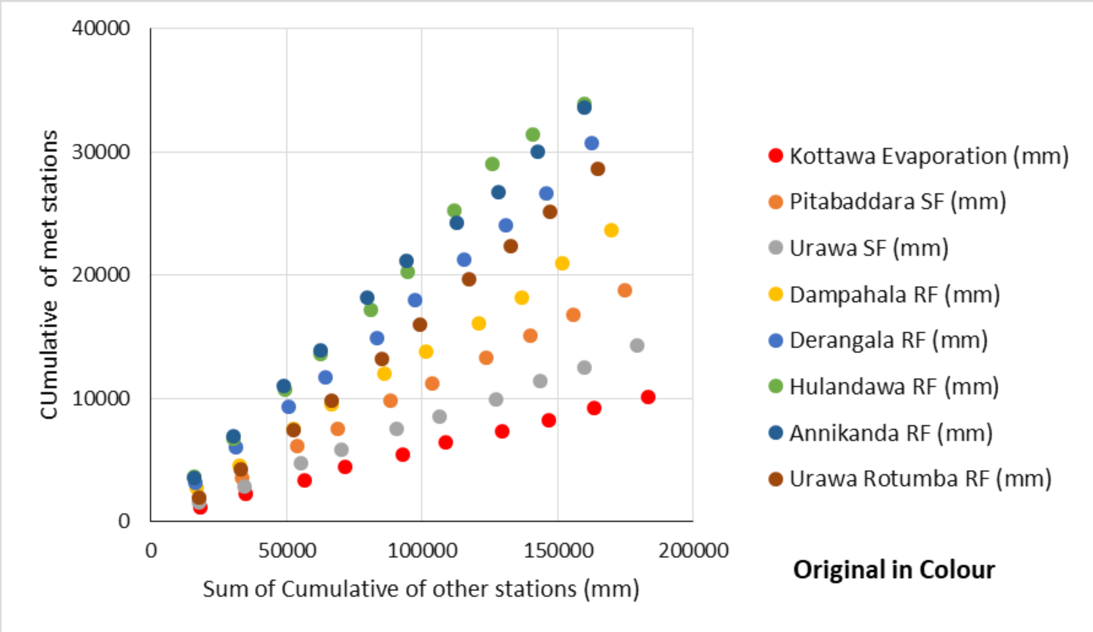

Figure 4-10: Double mass curve for each rainfall (RF), streamflow (SF) and Evaporation stations

4.7 Visual data checking

Data was checked visually to assess streamflow responses to rainfall for selected rainfall stations to identify data inconsistencies and the outliers in the datasets. The red colour circles in Figure 4-11, Figure 4-12, Figure 4-13 and Figure 4-14 shows where rainfall and streamflow behavior was nonresponsive.

This assessment was done for both Pitabaddra and Urawa watersheds,

1. streamflow responses to average rainfall calculated from the Thiessen methods
2. streamflow responses with respect to rainfall in each gauging station

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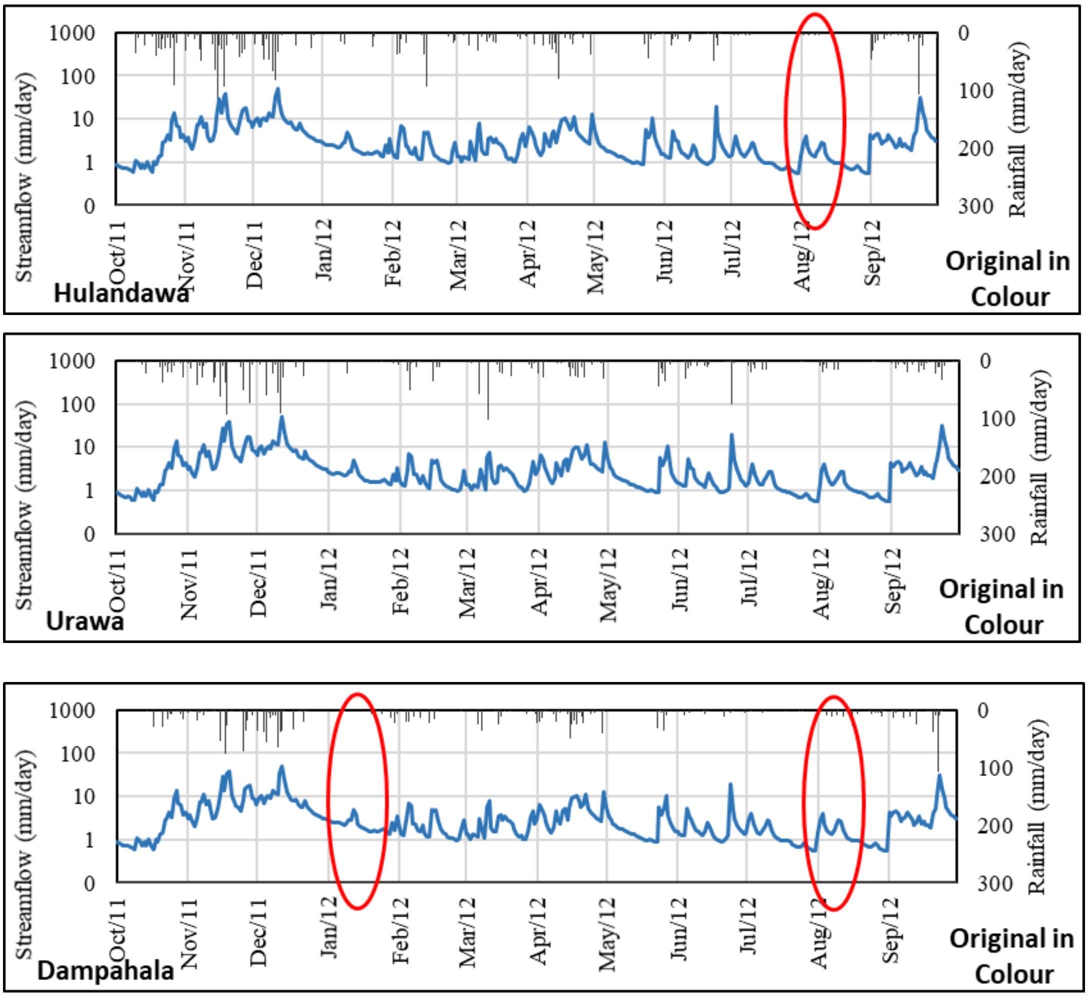
4.7.1 Visual data checking for Pitabaddara

Visual data checking for the year 2011/12 for each station is shown in Figure 4-11 and for other years are shown in Appendix B.

Responsiveness of streamflow at Pitabaddara was higher with Urawa Rotumba, Hulandawa and Derangala rainfall gauging stations and comparatively low with Anningkanda and Dampahala rainfall stations. Anningkanda and Dampahala stations are located in the upper part of the watershed and faraway than other stations.

As shown in Figure 4-11 increase of streamflow in Aug/2012 was not matched with allied rainfall at Hulandawa and Dampahala. Also, streamflow variation in March 2012 and January 2012 were not compatible with respective rainfall at Anningkanda and Dampahala.Rotumba



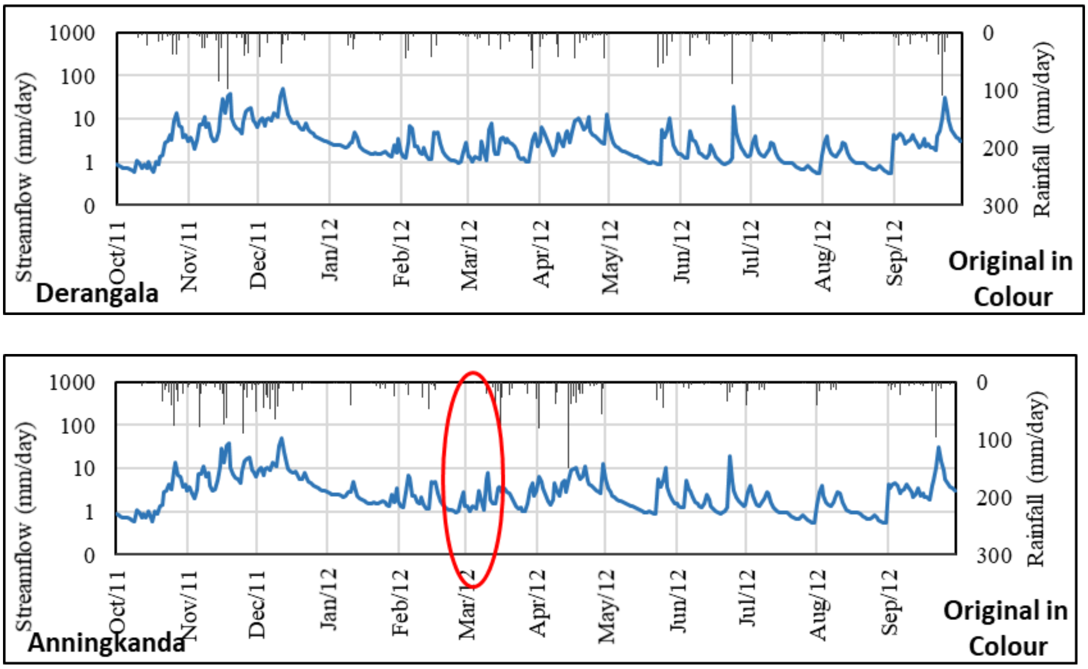
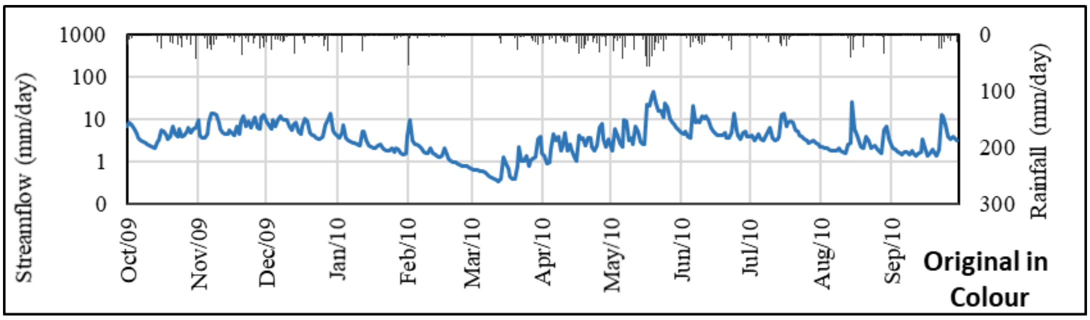


Figure 4-11: Visual data checking for Pitabaddara - Year 2011/12

Figure 4-12 shows Pitabaddra streamflow responses for average rainfall from water year 2008/09 to 2017/18. Average rainfall was computed using the Thiessen method and the response of streamflow to average rainfall was acceptable as shown in Figure 4-12. Streamflow in March and September in 2012 depicted an increasing and there was no corresponding high rainfall has been recorded at that time. It was observed by the graphical representation that streamflow at Pitabaddara responses to the average rainfall for the selected time.



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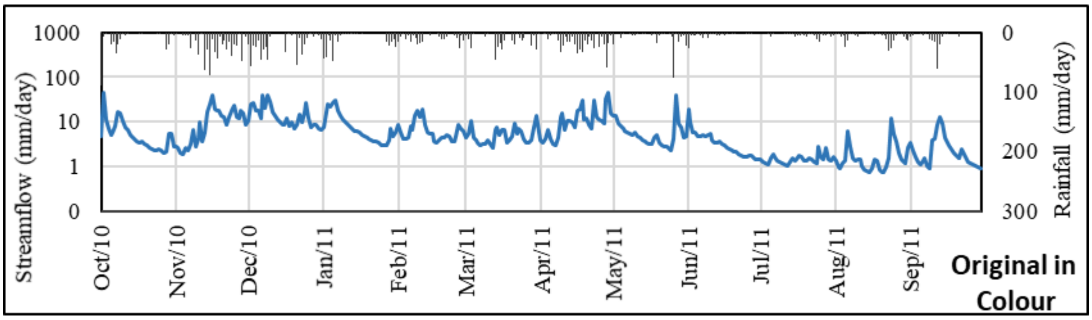
Streamflow (mm/day)
1000
100
10
1
0
Rainfall (mm/day)
0
100
200
300
Oct/10
Nov/10
Dec/10
Jan/11
Feb/11
Mar/11
Apr/11
May/11
Jun/11
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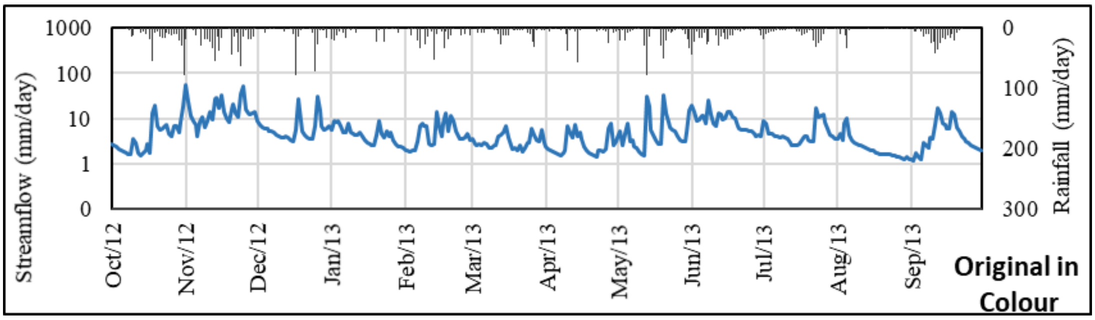
Aug/11
Sep/11
Original in Colour


Streamflow (mm/day)
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100
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1
0
Rainfall (mm/day)
0
100
200
300
Oct/12
Nov/12
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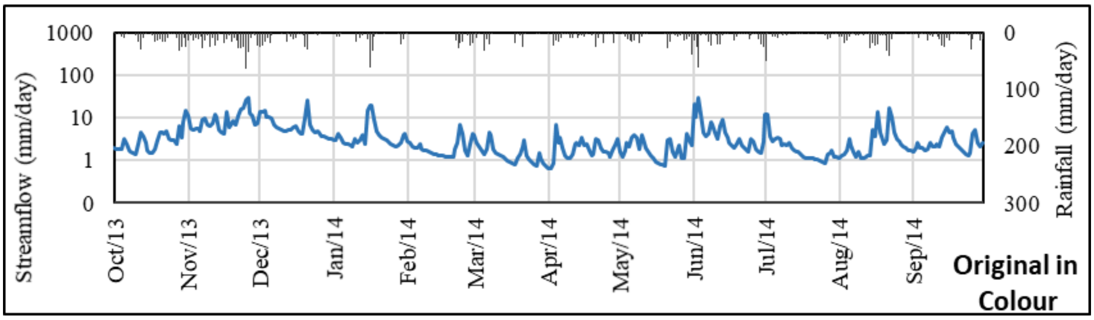
Sep/13
Original in Colour


Streamflow (mm/day)
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1
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Rainfall (mm/day)
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Oct/13
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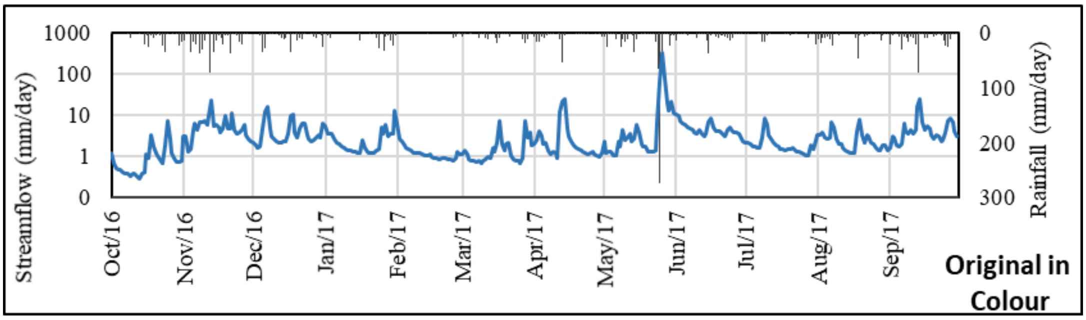
Original in Colour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100
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1
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Rainfall (mm/day)
0
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Oct/16
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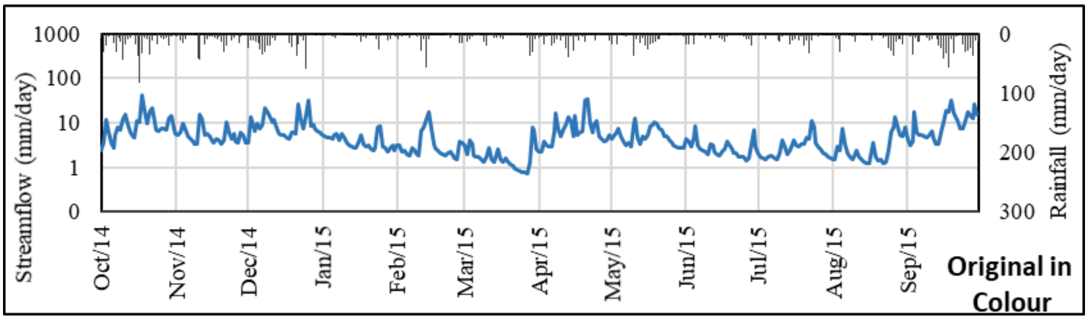
Aug/17
Sep/17
Original in Colour


Streamflow (mm/day)
1000
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1
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Rainfall (mm/day)
0
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Oct/14
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Feb/15
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Original in Colour

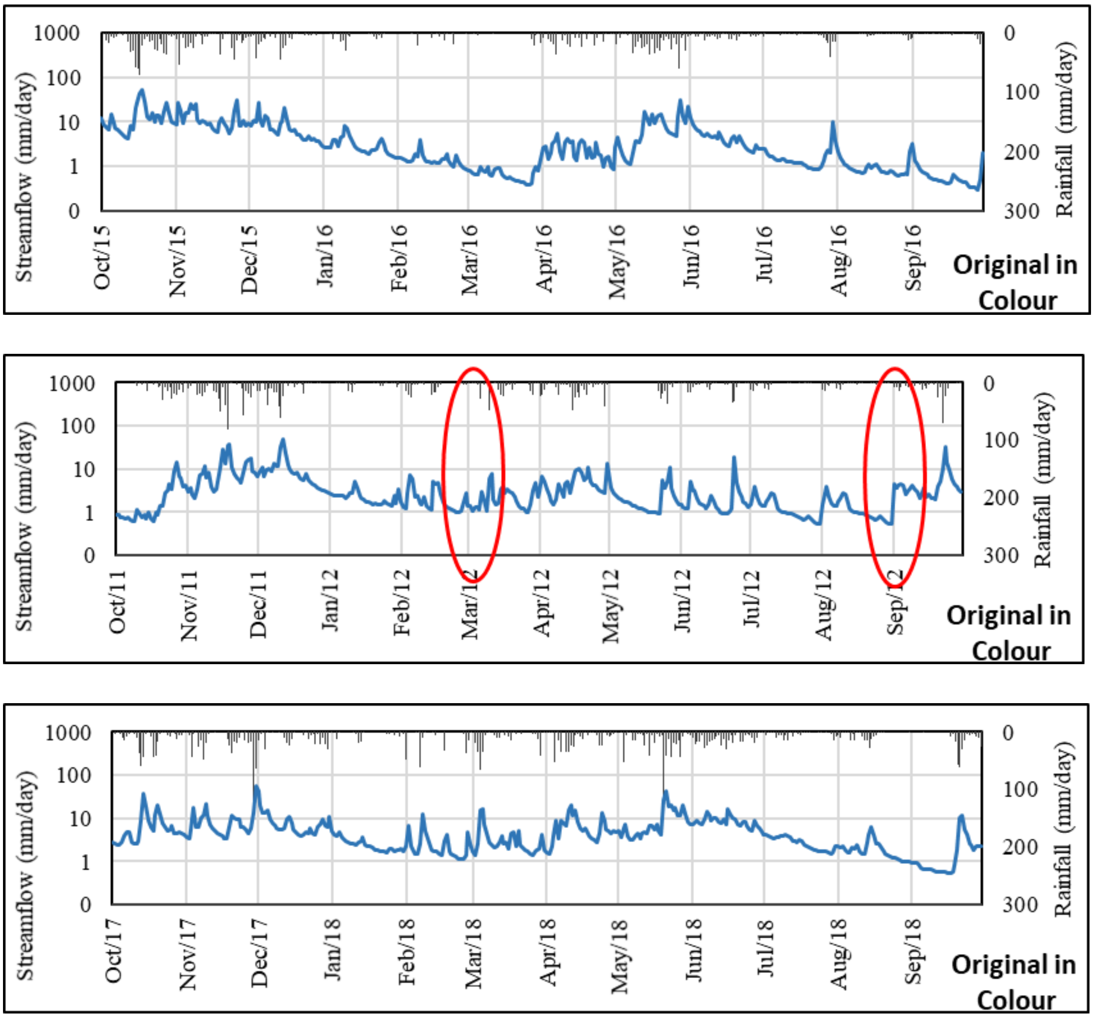


Figure 4-12: Pitabaddara Streamflow vs Thissen Rainfall Variation

4.7.2 Visual data checking for Urawa

Following Figure 4-13 shows the reaction of streamflow for rainfall stations at Urawa and Dampahala for year 2011/12 and graphical representation of other years is attached with Appendix B. Rainfall data at Anningkanda gauging station had satisfactory relation with streamflow at Urawa than rainfall data at Dampahala station. Though an increase of streamflow in July 2012 was identified, related rainfall was not recorded at Dampahala station.

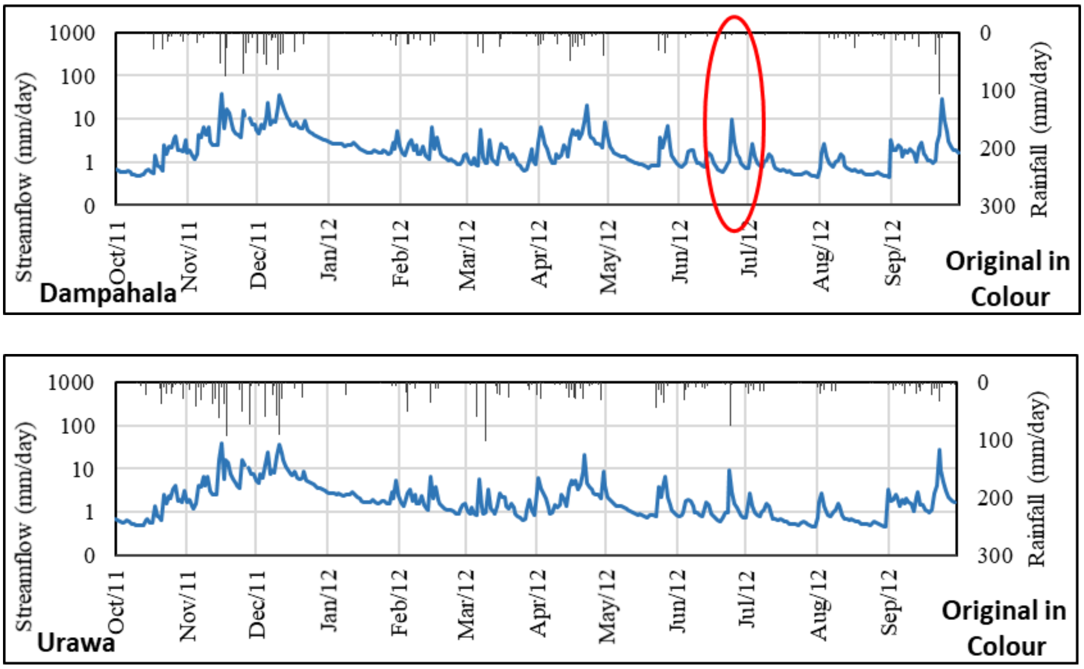
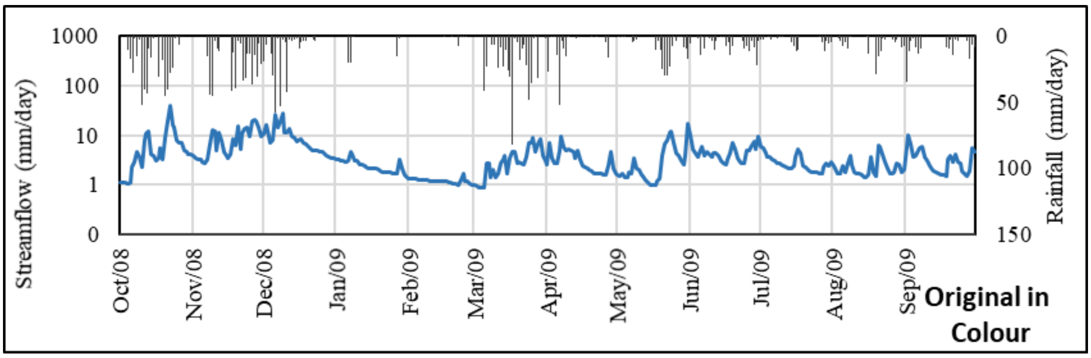


Figure 4-13: Visual data checking for Urawa - Year 2011/12

Streamflow at Urawa and average rainfall, calculated using the Thiessen method were graphed as depicts in Figure 4-14. Nonconformities were identified in April 2011, September 2014, and May 2018. In May 2018, it had not recorded an increase of streamflow for high average rainfall. However, except for these special few situations, streamflow at Urawa positively responded to the average rainfall as shown in Figure 4-14.



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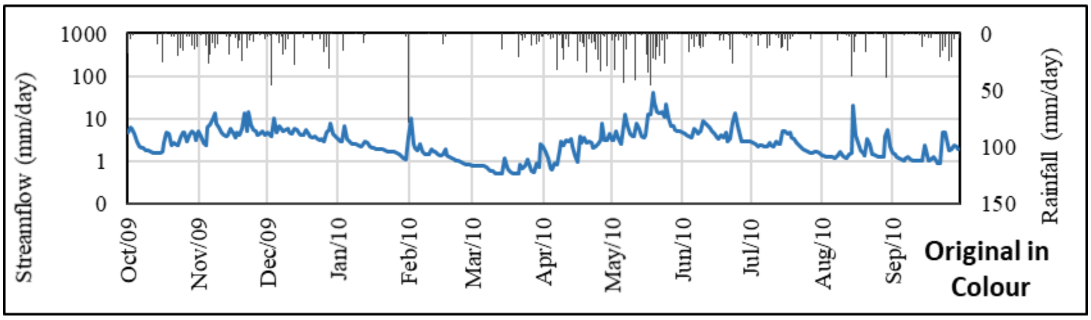
Streamflow (mm/day)
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Rainfall (mm/day)
Oct/09
Nov/09
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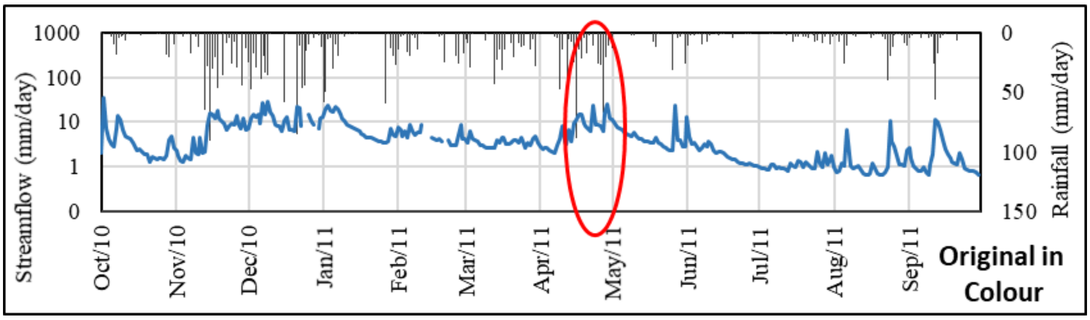
Sep/10
Original in Colour


Streamflow (mm/day)
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Rainfall (mm/day)
Oct/10
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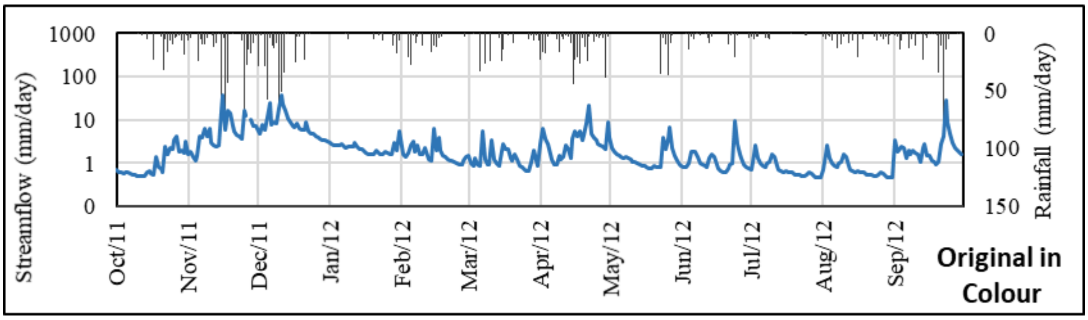
Aug/11
Sep/11
Original in Colour


Streamflow (mm/day)
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Rainfall (mm/day)
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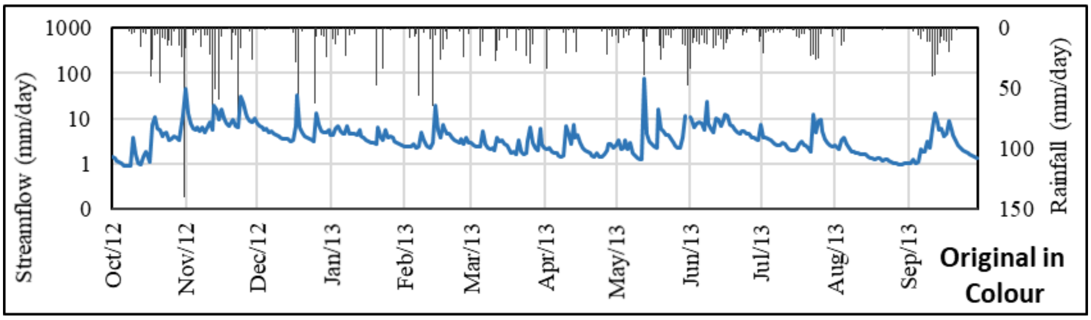
Sep/12
Original in Colour


Streamflow (mm/day)
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Rainfall (mm/day)
Oct/12
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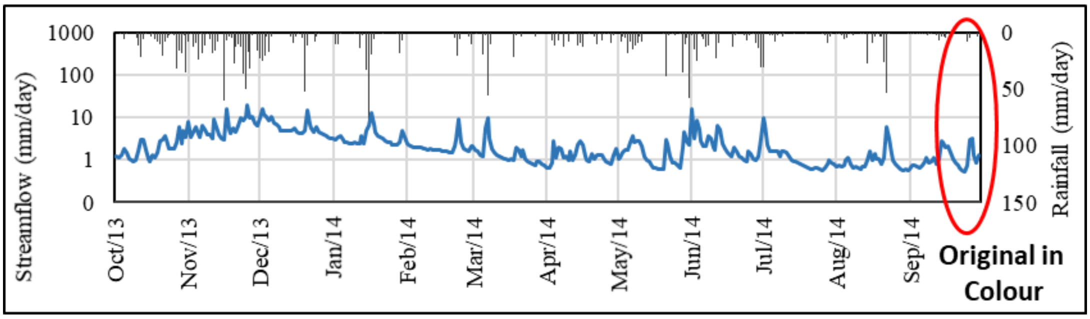
Streamflow (mm/day)
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Rainfall (mm/day)
Oct/13
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Original in Colour

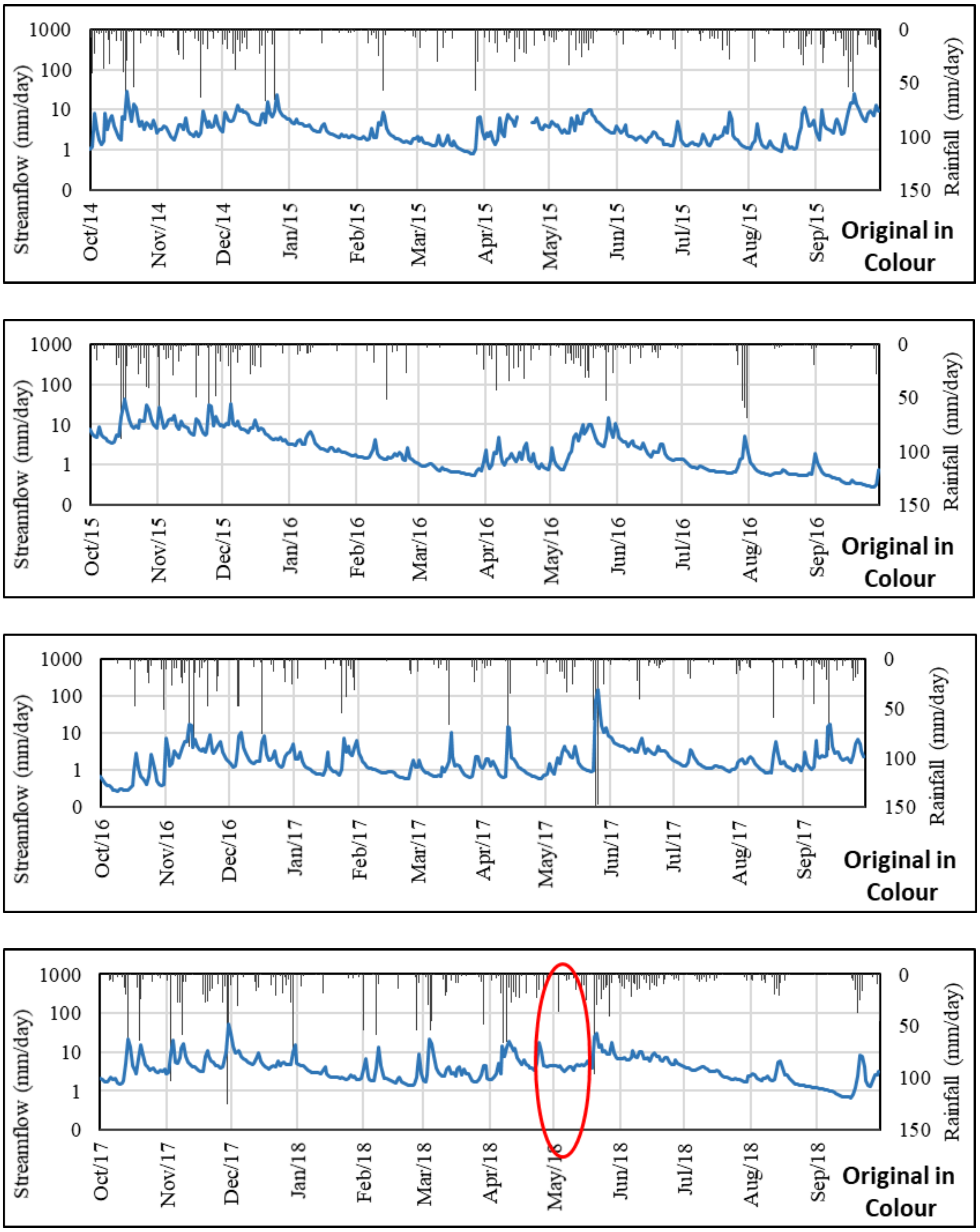

Figure 4-14: Urawa Streamflow vs Thiessen Rainfall Variation

4.8 Monthly and Annual Rainfall

The monthly average rainfall of Hulanduwa, Urawa Rotumba, Dampahala, Anningkanda, and Derangala rainfall stations are given in Table 4-8 and graphical representation by Figure 4-15. The rainfall variation followed with two peaks concerning two seasonal rainfall patterns name North-East Monsoon (October to

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March) and South-West Monsoon (April to September) as illustrated by Figure 4-15. The lowest annual rainfall was marked for the Anningkanda rainfall observatory whilst the highest annual rainfall was noted for the Dampahala rainfall observatory.

Table 4-8: Comparison of monthly average rainfall

Month	Monthly Average Rainfall (mm)				
	Urawa Rotumba	Anningkanada	Hulandawa	Derangala	Dampahala
Oct	320	252	340	410	406
Nov	435	336	412	526	449
Dec	297	259	251	360	325
Jan	104	93	165	169	163
Feb	135	91	139	150	179
Mar	191	151	199	223	214
Apr	259	191	250	386	300
May	374	156	391	413	403
Jun	220	86	290	206	282
Jul	131	69	162	109	155
Aug	149	93	163	163	208
Sep	249	122	280	245	302

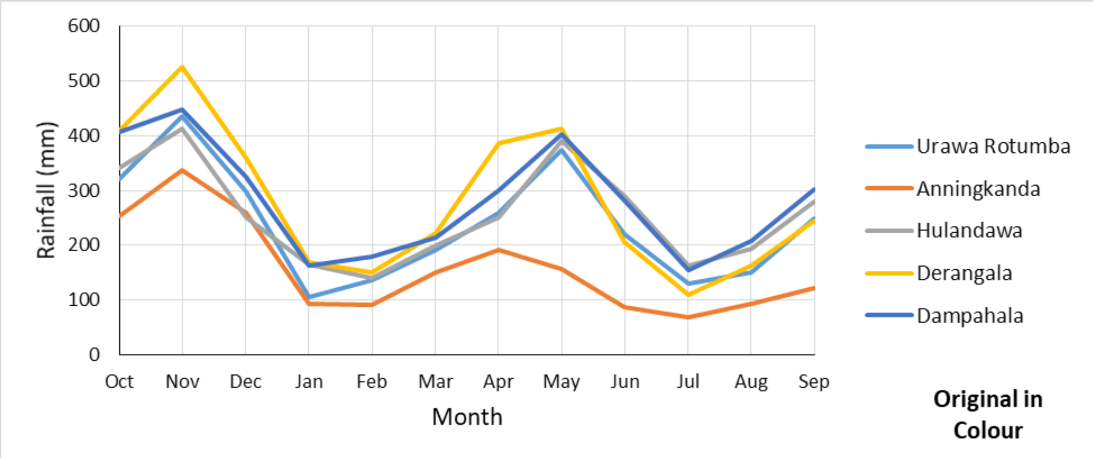

Figure 4-15: Comparison of monthly average rainfall

Following Figure 4-16 shows a graphical comparison of monthly Thiessen rainfall and streamflow for Urawa and Pitabaddara watersheds. Streamflow responded to the Thiessen rainfall was seem to be acceptable for both Pitabaddara and Urawa watersheds.

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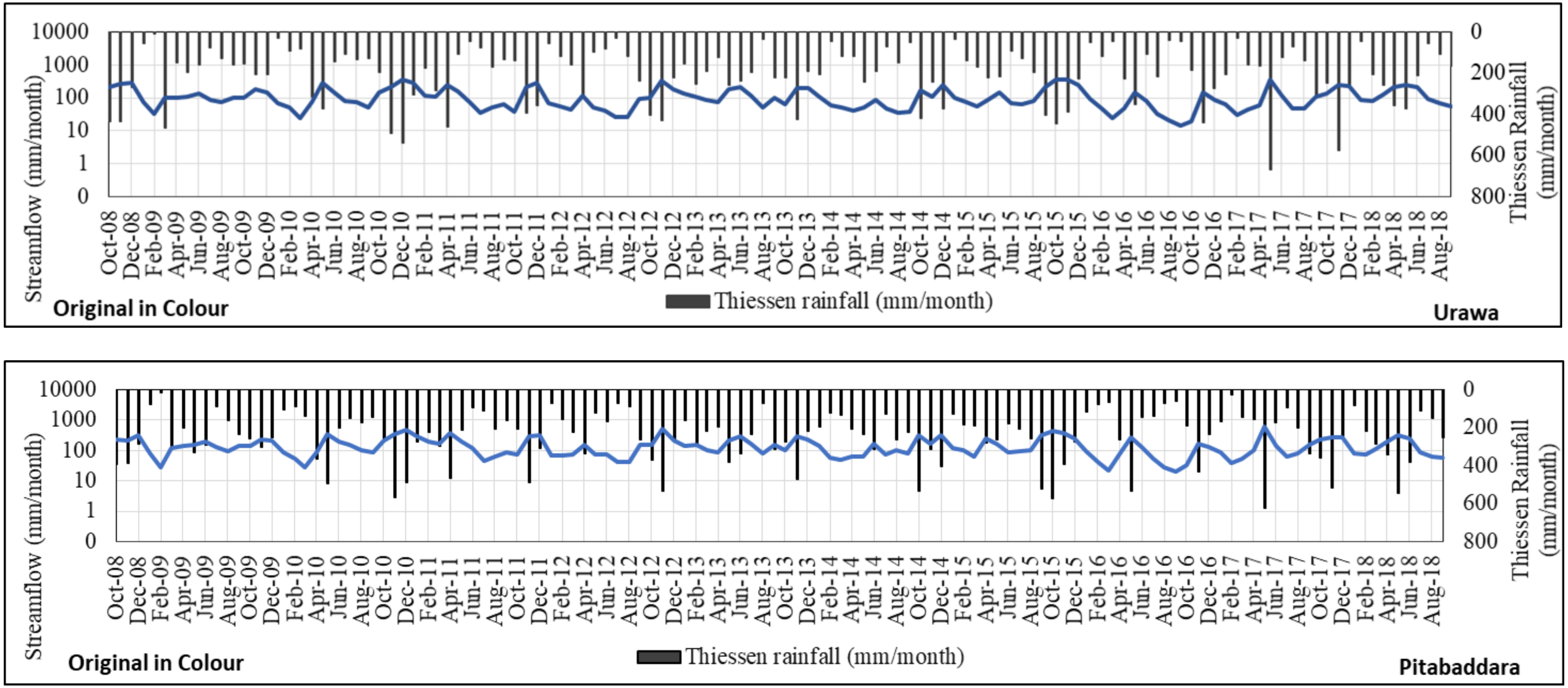

Figure 4-16:: Comparison of Monthly Thiessen Rainfall and Streamflow in Pitabaddara and Urawa Watersheds

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5 MODEL DEVELOPMENT AND RESULTS

5.1 Catchment Selection

Origination of the Nilwala river is at Deniyaya Hills, located at 1,050 m MSL. The river reaches Pitabaddara within the first 36 km and drops to 12 m MSL. Though a significant slope is recorded in the upper part, it has a gentle slope down to the sea in the last 42 km in downstream from Pitabeddra to Matara (Asian Disaster Reduction Center, 2009).

Accordingly, Urawa and Pitabeddra catchments (Figure 5-1) were selected for the study located in the upper part of the river basin and Urawa watershed is a sub-catchment of Pitabaddara catchment. These catchments were selected considering the availability of hydrological information and as well as physical catchment characteristics to the level of simple hydrological modelling. The catchment area of Pitabeddara and Urawa catchments are 291 km^2 and 54 km^2 respectively.

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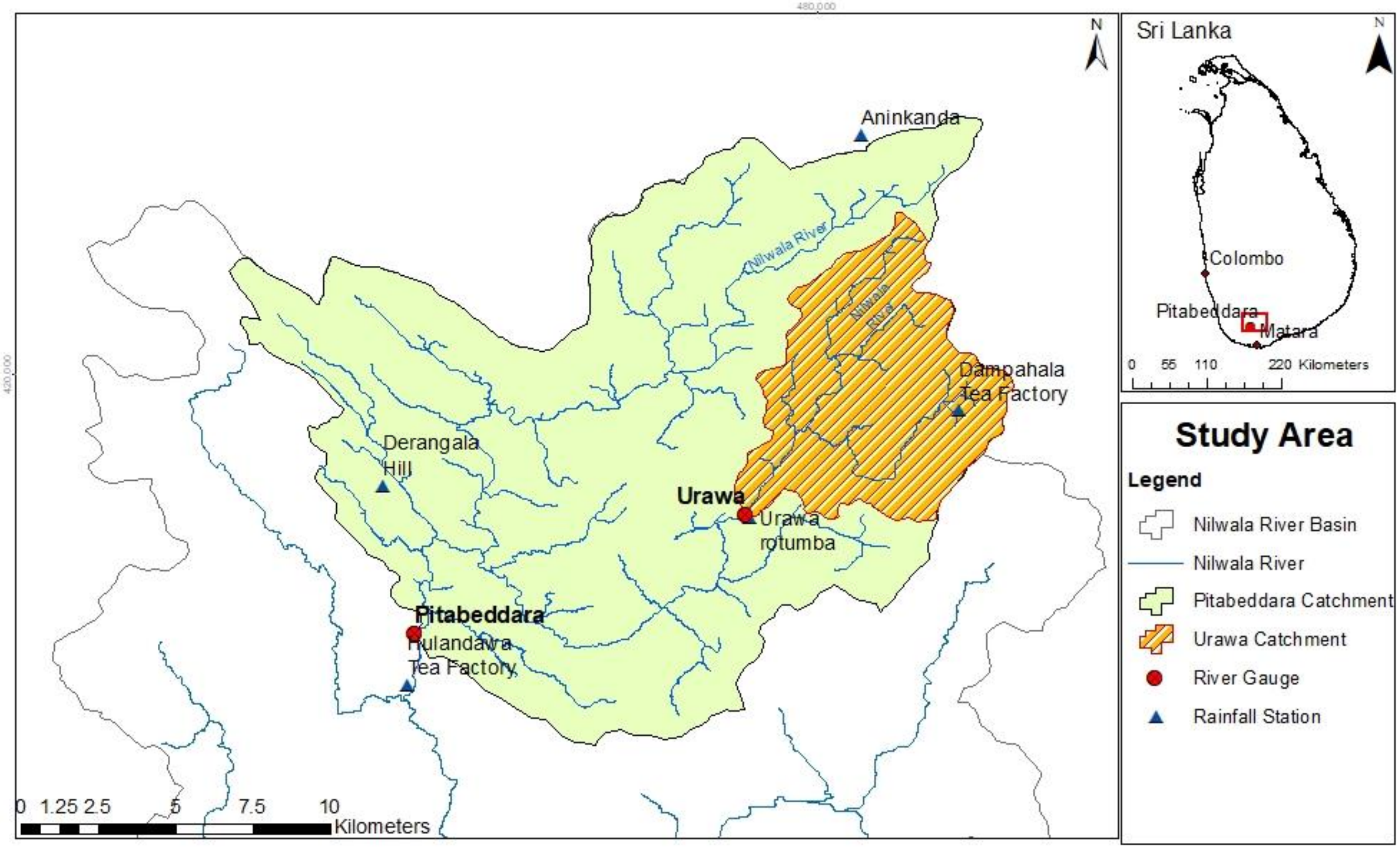

Figure 5-1: Pitabeddara and Urawa catchments

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5.2 Model Selection

The selection of the model for the hydrologic model was done evaluating criteria that introduced subject to the objective of the research. Detail of the model selection has been included in chapter 2.4.

5.3 Development of Basin model

5.3.1 Canopy Model

The selection of the canopy model concerning subjective criteria is discussed in chapter 2.9.1.1. Accordingly simple canopy model was selected and initial and maximum storage of canopy, crop coefficient, and the water uptake methods from the soil are to be assigned in the Simple canopy model (Scharffenberg et al., 2018).

Canopy model developed in HEC-HMS 4.3 has two methods to extract water from the soil. Those are water extraction from the potential evapotranspiration rate method and Tension reduction methods. However, Deficit Constant method can be applied with the potential evapotranspiration rate method and Soil Moisture Accounting model can be used with both water extraction methods. Further potential evapotranspiration rate is reduced when water-extracting in the tension zone. (Scharffenberg et al., 2018).

5.3.1.1 Canopy Model Parameter

Parameters, initially filled canopy storage (%), maximum storage of canopy (mm) and crop coefficient should be assigned in the canopy model. Mcenroe and Ph (2010) simulated continuous streamflow at Kansas and used initially filled canopy storage as 0%. Nevertheless, the International Sava River Basin Commission (2017) has done studied for the Sava river basin for flood studies and assumed storage of the canopy in the initial stage as full. Therefore, the initially filled storage was assigned as 0% to the intention of continuous streamflow simulation for water resource management.

Many studies have been carried out to identify precipitation losses due to interception. Curtis (2017) stated 10-25% annual precipitation is lost by interception and it depends on meteorological and vegetation factors. Pócs (1982) and Veneklaas and Van Ek

(1990) identified canopy storage capacity as 5 mm in moss-rich primary forest in Tanzania and mossy old-growth upper montane cloud forest in Colombia respectively.

Hall, Calder, Gunawardena, and Rosier (1996) carried out a two-layer stochastic model to assess the interception of rainfall in tropical forest (Kandyan Forest Garden) in Sri Lanka and concluded maximum canopy storage capacity in the range of 3.4 – 6.24 mm. Richard, Luis, Dirk, and Martin (1998) presented crop coefficient values with an updated procedure for calculating reference and crop evapotranspiration.

Accordingly, 6 mm canopy storage capacity, 0% initial storage and simple water extraction method were assigned for both Piabeddara and Urawa watersheds.

5.3.2 Surface model

5.3.2.1 Surface Model Parameter

Bennett (1998) presented value for surface storage by following Table 5-1 based on land use and basin slope. That value is used by Singh and Jain (2015), Ouédraogo, Raude, and Gathenya (2018) and Fleming and Neary (2004) for continuous streamflow simulation studies in HEC-HMS models.

Table 5-1:Surface Depression Storage

Description	Slope (%)	Surface Storage (mm)
Paved impervious areas	NA	3.2-6.4
Steep, smooth slopes	>30	1.0
Moderate to gentle slopes	5 - 30	12.7 - 6.4
Flat, furrowed land	0 - 5	50.8

Source: (Bennett, 1998)

Based on Table 5-1, 12 mm surface depression storage was assigned for both Pitabaddara and Urawa watershed in initial simulation.

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5.3.3 Precipitation loss model

The selection of precipitation loss model has been discussed in chapter 2.9.1.3. Deficit and constant loss model is a quasi-continuous variation on the Initial and Constant Rate model and the specialty of the model is the initial model is recovered after a prolonged period of no rainfall (Feldman, 2000). Also, it uses a single soil layer to account for continuous changes in moisture content (Meenu et al., 2012).

5.3.3.1 Deficit and Constant Rate Loss model parameter

Deficit and Constant Rate loss method has four parameters as Constant Rate, Initial Deficit, Maximum Deficit, and percentage of impervious area. The land area directly connected to the streamflow of the basin surface is indicated by the percentage of impervious (Ahbari et al., 2018).

Skagga and Khaleel (1982) proposed to commence the simulation three days after the precipitation allowing the soil to drain water to reach field capacity and which is used as Initial Deficit. Saxton and Rawls (2006) presented soil water characteristics such as field capacity, saturated conductivity, and wilting point, etc., estimated by texture and organic matter of the soil to apply for the estimation of initial deficit parameter. The maximum deficit is the maximum amount of water; soil layer can hold. An upper bound defines as the multiplication of depth of the active soil layer and porosity (Scharffenberg et al., 2018).

Chow et al. (1988) calculated maximum potential retention which is similar to the maximum storage using SCS equation. CN values for relevant catchments were calculated reference to the land use (Figure 5-2), hydrological soil group and Antecedent Moisture Condition. Antecedent moisture condition II and hydrological soil group C was selected to derive weighted CN value as shown in Table 5-2 and Table 5-3

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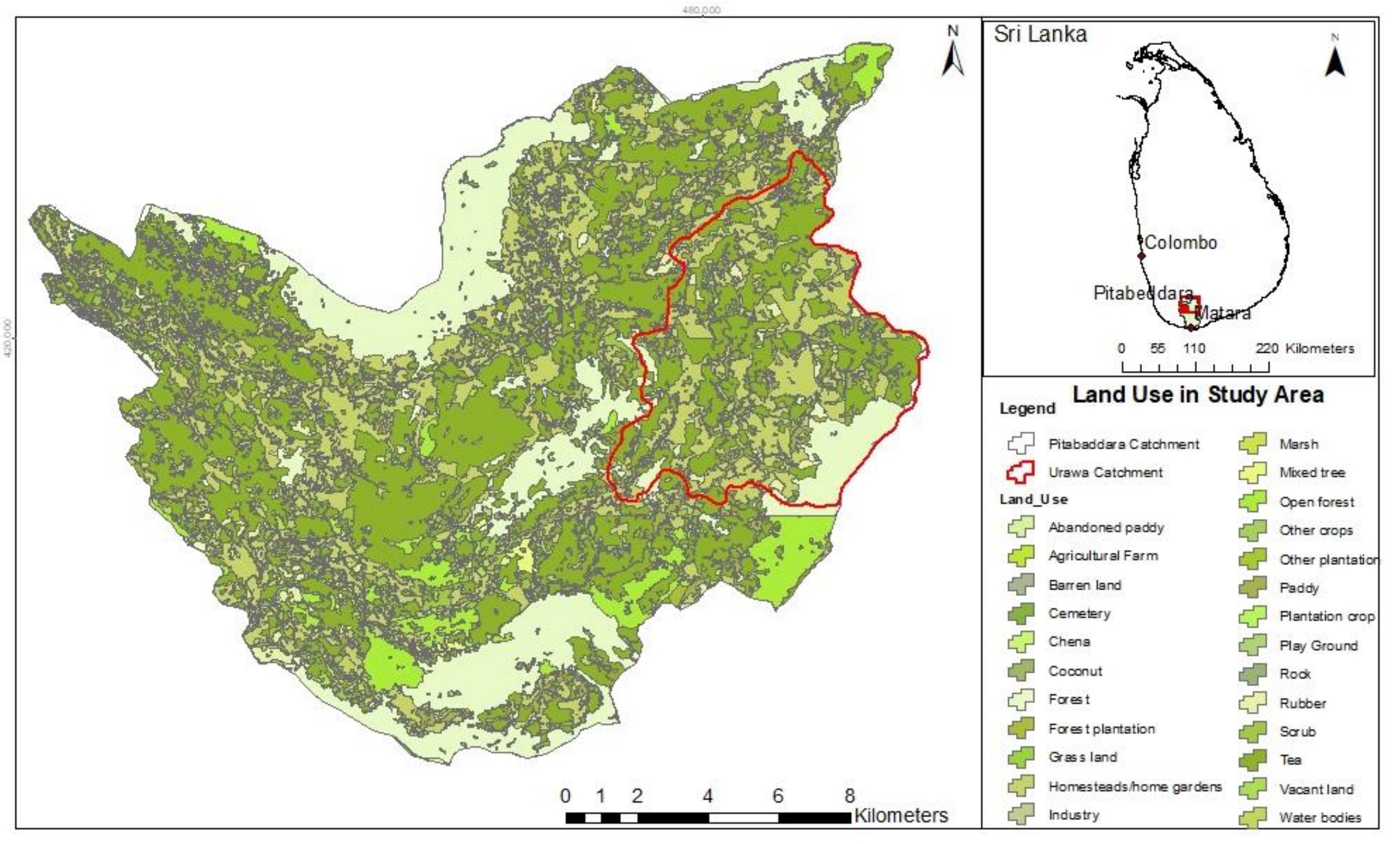

Figure 5-2: Land use distribution of study area

Source: Survey Department (2002)

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Table 5-2: Weighted curve number calculation for Pitabaddara Watershed

Land Use Type	Area (%)	Soil Group C	
		CN value	Weighted CN
Abandoned paddy	0.36%	88	0.31
Barren land	0.06%	91	0.05
Coconut	0.25%	82	0.20
Forest	18.03%	77	13.89
Forest plantation	0.31%	77	0.24
Grass land	0.04%	79	0.03
Homesteads/home gardens	24.58%	80	19.66
Industry	0.03%	91	0.02
Marsh	0.03%	88	0.03
Mixed tree	0.84%	73	0.61
Open forest	5.44%	73	3.97
Other crops	0.18%	84	0.16
Other plantation	0.27%	81	0.22
Paddy	6.28%	88	5.53
Play Ground	0.03%	79	0.02
Rubber	1.13%	82	0.93
Scrub	3.06%	74	2.26
Tea	38.43%	79	30.36
Vacant land	0.02%	77	0.01
Water bodies	0.62%	100	0.62
Total	**100%**		**79.15**

Table 5-3: Weighted curve number calculation for Urawa Watershed

Land Use Type	Area (%)	Soil Group C	
		CN value	Weighted CN
Abandoned paddy	0.22%	88	0.19
Coconut	0.31%	82	0.25
Forest	10.79%	77	8.31
Forest plantation	0.69%	77	0.53
Homesteads/home gardens	35.11%	80	28.09
Mixed tree	0.03%	73	0.02
Open forest	0.39%	73	0.28
Other crops	0.08%	84	0.07
Paddy	8.53%	88	7.51
Play Ground	0.01%	79	0.00
Rubber	2.44%	82	2.00
Scrub	0.63%	74	0.46
Tea	39.95%	79	31.56
Water bodies	0.84%	100	0.84
Total	**100%**		**80.12**

`

Maximum deficit or maximum potential retention (S) was calculated using Equation 5-1 and Initial deficit (I_a) by Equation 5-2 as mentioned in Chow et al. (1988). S and I_a values for both catchments are shown in Table 5-5.

$$S = (\frac{1000}{CN} - 10) \quad \text{Equation 5-1}$$

$$I_a = 0.2\,S \quad \text{Equation 5-2}$$

The ultimate infiltration capacity of the soil is defined as the constant loss rate, which defines the infiltration rate when the soil layer is saturated. Soil is categorized base on infiltration capacity by Soil Conservation Service (1986) and Skagga and Khaleel (1982) presented estimates for infiltration rate for the soil types as shown in below Table 5-4.

Table 5-4: SCS soil groups and infiltration loss rates

Soil Group	Description	Range of Loss Rates (in/hr)
A	Deep sand, deep loess, aggregated silts	0.30 - 0.45
B	Shallow loess, sandy loam	0.15 - 0.30
C	Clay loams, shallow sandy loam, soils low in organic content, and soils usually high in clay	0.05 - 0.15
D	Soils that swell significantly when wet, heavy plastic clays, and certain saline soils	0.00 - 0.05

Source : (Skagga & Khaleel, 1982) & (Soil Conservation Service, 1986)

Accordingly, a summary of the relevant parameters for the deficit and constant rate loss model was shown in Table 5-5.

Table 5-5: Summary of the parameters of the deficit constant rate loss model

Parameter	Pitabaddara Catchment	Urawa Catchment
Weighted CN value	79.0	80.0
S - Maximum Storage (mm)	67.1	63.1
Initial Deficit (mm)	13.4	12.6
Constant rate (mm/hr)	2.0	2.0
Impervious percentage (%)	25.0	25.0

`

5.3.4 Transform method

The selection of the Transform model has been discussed in chapter 2.9.1.4. SCS unit hydrograph has been used widely for many different environments and has provided an acceptable level of accurate results for estimating surface runoff in many hydrologic applications (Chu & Steinman, 2009).

5.3.4.1 SCS Unit Hydrograph Model Parameter

Ouédraogo et al. (2018) modelled Mkurumudzi River catchment in Kenya using the SCS unit hydrograph and applied lag time by using the following Equation 5-3 and Equation 5-4. They concluded acceptable precision in their model and suitability of the model to apply the studied area.

$$T_{LAG} = L^{0.8}(S+1)^{0.7}/1900\sqrt{Y} \qquad \text{Equation 5-3}$$

$$\mathrm{S} = \frac{25400}{\mathrm{CN}} - 254 \qquad \text{Equation 5-4}$$

Where, T_{LAG} = lag time (h), L = hydraulic length of the watershed (ft.), Y = watershed slope (%), S = maximum retention in the watershed (mm), CN = SCS curve number for the watershed.

Kirpich Formula has been used by Majidi and Shahedi (2012), Saleh, Ghobad, and Noredin (2011), Al-Mukhtar and Al-Yaseen (2019), Rathod, Borse, and Manekar (2015) and Jayadeepa (2016) to calculate the time of concentration to derive lag time for SCS unit hydrograph for transform model.

$$T_{LAG} = 0.6T_C \qquad \text{Equation 5-5}$$

$$T_C = 0.0078\, L^{0.77} S^{-0.385} \qquad \text{Equation 5-6}$$

Where, T_{LAG} = lag time (min), Tc = Time of Concentration (min), L = The reach length in feet, and S is the slope in (ft/ft) (Chow et al., 1988). The calculation of lag time for both catchments is shown in Table 5-6.

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Table 5-6: Lag time calculation

Catchment	Longest river length	T_c	T_{LAG}
Pitabeddara	107,907 feet	345 min	207 min
Urawa	45,505 feet	302 min	158 min

Peak rate factor reflects the percentage of runoff occurring before the peak (PRF) (Scharffenberg et al., 2018). Unit hydrographs with specific peak rate factors are defined in the National Engineering Handbook (NRCS, 2007). The default unit hydrograph has a PRF of 484 in the HEC-HMS model and that was selected for the initial model.

5.3.5 Baseflow model

The selection of the appropriate baseflow model has been described in chapter 2.9.1.5. Recession model has been used for many hydrologic studies due to its simplicity and ease of application (International Sava River Basin Commission, 2017). This method can be applied for both events and continuous modelling since its capability to automatically reset after each storm event (Scharffenberg et al., 2018; Silva et al., 2014).

5.3.5.1 Recession Baseflow model parameter

The exponential recession model equation is presented below.

$$Q_t = Q_0 k^t \qquad \text{Equation 5-7}$$

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

Initial flow, the threshold flow and the recession ratio are the parameters for the recession model in the HEC-HMS program. The initial flow can be considered as average annual flow in the stream for frequent events. The recession constant, k, depends upon the source of baseflow (Feldman, 2000). Pilgrim and Cordery (1992) have proposed typical value for the recession constant. Also, recession and threshold

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value can be estimated using the available gauged flow data (Feldman, 2000). Initially, assigned Recession model parameters are shown in Table 5-7.

Table 5-7: Initial value for Baseflow Model parameter

Catchments	Initial discharge (m3/s)	Recession Constant	Threshold ratio
Pitabeddara	3.37	0.95	25.25
Urawa	0.58	0.9	20.68

5.4 Selection of Objective Function

According to the objective of the study main concern was to capture high and intermediate flow which are mainly contributed to decision-taking in water resource management, planning, and designs. However, there was not any objective function in the built-in HEC-HMS model which provides relative error concerning observed streamflow. As discussed in chapter 2.8.2 among the most popular and best performed objective functions in the HEC-HMS model, RMSE was deployed as an objective function for the study. The optimal value of RMSE is zero and it varies from zero to infinity.

5.5 Selection of Search Algorithms

Available search algorithms in the HEC-HMS model have been described in chapter 2.8.3. There was preference on deterministic searching algorithms than stochastic search method due to the capability of represent catchment properties through developed processed based model parameters (Nandalal & Ratmayake,2010; Samuel et al. ,2011a; Ouédraogo et al.,2018)).

Tassew et al. (2019), Nandalal and Ratmayake (2010) and Gyawali and Watkins (2013) have applied the Univariate Gradient Method and Meenu et al. (2012) applied Nelder and Mead method solely to optimize the model in automatically. Nevertheless, Juraj and Slobodan (2004), Singh and Jain (2015), Ouédraogo et al. (2018), Gebre (2015) have revealed uncertainty and limitation of fully automatic approach in model optimization and identified automatic calibration conjunction with manual calibration to develop catchment's representative model parameters.

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5.6 Model performance evaluation

Root mean square error (RMSE) was selected as an objective function to optimize the model. The comprehensive literature review reveals, the necessity and importance of evaluating model performance by various criteria as stated in chapter 2.8.4. Among the various type of key indicators, Wagener et al. (2004) state the sorted and unsorted flow duration as one of the bests criteria, since its capability to illustrate the variation of flow spectrum for a selected period, with the comparison of observed streamflow.

Because of that, the following list of criteria was evaluated in model calibration, validation, and model parameter transformation to assess the performance of the model.

1. Graphical evaluation of total hydrograph
2. Sorted Flow duration curve – graphically and numerically (RMSE, MRAE) for total flow spectrum and flow regimes (high, medium, low)
3. Un sorted flow duration curve - graphically and numerically (RMSE, MRAE) for total flow spectrum and flow regimes (high, medium, low)
4. Annual Water Balance

5.7 Identification of flow thresholds

In brief, as per the literature review, thresholds for flow regimes are a signature of the catchment. Therefore, the classification of the specific threshold value, in general, is pointless (Hansen, Shafiei Shiva, McDonald, & Nabors, 2019). Therefore, in this study thresholds for flow regimes were calculated considering the variation of streamflow gradient, for the change in the order of magnitude in streamflow.

Accordingly, for Pitabaddara catchment high and low flow thresholds were 8% and 87% and for Urawa catchment 8% and 82% respectively. Figure 5-3 and Figure 5-4 illustrate streamflow thresholds identification for Pitabaddara and Urawa catchments.

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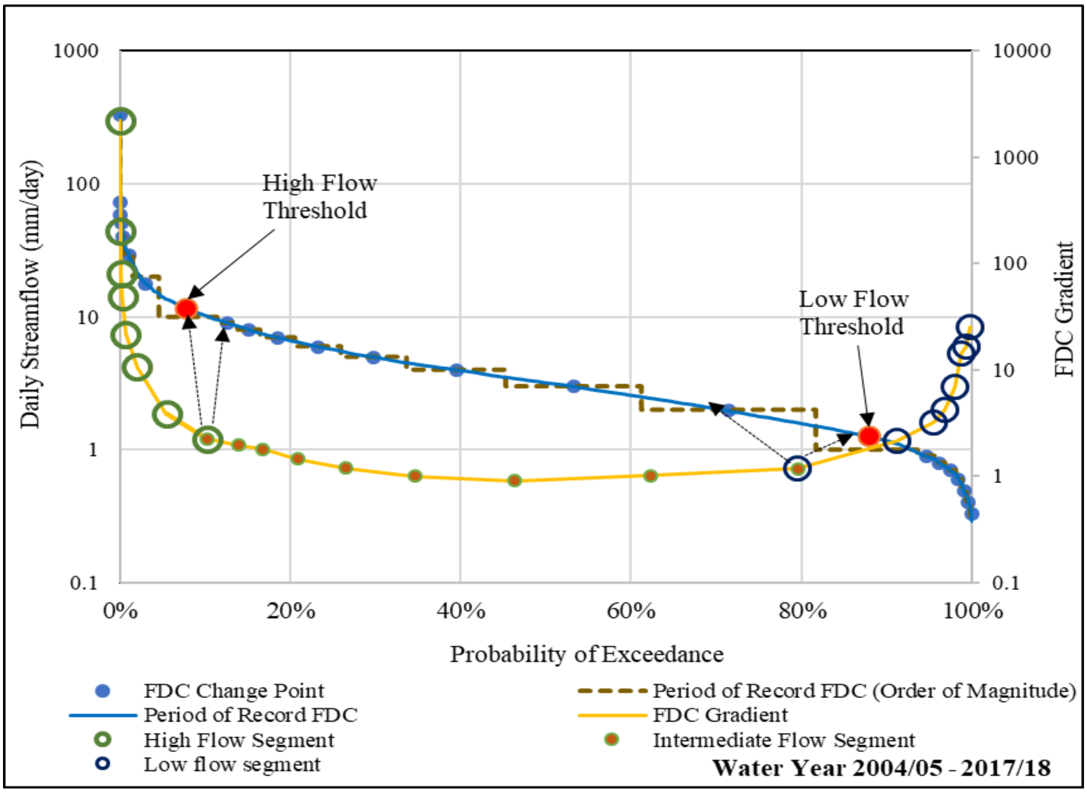

Figure 5-3: Streamflow thresholds for Pitabaddara Catchment

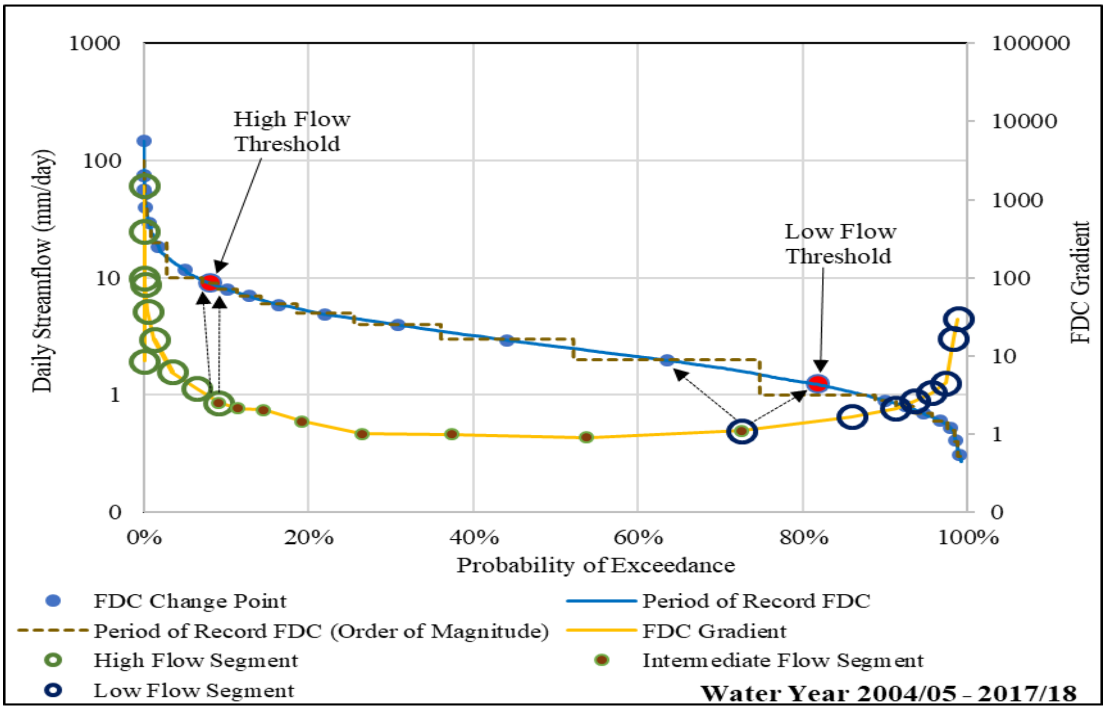

Figure 5-4: Streamflow thresholds for Urawa Catchment

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5.8 Calibration results of HEC-HMS model

5.8.1 Calibration result of Pitabeddara watershed

The model was calibrated for 6 water years' period from 2008/09 – 2013/14. The initial and optimized parameter for the Pitabeddara catchment is shown in Table 5-8.

Table 5-8: Optimized parameter for Pitabeddara Catchment

Hydrological Process	Model parameter	Unit	Initial Parameter	Optimized Parameter
Canopy method	Initial storage	%	0	0.35
	Max storage	mm	5	10.18
Surface-simple method	Initial storage	mm	0	0.19
	Max storage	mm	10	33.864
Deficit and Constant loss method	Initial deficit	mm	13.4	21.8
	Maximum deficit	mm	67.1	37.028
	Constant rate	mm/hr	2	0.27468
Transform method	Lag time	min	207	406.64
Baseflow method	Initial discharge	m3/s	3.37	4.3933
	Recession Constant		0.95	0.94257
	Threshold ratio		0.25	0.24771

5.8.1.1 The Goodness of fit measures for calibration of Pitabeddara watershed

As states in chapter 5.6, the goodness of fit was assessed using graphical and numerical measures. The performance of annual water balance, hydrographs, and flow duration curves was evaluated graphically and numerically.

5.8.1.1.1 Flow duration curve

Statistical evaluation of model performance for total flow spectrum and flow regimes, high, medium, low is shown in Table 5-9.

Table 5-9: Numerical measures for Calibration of Pitabaddara watershed

Gauging Station	RMSE (mm/day)	MRAE	Monthly Water Balance Error (%)	Flow Duration Curve - Unsorted					
				High		Medium		Low	
				RMSE (mm/day)	MRAE	RMSE (mm/day)	MRAE	RMSE (mm/day)	MRAE
Pitabeddara	3.2	0.394	-1.65	8.07	0.308	2.49	0.393	0.58	0.463

Unsorted flow duration curve is shown in Figure 5-5 and the statistical performance of the model in terms of RMSE and MRAE value is shown in Table 5-9. Black dotted lines illustrate the separations of flow regimes. There was a reduction of RMSE value from high to low flow regime and vice versa for MRAE value.

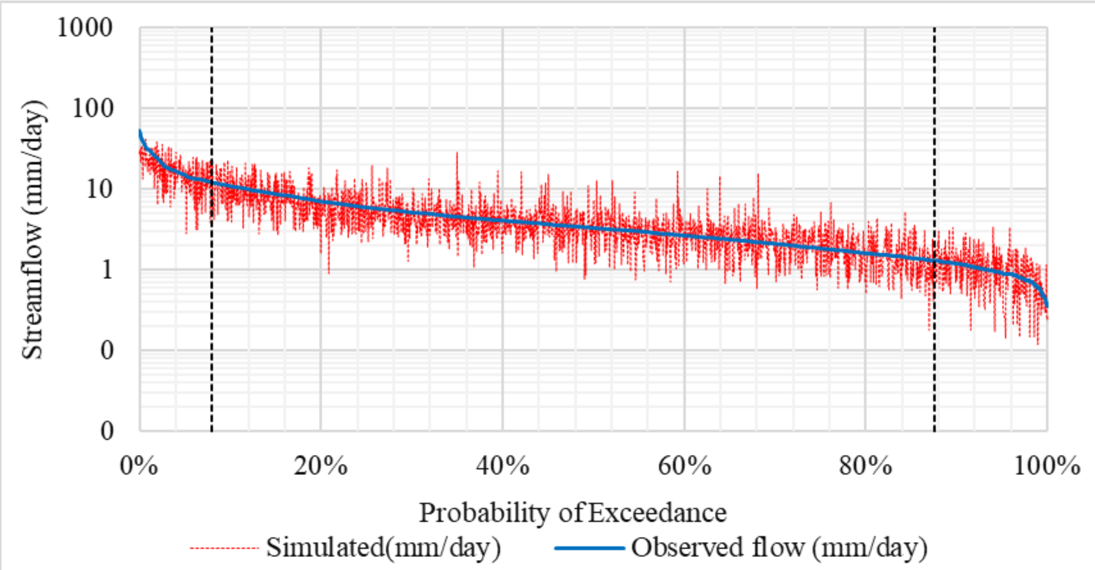


Figure 5-5: Unsorted flow duration curve for the calibration period of Pitabeddara Catchment

Figure 5-6 illustrates sorted FDC and Table 5-10 shows the respective goodness of fit measures in numerically for total flow series and flow regimes concerning RMSE and MRAE vales.

Table 5-10: Numerical measures of sorted flow duration curve for the calibration period of Pitabaddara watershed

Gauging Station	RMSE	MRAE	Flow Duration Curve - Sorted					
			High		Medium		Low	
			RMSE (mm/day)	MRAE	RMSE (mm/day)	MRAE	RMSE (mm/day)	MRAE
Pitabeddara	0.88	0.077	3.02	0.111	0.23	0.041	0.25	0.282

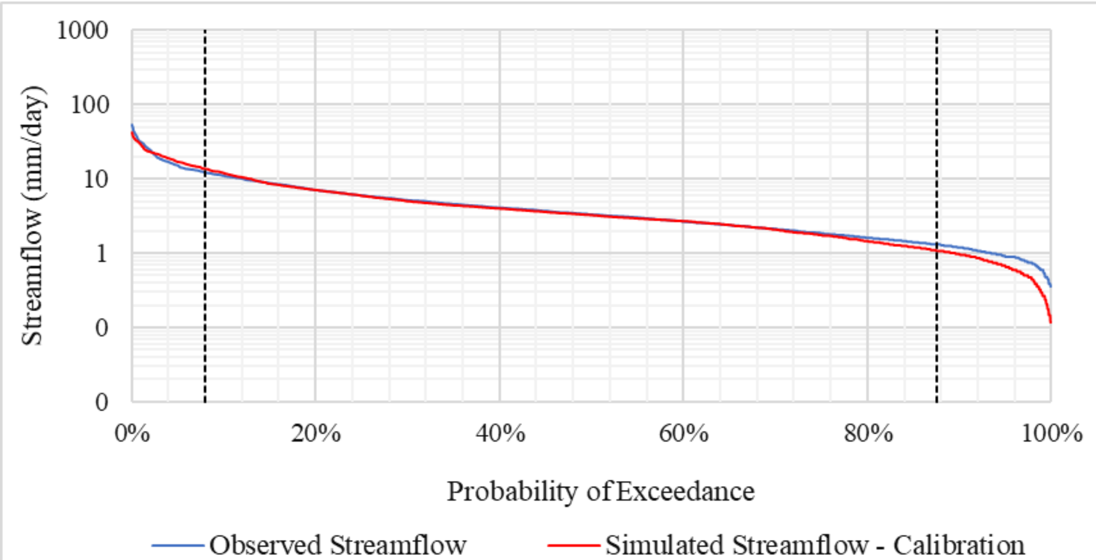
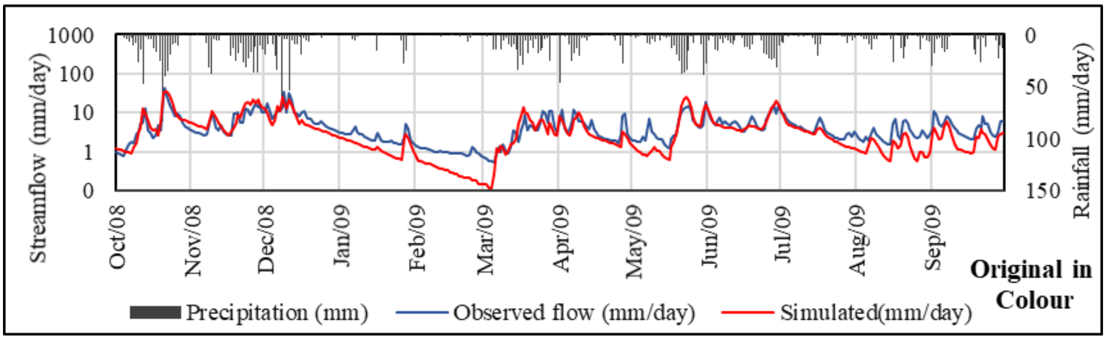


Figure 5-6: Flow Duration Curve for Calibration of Pitabaddara Watershed

5.8.1.1.2 Matching of Observed and Simulated hydrograph

The similarity of observed and simulated flow is shown in Figure 5-7. Each graph represents one water year.



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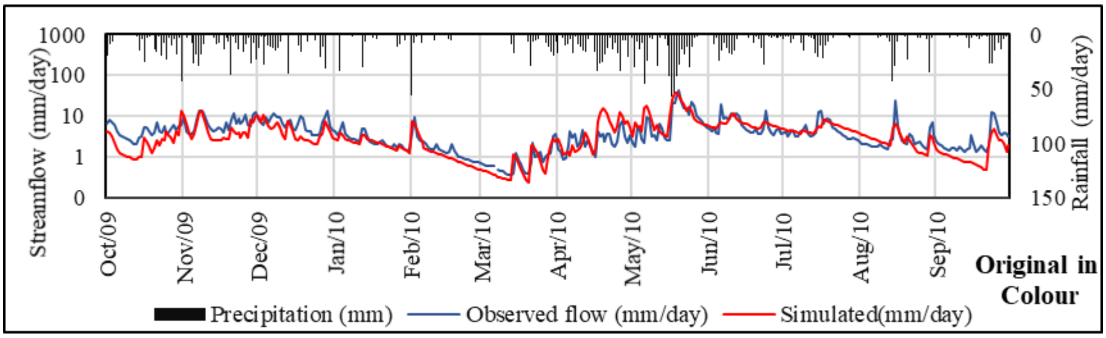
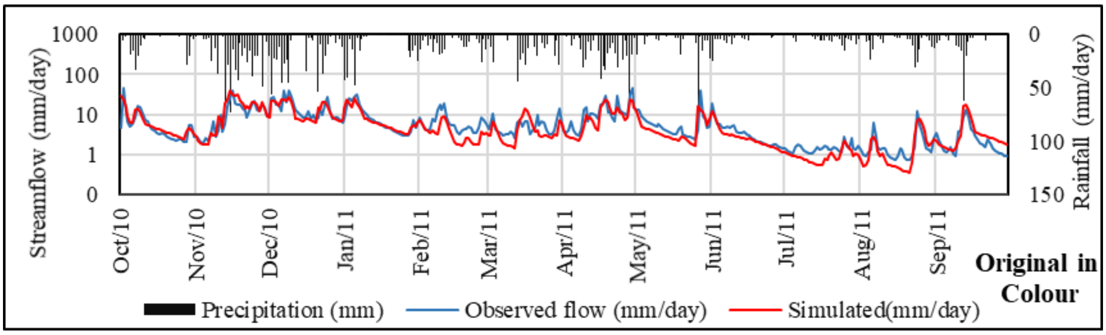
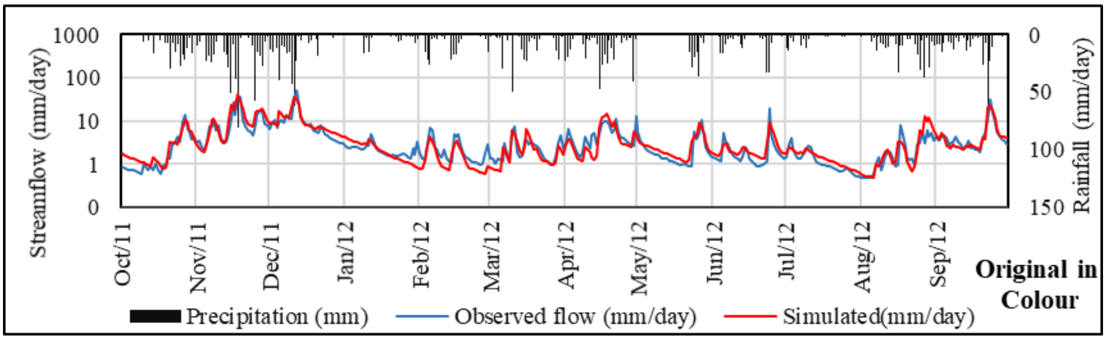
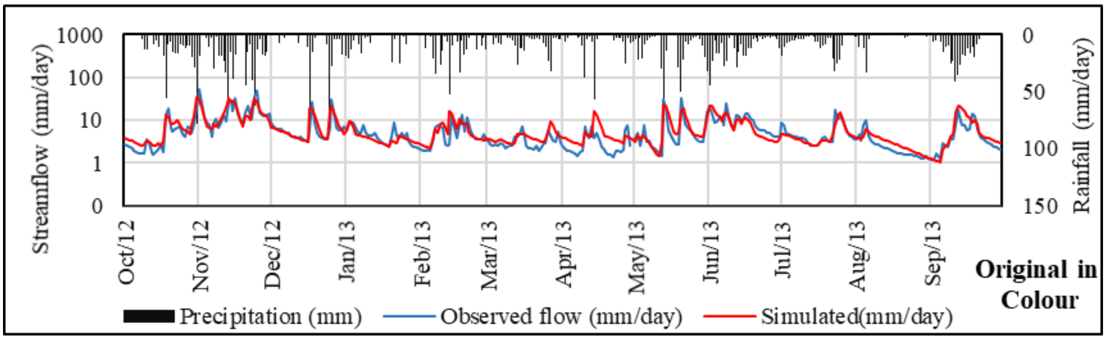

Streamflow (mm/day)
Rainfall (mm/day)
Oct/09
Nov/09
Dec/09
Jan/10
Feb/10
Mar/10
Apr/10
May/10
Jun/10
Jul/10
Aug/10
Sep/10
Original in Colour
Precipitation (mm)
Observed flow (mm/day)
Simulated(mm/day)


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


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


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

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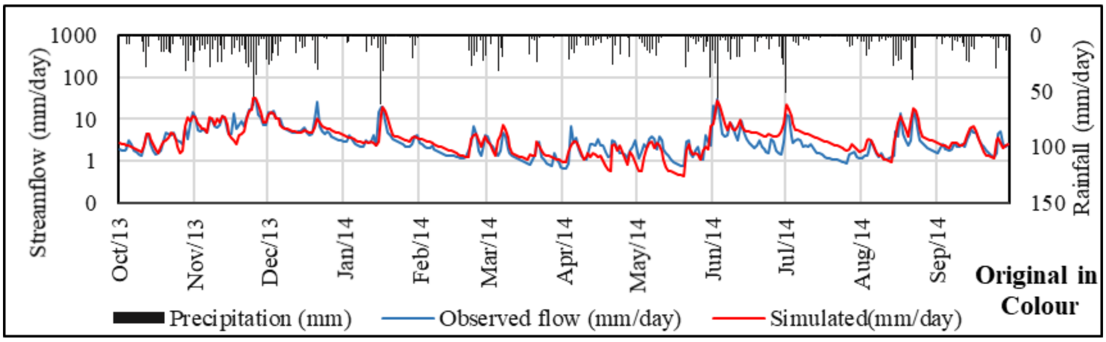

Figure 5-7 Calibration Result for Pitabaddara Watershed - Semi Log plot

5.8.1.1.3 The Annual Water Balance

Annual water balance error (AWBE) calculation is shown in Table 5-11 and graphical representation is shown in Figure 5-8. The highest AWBE has been recorded in water year 2013/14 as 12.74%, which is an overestimation of streamflow. However, in average 1.65% streamflow underestimation was identified for the year 2008/09 to 2013/14.

Table 5-11: Annual Water Balance for Calibration of Pitabaddara Watershed

Water Year	RF (mm/ year)	Sim. SF (mm/ year)	Obs. SF (mm/ year)	WB for Sim. SF (mm/ year)	WB for Obs. SF (mm/ year)	AWBE (mm/ year)	Percentage error	Sim. Run off Coeff	Obs. Runoff Coeff
2008/09	2749	1623	1818	1126	931	-194	-10%	0.59	0.66
2009/10	2653	1545	1705	1108	947	-160	-9%	0.58	0.64
2010/11	3366	2295	2535	1071	831	-240	-9%	0.68	0.75
2011/12	2692	1560	1461	1131	1231	99	6%	0.58	0.54
2012/13	3351	2395	2265	956	1086	130	5%	0.71	0.68
2013/14	2776	1603	1422	1173	1354	181	12%	0.58	0.51
Average	2931	1837	1868	1094	1063	-30	-1%	0.63	0.64

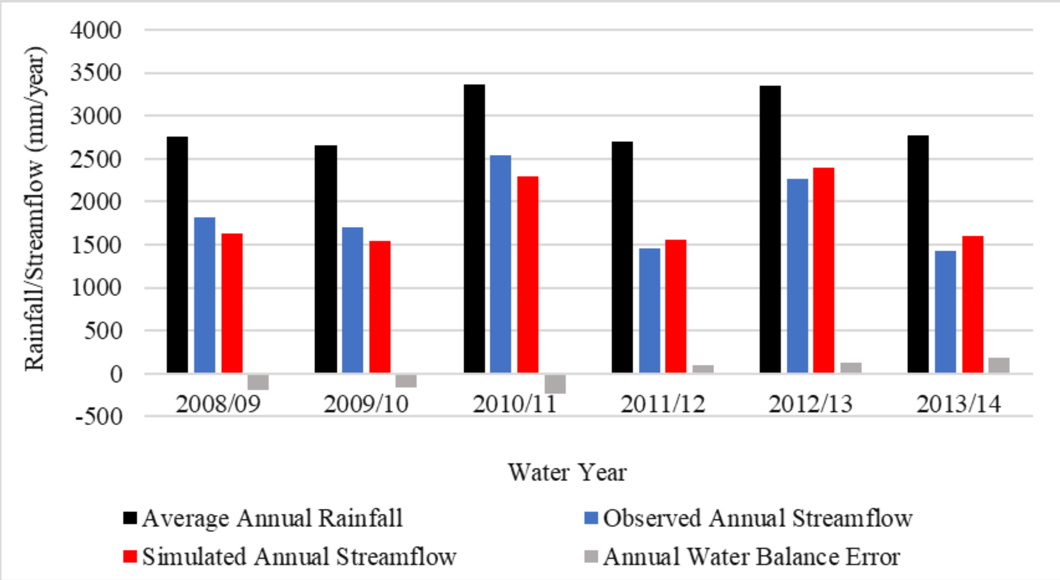

Figure 5-8: Annual Water Balance for Pitabaddara Watershed for Calibration Period

5.8.1.2 Fully Automatic Calibration

The model was calibrated in the combination of manual and automatic approaches. In addition to that, the model's performance was evaluated for filly automatic optimization with Nelder and Mead searching algorithm, assigning optimized parameters as initial parameters. Optimized Parameters are shown in Table 5-12.

Table 5-12: Optimized Parameter from Automatic Calibration - Pitabaddara Watershed

Hydrological Process	Model parameter	Unit	Initial Parameter	Optimized Parameter
Canopy method	Initial storage	%	0.35	0.30082
	Max storage	mm	10.18	8.0398
Surface-simple method	Initial storage	mm	0.19	0.23894
	Max storage	mm	33.864	32.538
Deficit and Constant loss method	Initial deficit	mm	21.8	22.83
	Maximum deficit	mm	37.028	37.691
	Constant rate	mm/hr	0.27468	0.29124
Transform method	Lag time	min	406.64	348.98
Baseflow method	Initial discharge	m3/s	4.3933	4.1242
	Recession Constant		0.94257	0.90587
	Threshold ratio		0.24771	0.36506

`

Comparison of RMSE and MRAE value for flow spectrum and flow regimes are shown in Table 5-13. Further, Figure 5-9 illustrates respective sorted FDC curves. According to the result, key indicators selected for the study to measure model performance were at a low level than the result of manual - automatic calibration.

Table 5-13: Numerical measures for the goodness of fit – Fully Automatic Optimization-Pitabaddara Watershed

Optimization Procedure	RMSE (mm/day)	MRAE	Annual Water Balance Error (%)	Flow Duration Curve - Unsorted					
				High		Medium		Low	
				RMSE (mm/day)	MRAE	RMSE (mm/day)	MRAE	RMSE (mm/day)	MRAE
Manual + Automatic	3.2	0.394	-1.65	8.07	0.308	2.49	0.393	0.58	0.463
Fully Automatic	3.2	0.400	-16.71	8.96	0.337	2.3	0.401	0.52	0.431

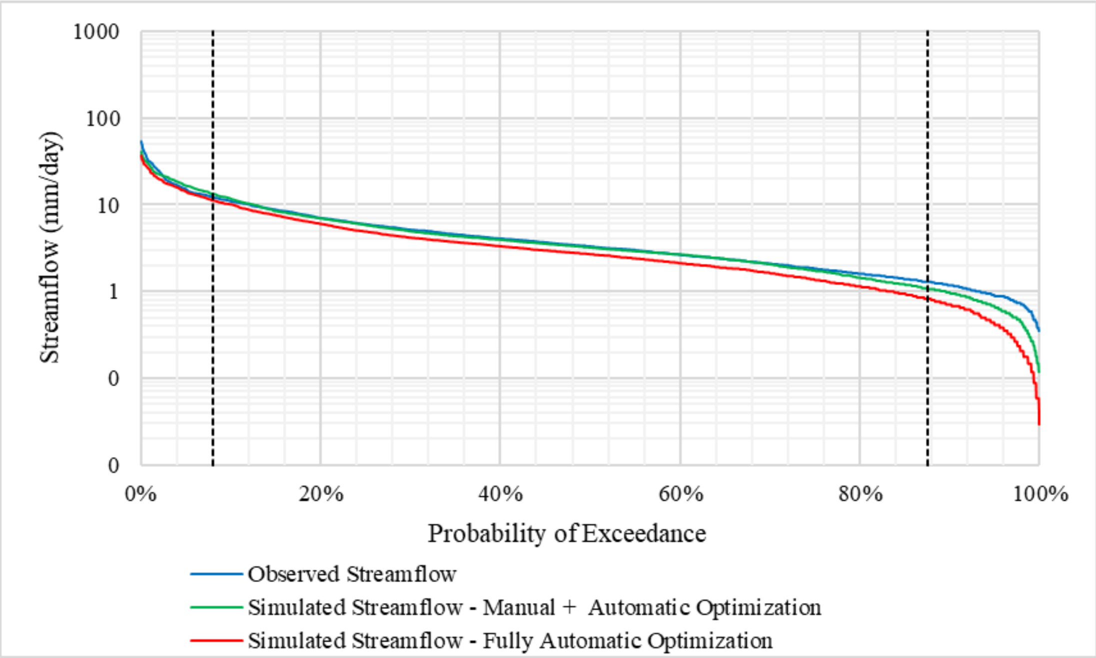

Figure 5-9: FDC for fully automatic optimization – Pitabaddara watershed

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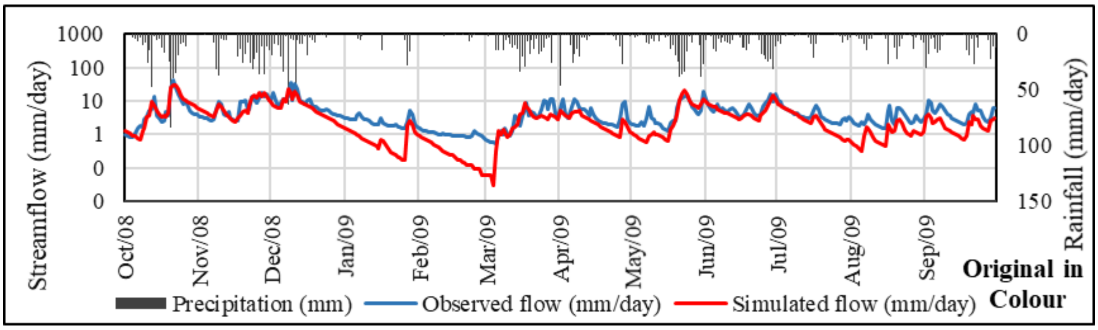
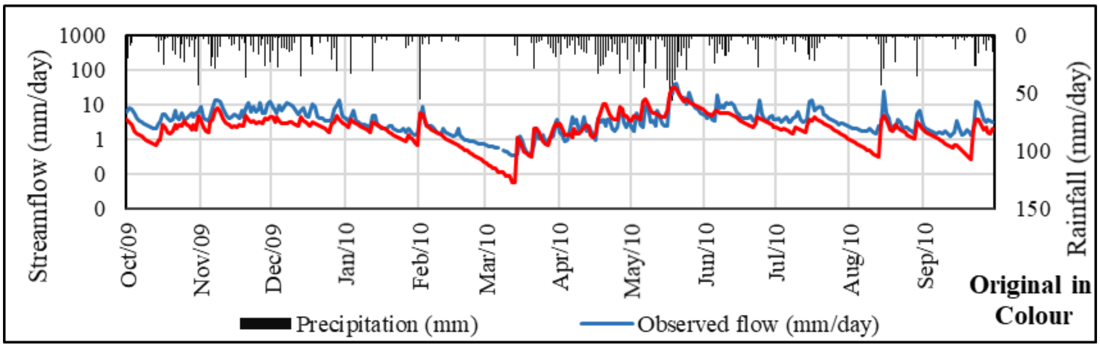
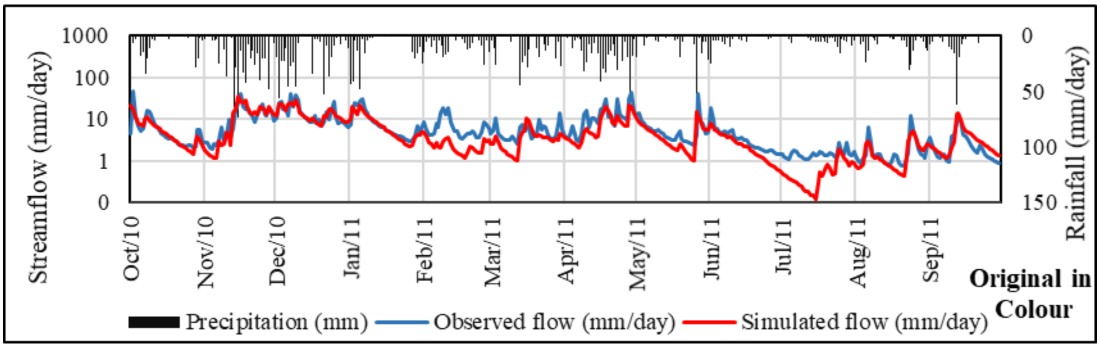
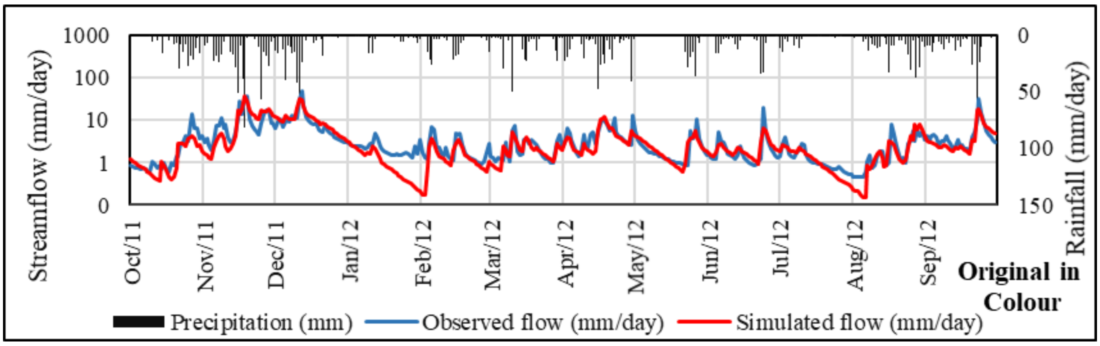
Matching of Observed and Simulated streamflow hydrographs (Semi log plot) is shown in

Figure 5-10 and the respective normal plot hydrographs are in Figure D- 1.









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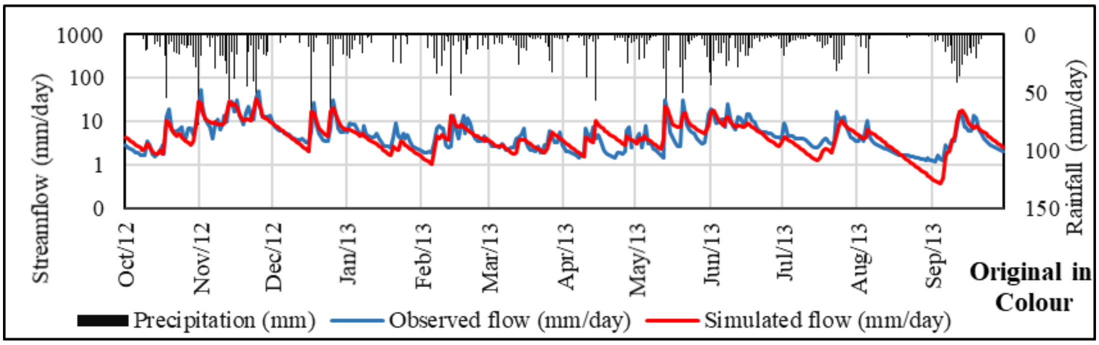

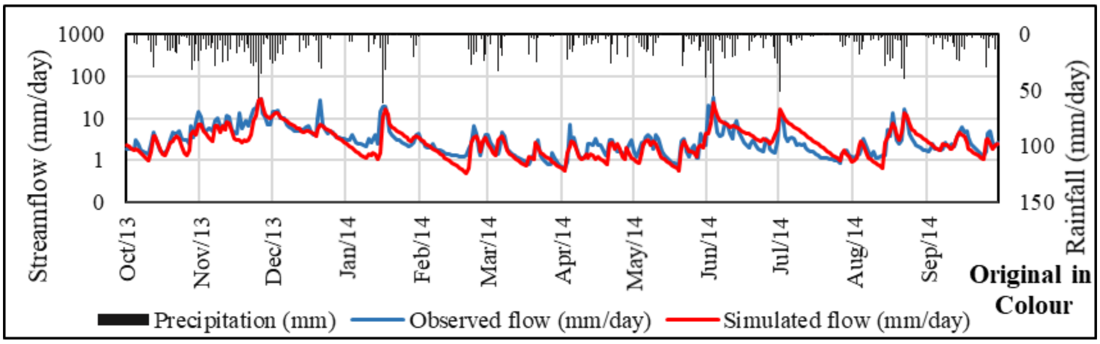

Figure 5-10: Fully Automatic model optimization - Hydrograph (Semi Plot)

5.8.2 Model calibration for Urawa watershed

Same as Pitabaddara watershed model was calibrated for 6 years' period from 2012/13 to 2017/18. Table 5-14 depicts the initial and optimized model parameters.

Table 5-14: Optimized parameter for Urawa watershed

Hydrological Process	Model parameter	Unit	Initial Parameter	Optimized Parameter
Canopy method	Initial storage	%	0	0.5
	Max storage	mm	5	13.094
Surface-simple method	Initial storage	mm	0	0.5
	Max storage	mm	10	39.496
Deficit and Constant loss method	Initial deficit	mm	10.2	12.6
	Maximum deficit	mm	63.1	63.949
	Constant rate	mm/hr	2.54	0.7
Transform method	Lag time	min	177	261.79

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Hydrological Process	Model parameter	Unit	Initial Parameter	Optimized Parameter
Baseflow method	Initial discharge	m3/s	0.58	1.2143
	Recession Constant		0.9	0.97
	Threshold ratio		20.68	0.19

5.8.2.1 The Goodness of fit measures for calibration of Urawa watershed

The performance of the model in terms of hydrographs, flow duration curves, and annual water balance was evaluated graphically and numerically.

5.8.2.1.1 Flow duration curve

Statistical evaluation of model performance for total flow series and flow regimes, high, medium and low is shown in Table 5-15.

Table 5-15: Numerical measures for Calibration of Urawa watershed

Gauging Station	RMSE (mm/day)	MRAE	Monthly Water Balance Error (%)	Flow Duration Curve - Unsorted					
				High		Medium		Low	
				RMSE (mm/day)	MRAE	RMSE (mm/day	MRAE	RMSE (mm/day	MRAE
Urawa	4.36	0.746	11	13.53	0.281	3.31	0.605	1.62	1.475

Unsorted flow duration curve is shown in Figure 5-11 and the statistical performance of the model in terms of RMSE and MRAE value is shown in Table 5-15. Black dotted lines show the separation of flow regimes. The reduction of RMSE value could see from high to low flow regime and vice versa for MRAE value.

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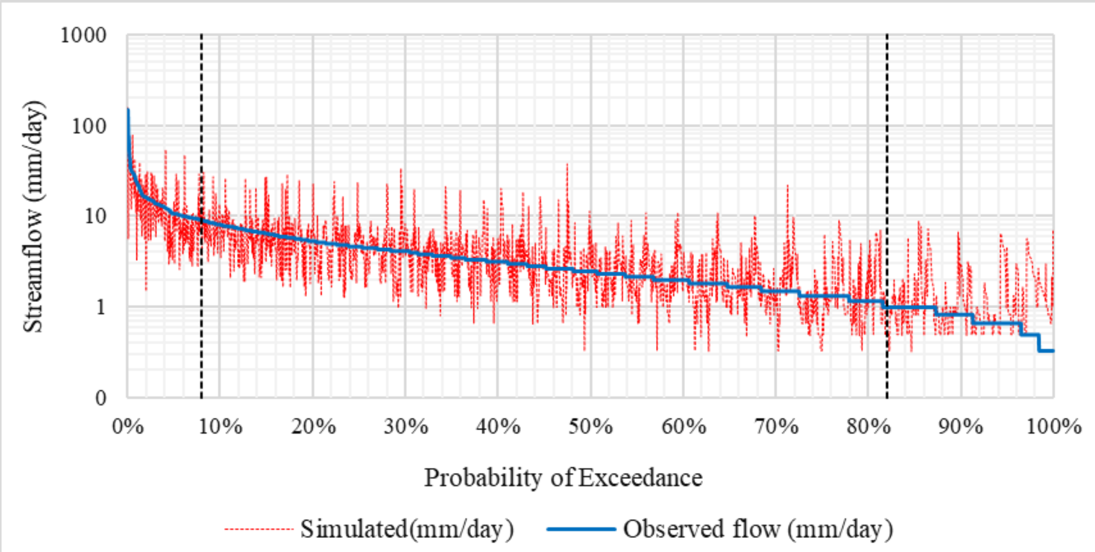

Figure 5-11: Unsorted flow duration curve for the calibration period of Urawa Catchment

Figure 5-12 illustrates sorted FDC and Table 5-16 shows the respective goodness of fit measures in numerically for total flow series and flow regimes for RMSE and MRAE vales.

Table 5-16: Numerical measures of flow duration curve for the calibration period of Urawa watershed

Gauging Station	RMSE (mm/day)	MRAE	Flow Duration Curve - Sorted					
			High		Medium		Low	
			RMSE (mm/day)	MRAE	RMSE (mm/day)	MRAE	RMSE (mm/day)	MRAE
Urawa	1.686	0.081	5.861	0.177	0.341	0.073	0.086	0.07

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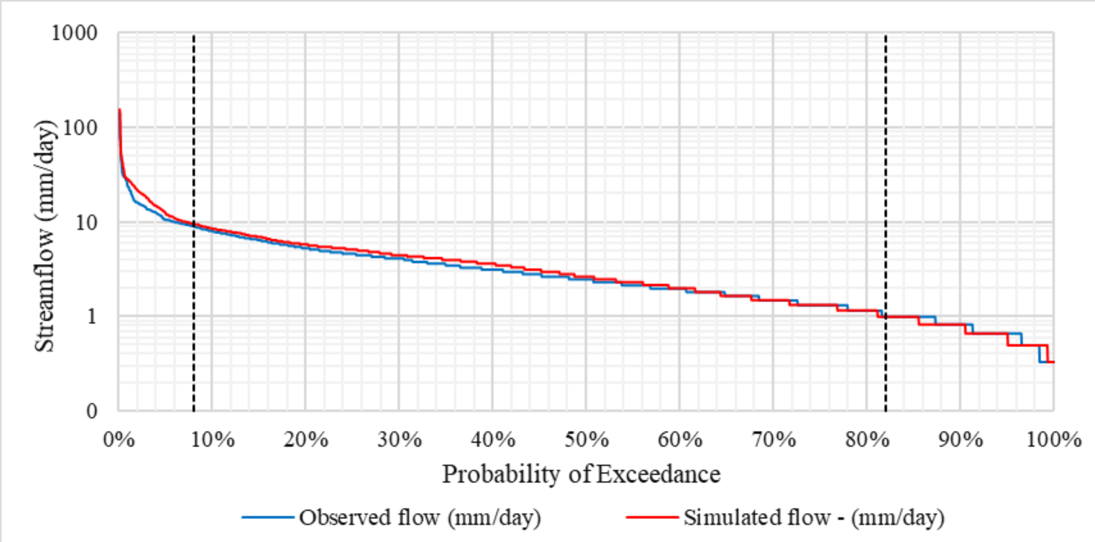
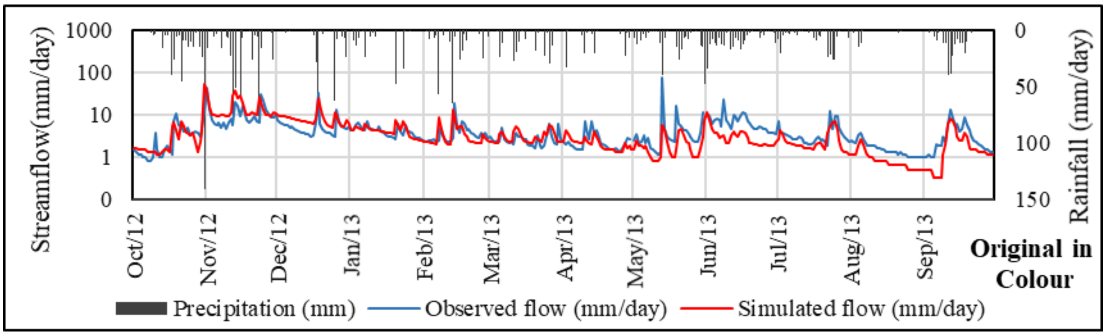
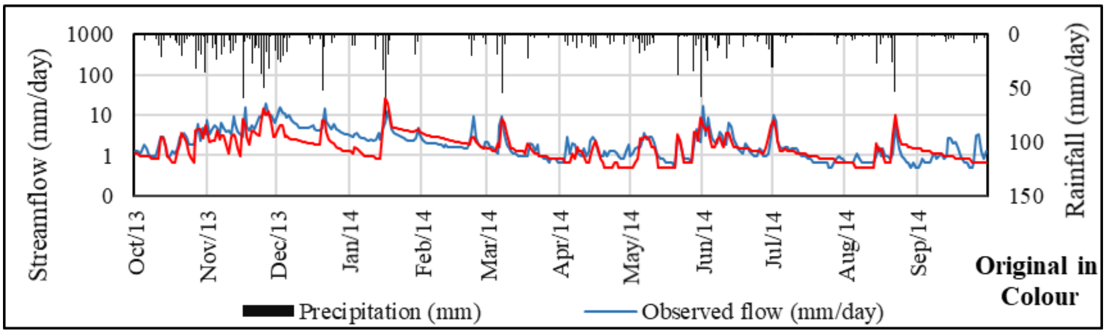


Figure 5-12: Flow Duration Curve for calibration of Urawa Watershed

5.8.2.1.2 Matching of Observed and Simulated hydrograph

The similarity of observed and simulated flow is shown in Figure 5-13. Each graph represents one water year.





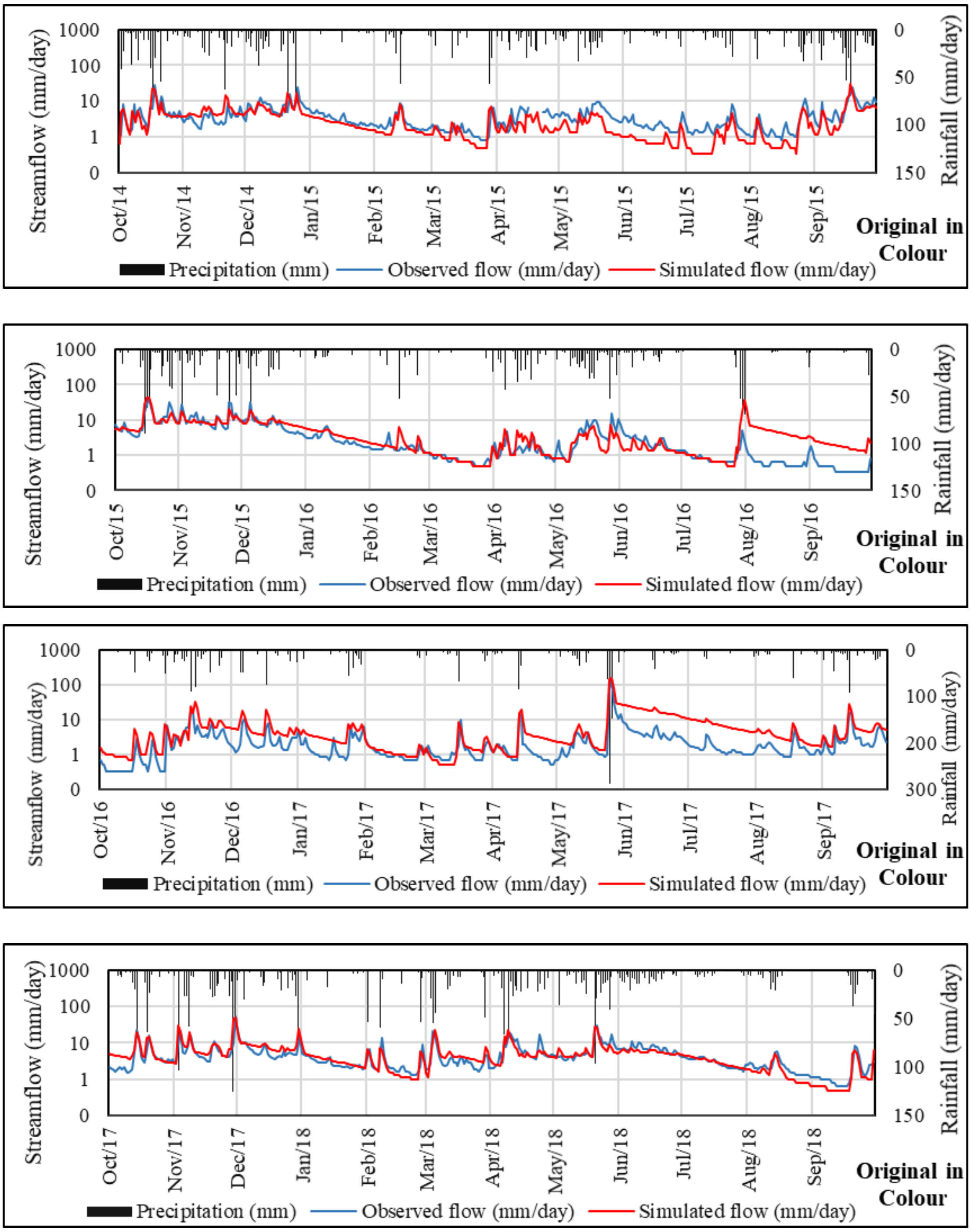


Figure 5-13 Calibration Result for Urawa Watershed - Semi Log plot

5.8.2.1.3 The Annual Water Balance

AWBE calculation for Urawa watershed is shown in Table 5-17 and graphical representation in Figure 5-14. The best performance in terms of AWBE has been

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recorded in the water year 2017/18 as 114.5 mm. However, on average 11% streamflow overestimation was identified for the year 2012/13 to 2017/18.

Table 5-17: Annual Water Balance for Calibration of Urawa Watershed

Water Year	RF (mm/ year)	Sim. SF (mm/ year)	Obs. SF (mm/ year)	WB for Sim. SF (mm/ year)	WB for Obs. SF (mm/ year)	AWBE (mm/ year)	Percentage error	Sim. Runoff Coeff	Obs. Runoff Coeff
2012/13	2714	1559	1683	1154	1030	-123	-7%	0.57	0.62
2013/14	2029	786	979	1243	1051	-193	-20%	0.39	0.48
2014/15	2559	1098	1405	1461	1155	-307	-22%	0.43	0.55
2015/16	2253	1630	1449	622	803	181	12%	0.72	0.64
2016/17	2772	2368	1106	404	1666	1262	114%	0.85	0.40
2017/18	2848	1885	1771	963	1077	115	6%	0.66	0.62
Average	2529	1555	1399	975	1130	156	11%	0.61	0.55

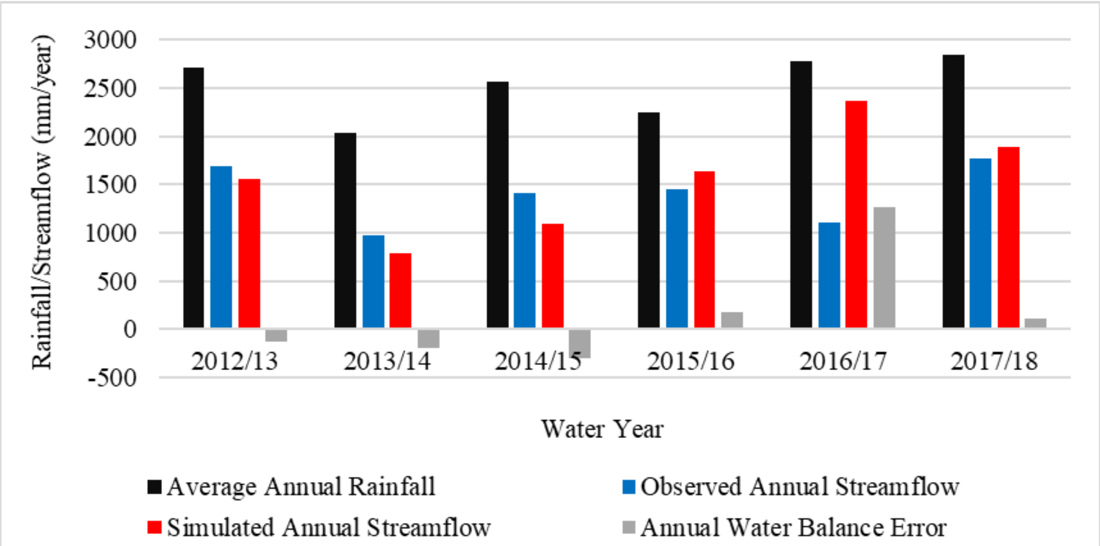

Figure 5-14: Annual Water Balance for Urawa Watershed for Calibration Period

5.8.2.2 Fully Automatic Calibration

In addition to the model calibration in a systematic way, the model was optimized fully automatically, assigning optimized parameters as initial parameters to verify identified optimal model parameters. Optimized model Parameters are shown in Table 5-18.

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Table 5-18: Optimized parameters for Automatic Optimization for Urawa Watershed

Hydrological Process	Model parameter	Unit	Initial Parameter	Optimized Parameter
Canopy method	Initial storage	%	0.5	0.51202
	Max storage	mm	13.094	12.623
Surface-simple method	Initial storage	mm	0.5	0.49501
	Max storage	mm	39.496	39.44
Deficit and Constant loss method	Initial deficit	mm	12.6	11.792
	Maximum deficit	mm	63.949	71.949
	Constant rate	mm/hr	0.7	0.94029
Transform method	Lag time	min	261.79	249.93
Baseflow method	Initial discharge	m3/s	1.2143	1.1989
	Recession Constant		0.97	0.92873
	Threshold ratio		0.19	0.20219

The performance of the model result is shown in Table 5-19 and Sorted FDC in Figure 5-15.

Table 5-19: Numerical measures for the goodness of fit – Fully Automatic Optimization-Urawa Watershed

Optimization Procedure	RMSE (mm/day)	MRAE	Annual Water Balance Error (%)	Flow Duration Curve - Unsorted					
				High		Medium		Low	
				RMSE (mm/day)	MRAE	RMSE (mm/day)	MRAE	RMSE (mm/day)	MRAE
Manual + Automatic Optimization	4.36	0.746	11	13.53	0.281	3.31	0.605	1.62	1.475
Fully Automatic Optimization	3.27	0.595	-22	12.89	0.218	2.56	0.541	1.02	0.866

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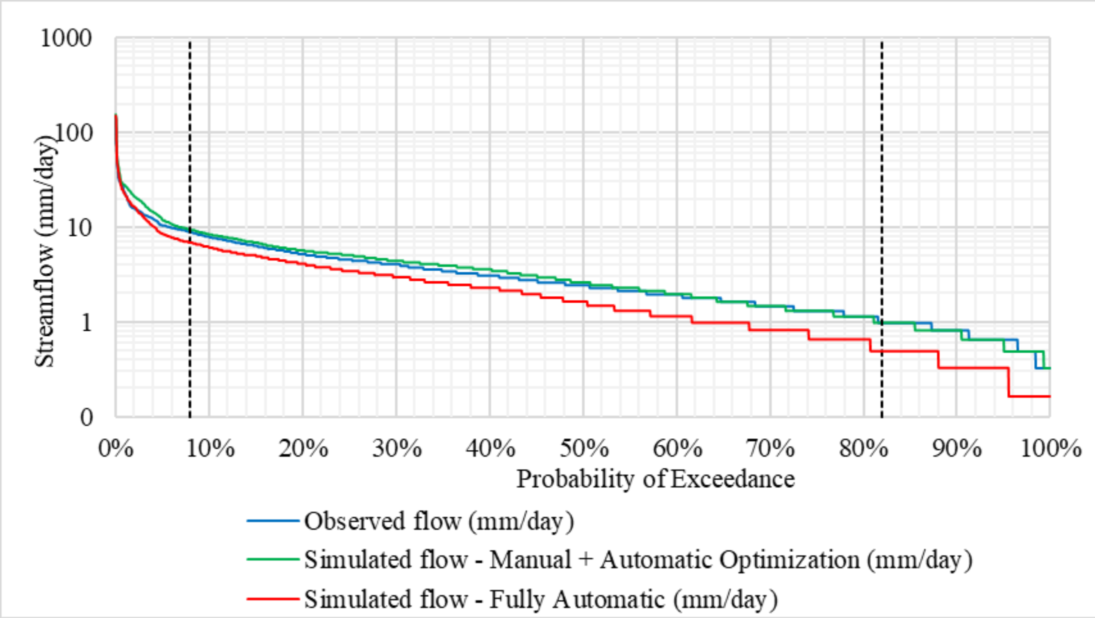
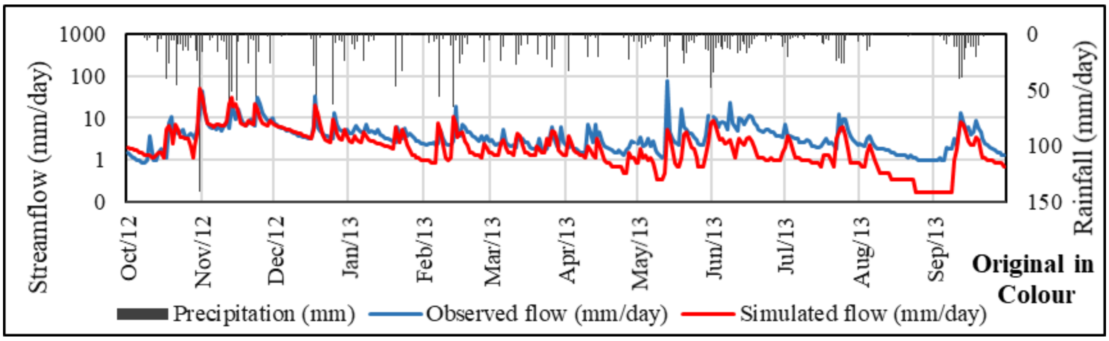
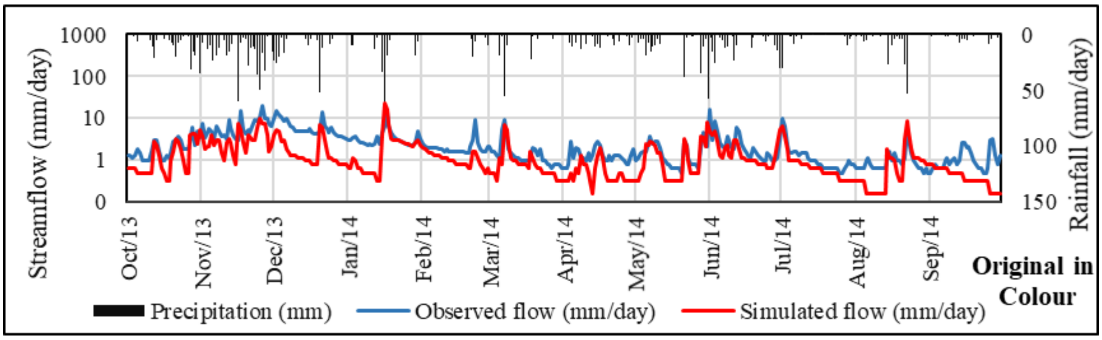


Figure 5-15: FDC for automatic optimization - Urawa watershed

Matching of flow hydrograph for automatic optimization is shown in

Figure 5-16 and respective normal plotted hydrograph in Figure D- 2.





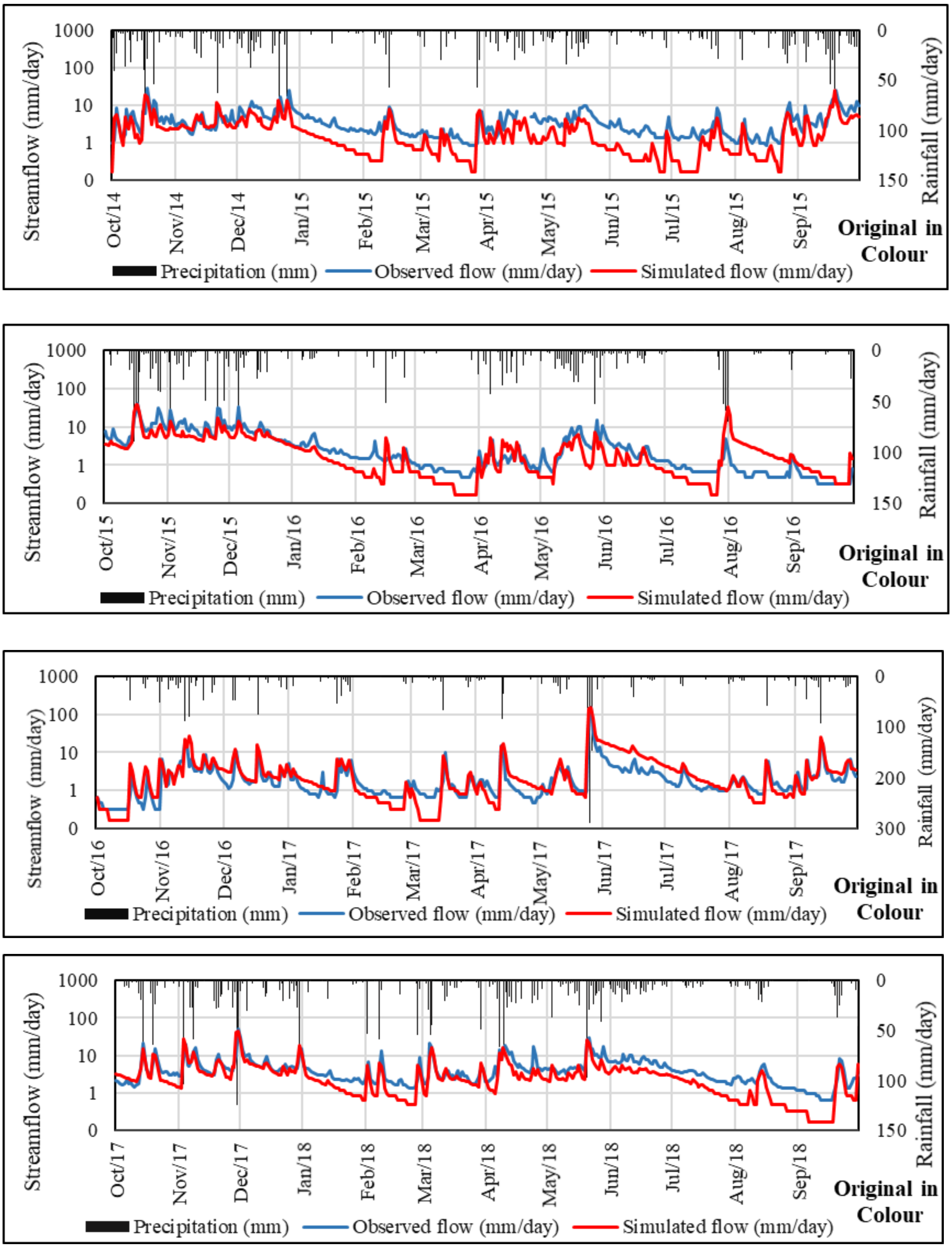


Figure 5-16: Flow hydrograph for fully automatic optimization - Urawa watershed (Semi Log Plot)

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5.9 Verification results of HEC-HMS model

HEC-HMS models for Pitabaddara and Urawa watershed were verified for 4 water years’ period.

5.9.1 Model verification for Pitabaddara Catchment

HEC-HMS models for Pitabaddara was verified for water years 2014/15 to 2017/18.

5.9.1.1 The goodness of fit measures for verification of Pitabeddara watershed

Model performance was evaluated applying numerical and graphical measures. For that flow duration curves, hydrographs and annual water balance errors were considered with RMSE and MRAE value.

5.9.1.1.1 Flow duration curve

Model performance in the validation period was assessed for total flow series and flow regimes, high, intermediate and low concerning RMSE and MRAE value as shown in Table 5-20. The respective graphical representation is shown in Figure 5-17.

Table 5-20: Numerical measures for verification of Pitabaddara watershed

Gauging Station	RMSE (mm/day)	MRAE	Annual Water Balance Error (%)	Flow Duration Curve - Unsorted					
				High		Medium		Low	
				RMSE (mm/day)	MRAE	RMSE (mm/day)	MRAE	RMSE (mm/day)	MRAE
Pitabeddara	7.79	0.604	32	23.92	0.445	4.33	0.624	0.63	0.58

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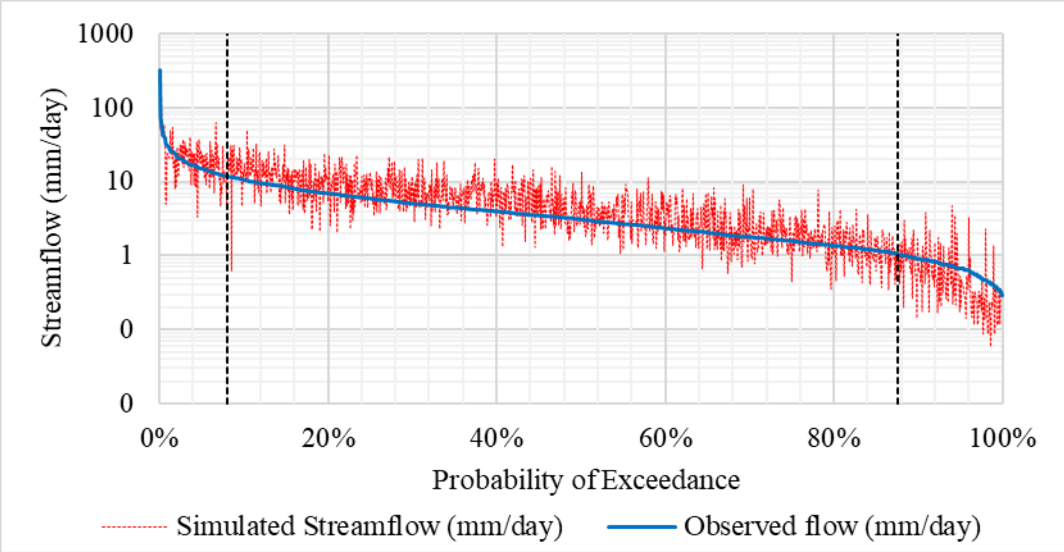

Figure 5-17: Unsorted flow duration curve for the verification period of Pitabeddara Catchment

Figure 5-18 illustrates sorted FDC and Table 5-21 shows respective goodness of fit measures in numerically for total flow series and flow regimes concerning RMSE and MRAE vales.

Table 5-21: Numerical measures of flow duration curve for the verification period of Pitabaddara watershed

Gauging Station	RMSE (mm/day)	MRAE	Flow Duration Curve - Sorted					
			High		Medium		Low	
			RMSE (mm/day)	MRAE	RMSE (mm/day)	MRAE	RMSE (mm/day)	MRAE
Pitabeddara	5.6	0.332	18.53	0.404	2.206	0.311	0.274	0.42

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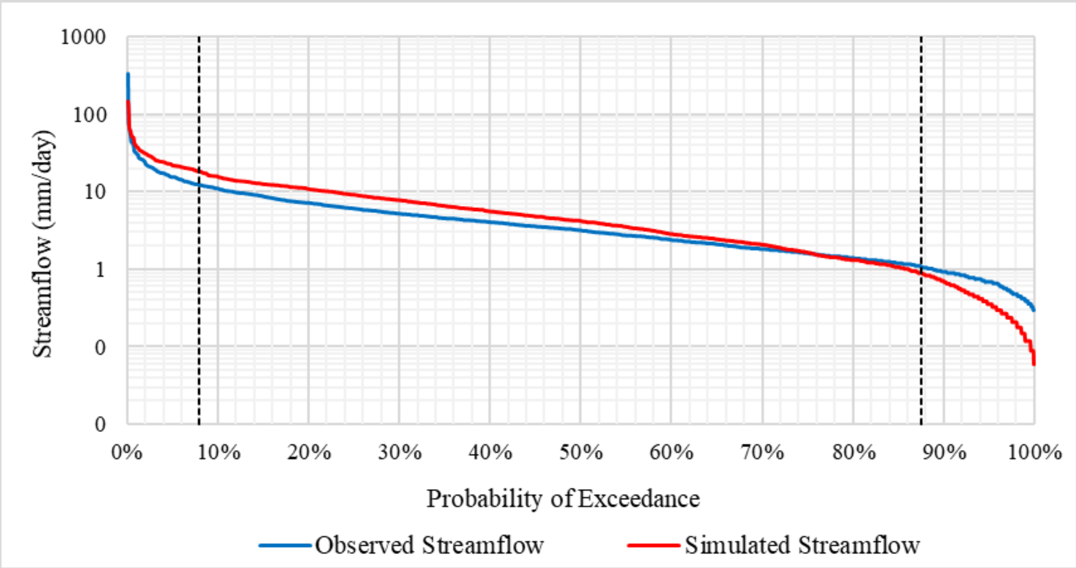
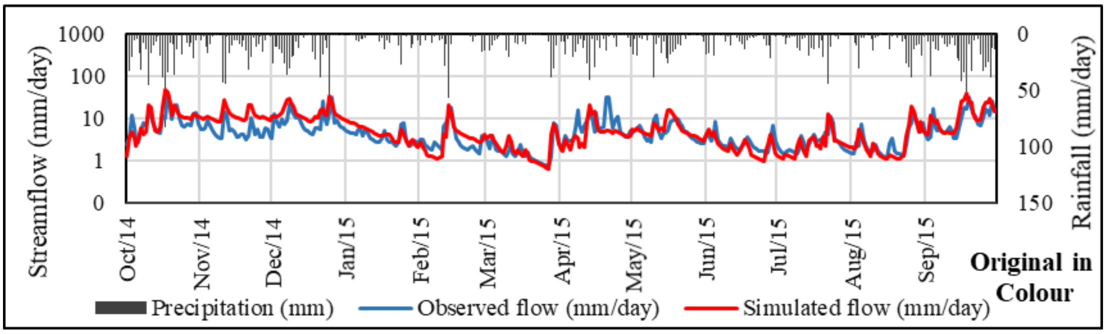
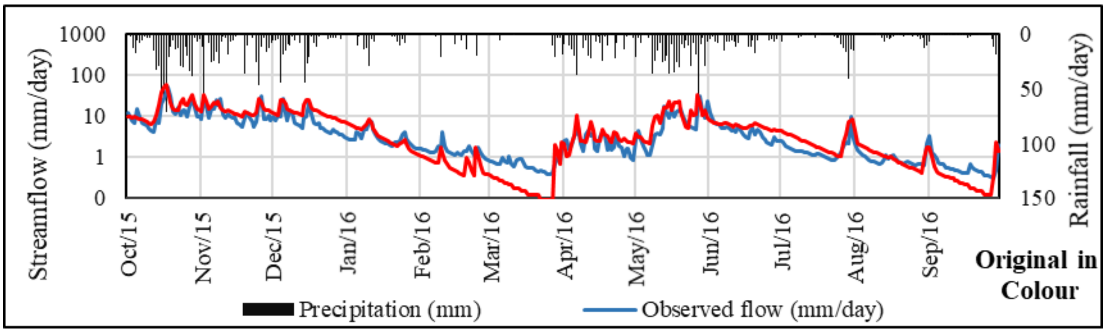


Figure 5-18: Flow Duration Curve for verification of Pitabaddara Watershed

5.9.1.1.2 Matching of Observed and Simulated hydrograph

The similarity of observed and simulated flow is shown in Figure 5-19. Each graph represents one water year.





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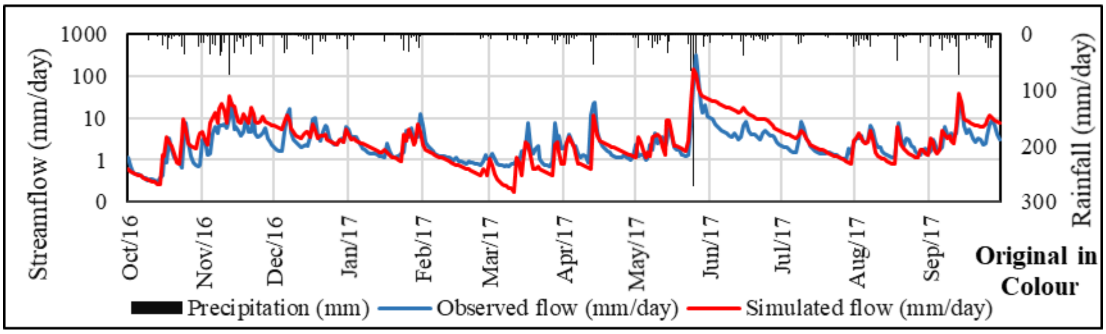

Figure 5-19 Verification Result for Pitabaddara Watershed - Semi Log plot

5.9.1.1.3 The Annual Water Balance

Table 5-22 and Figure 5-20 show AWBE in statistically and graphically in respectively. The lowest AWBE has been recorded in the water year 2014/15 as 24%. On average 33% streamflow overestimation was identified for the period of water year 2008/09 to 2013/14.

Table 5-22: Annual Water Balance for Verification of Pitabaddara Watershed

Water Year	RF (mm/ year)	Sim. SF (mm/y ear)	Obs. SF (mm/ year)	WB for Sim. SF (mm/ year)	WB for Obs. SF (mm/ year)	AWB E (mm/ year)	Perc enta ge error (%)	Sim. Run off Coef f	Obs. Runo ff Coef f
2014/15	3447	2596	2096	851	1351	500	24	0.75	0.61
2015/16	2719	2361	1803	358	915	558	31	0.87	0.66
2016/17	2762	2059	1647	703	1115	412	25	0.75	0.60
2017/18	3483	3027	2018	456	1465	1009	50	0.87	0.58
Average	3103	2511	1891	592	1211	620	33	0.81	0.61

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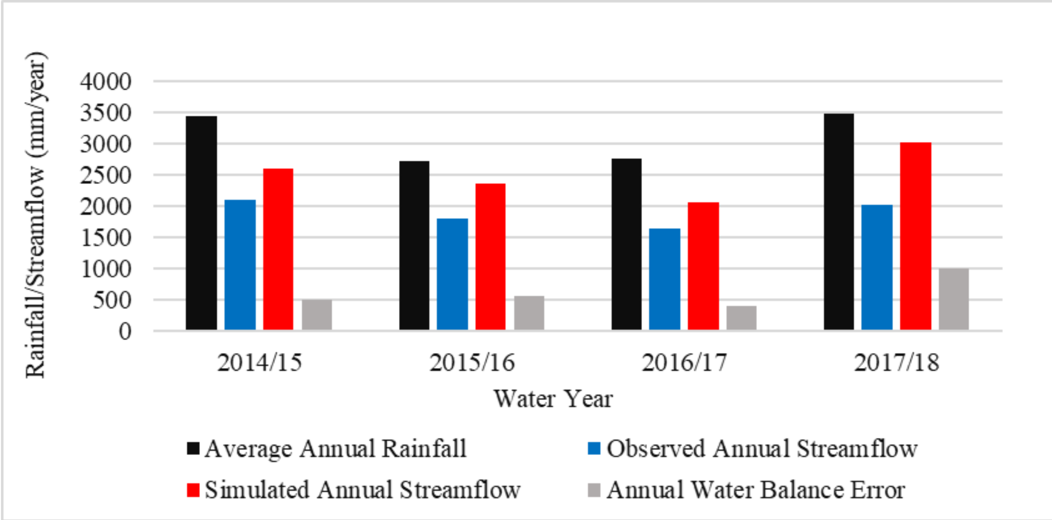

Figure 5-20: Annual Water Balance for Pitabaddara Watershed for Verification Period

5.9.2 Model verification for Urawa Catchment

HEC-HMS models for Urawa was verified for four water years 2008/09 to 2011/12.

5.9.2.1 The goodness of fit measures for verification of Urawa watershed

Model performance was evaluated in numerical and graphical measures using flow duration curves, hydrographs and annual water balance error with RMSE and MRAE value.

5.9.2.1.1 Flow duration curve

The performance of the model in the validation period was assessed for total flow series and for flow regimes, high, medium and low for RMSE and MRAE value as shown in Table 5-23. The corresponding graphical representation is shown in Figure 5-21.

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Table 5-23: Numerical measures for Verification of Urawa watershed

Gauging Station	RMSE (mm/day)	MRAE	Annual Water Balance Error (%)	Flow Duration Curve - Unsorted					
				High		Medium		Low	
				RMSE (mm/day)	MRAE	RMSE (mm/day)	MRAE	RMSE (mm/day)	MRAE
Urawa	3.25	0.523	-17	9.30	0.449	2.62	0.522	0.70	0.562

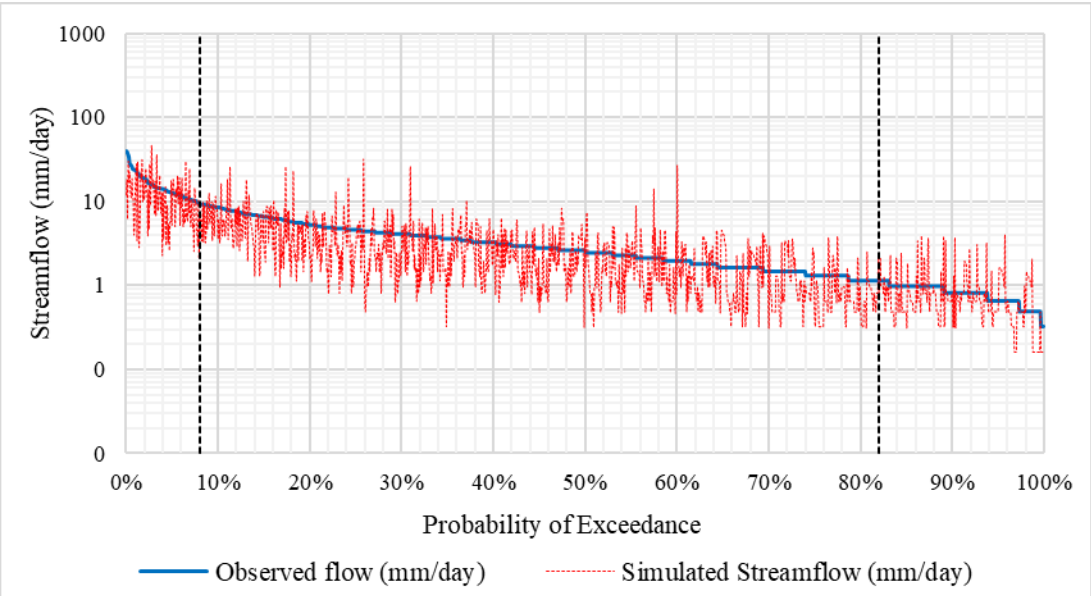

Figure 5-21: Unsorted flow duration curve for the verification period of Urawa Catchment

Figure 5-22 illustrates sorted FDC and Table 5-24 shows respective goodness of fit measures in numerically for total flow series and flow regimes for RMSE and MRAE vales.

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Table 5-24: Numerical measures of flow duration curve for the verification period of Urawa watershed

Gauging Station	RMSE (mm/day)	MRAE	Flow Duration Curve - Sorted					
			High		Medium		Low	
			RMSE (mm/day)	MRAE	RMSE (mm/day)	MRAE	RMSE (mm/day)	MRAE
Urawa	0.782	0.278	1.758	0.107	0.741	0.264	0.333	0.412

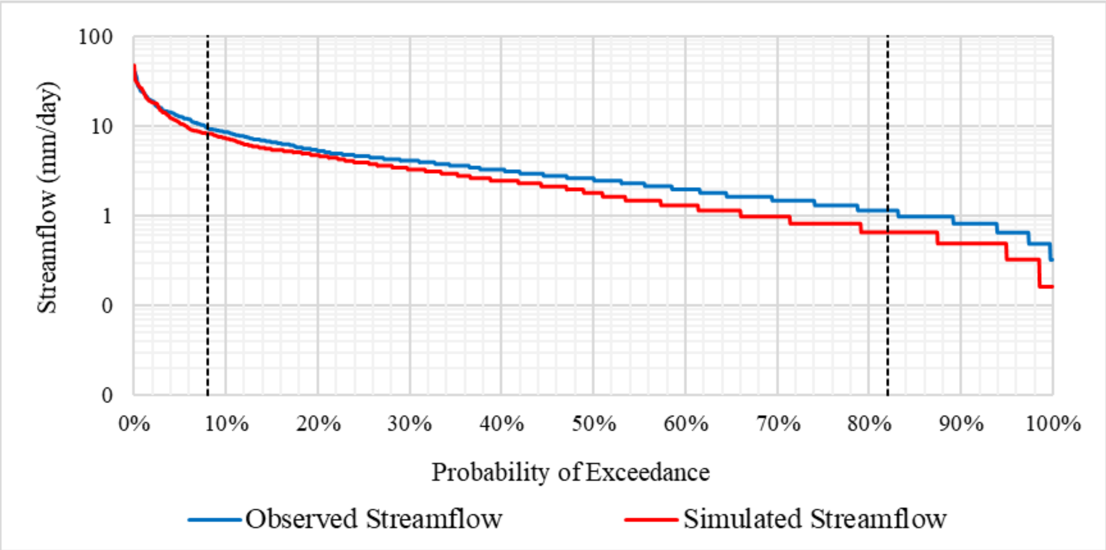
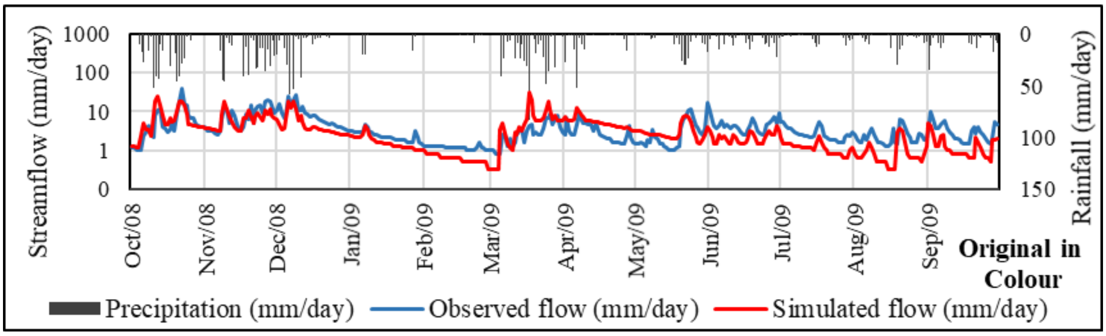


Figure 5-22: Flow Duration Curve for verification of Urawa Watershed

5.9.2.1.2 Matching of Observed and Simulated hydrograph

The similarity of observed and simulated flow is shown in Figure 5-23. Each graph represents one water year.



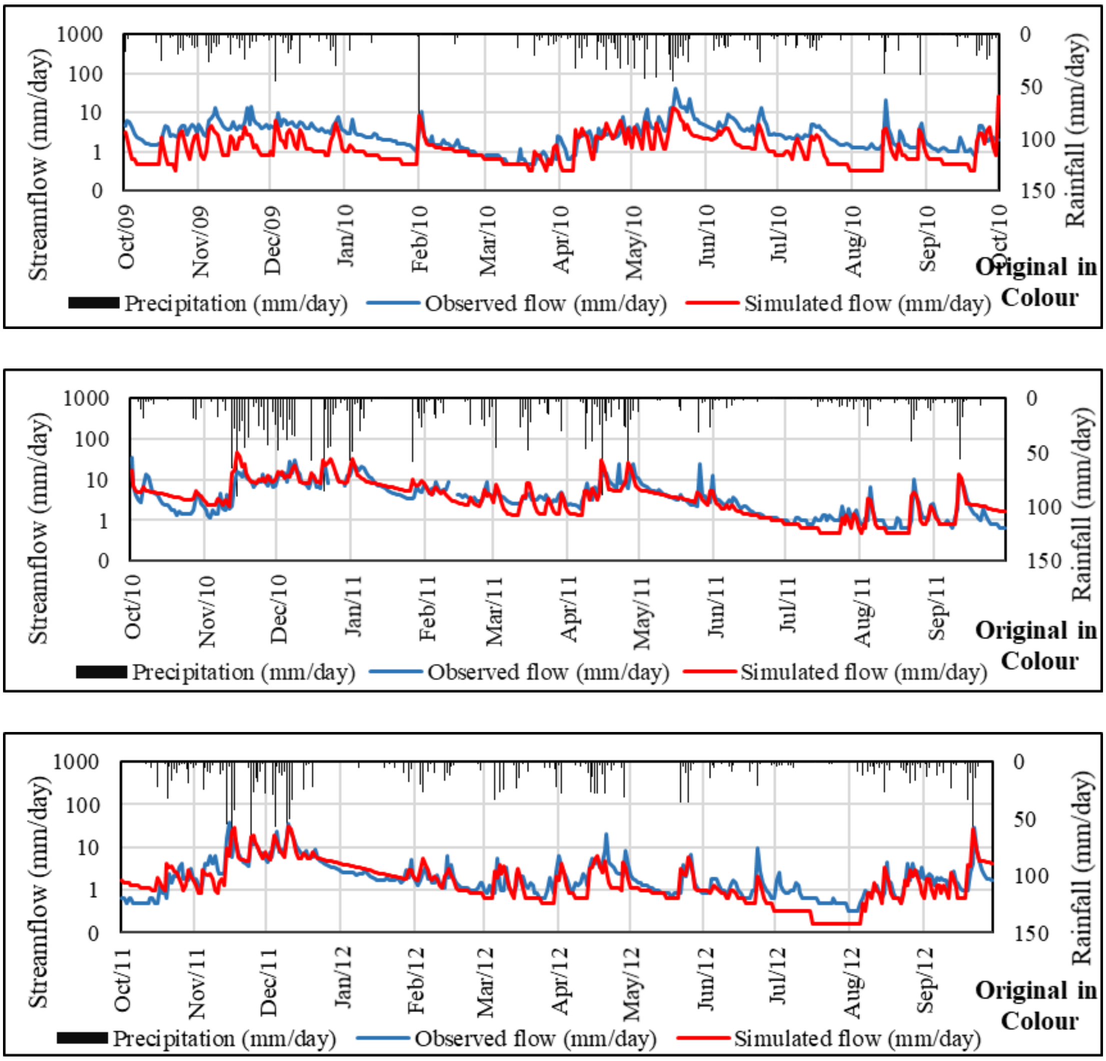


Figure 5-23: Verification Result for Urawa Watershed - Semi Log plot

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5.9.2.1.3 The Annual Water Balance

AWBE calculation is shown in Table 5-25 and corresponding graphical representation is shown in Figure 5-24. The lowest AWBE has been recorded in the water year 2010/11 at 1%. In average 17% streamflow underestimation was identified for the period of water year 2008/09 to 2011/12.

Table 5-25: Annual Water Balance for Verification of Urawa Watershed

Water Year	RF (mm/ year)	Sim. SF (mm/ year)	Obs. SF (mm/ year)	WB for Sim. SF (mm/ year)	WB for Obs. SF (mm/ year)	AWBE (mm/ year)	Percentage error (%)	Sim. Runoff Coeff	Obs. Runoff Coeff
2008/09	2526	1299	1564	1226	962	-265	-17%	0.51	0.62
2009/10	2059	625	1279	1434	780	-654	-51%	0.30	0.62
2010/11	2766	1840	1815	926	951	25	1%	0.67	0.66
2011/12	2097	979	1064	1118	1033	-85	-8%	0.47	0.51
Average	2362	1186	1431	1176	932	-245	-17%	0.50	0.61

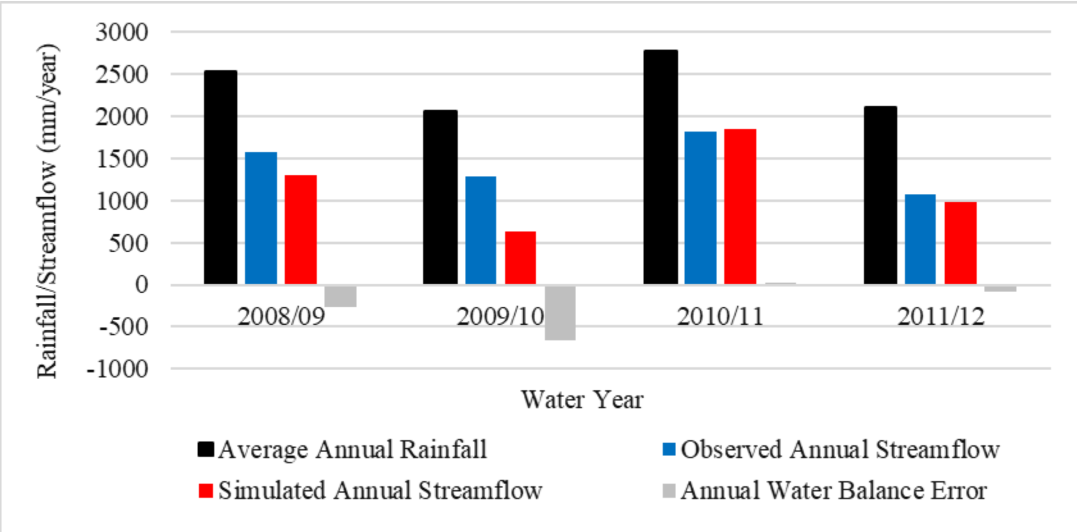

Figure 5-24: Annual Water Balance for Urawa Watershed for Verification Period

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5.10 Optimized HEC-HMS model parameters

The best-performed model parameters were finalized following systematic calibration and validation procedure with respect to evaluation criteria and set of optimal parameters are shown in Table 5-26.

Table 5-26: Optimized HEC-HMS model parameter for Pitabaddara and Urawa watershed

Hydrological Process	Model parameter	Unit	Optimized Parameter - Pitabaddara	Optimized Parameter - Urawa
Canopy method	Initial storage	%	0.35	0.5
	Max storage	mm	10.18	13.094
Surface-simple method	Initial storage	mm	0.19	0.5
	Max storage	mm	33.864	39.496
Deficit and Constant loss method	Initial deficit	mm	21.8	12.6
	Maximum deficit	mm	37.028	63.949
	Constant rate	mm/hr	0.27468	0.7
Transform method	Lag time	min	406.64	261.79
Baseflow method	Initial discharge	m3/s	4.3933	1.2143
	Recession Constant		0.94257	0.97
	Threshold ratio		0.24771	0.19

5.11 Model Parameter Transferability

Literature reveals a significant number of parameter transferability approaches identified by researchers for different regions, for various objectives. In this case, the main concern of the study is about sustainable water resource management in an ungauged catchment and this study has been tested applying the simplest form of parameter transformation method, direct model parameter transferability. Application of the methodology is comprehensible for water managers and water engineers, without any modification to the optimized parameter, concerning the characteristic of the ungauged catchments other than the catchment area.

In model parameter transformation, optimized model parameters of Pitabaddara catchment were transferred to Urawa catchment which is sub-catchment of Pitabaddara watershed and model parameters of Urawa catchment were transferred to Pitabaddra catchment.

5.11.1 Model parameter transfer schemes

According to the detailed literature review, three types of model parameter schemes could be identified as temporal, spatial and spatiotemporal (Patil & Stieglitz, 2015b). However, addition to aforesaid schemes, combination of three transfer schemes was tested including the total model calibrated period for streamflow estimation.

Therefore, initially optimized model parameters were assigned to the model to simulate streamflow for full data series (water year 2008/9 to water year 2017/18) for 10 water years to form a comparable platform to evaluate performance. Accordingly, re-derived sorted and unsorted flow duration curves and respective RMSE and MRAE values for flow spectrum and flow regimes are shown in the following sections.

In addition to that summary of the parameter, transferability approaches with regards to their spatial and temporal variations are shown in Table 5-27.

Table 5-27: Parameter transferability approaches with temporal and spatial variation

Streamflow	Transferred Type	Set of optimal parameters		Parameter Transformation	
		Calibrated Period	Calibrated Catchment	Transferred Period	Transferred From
Pitabaddara Catchment	Temporal Transferability	from 2008/09 to 2013/14	Pitabaddara	from 2014/15 to 2017/18	Pitabaddara
	Spatial Transferability	from 2012/13 to 2017/18	Urawa	from 2012/13 to 2017/18	Urawa
	Spatiotemporal Transferability	from 2012/13 to 2017/18	Urawa	from 2008/09 to 2011/12	Urawa

Streamflow	Transferred Type	Set of optimal parameters		Parameter Transformation	
		Calibrated Period	Calibrated Catchment	Transferred Period	Transferred From
	Spatiotemporal Transferability (with the calibrated period)	from 2012/13 to 2017/18	Urawa	from 2008/09 to 2017/18	Urawa
Urawa Catchment	Temporal Transferability	from 2012/13 to 2017/18	Pitabaddara	from 2008/09 to 2011/12	Pitabaddara
	Spatial Transferability	from 2008/09 to 2013/14	Pitabaddara	from 2008/09 to 2013/14	Pitabaddara
	Spatiotemporal Transferability	from 2008/09 to 2013/14	Pitabaddara	from 2014/15 to 2017/18	Pitabaddara
	Spatiotemporal Transferability (with the calibrated period)	from 2008/09 to 2013/14	Pitabaddara	from 2008/09 to 2017/18	Pitabaddara

5.11.1.1 Performance for optimized parameters for study period - Pitabaddara catchment

Following Table 5-28 and Figure 5-25 illustrate the model performance of Pitabaddara catchment for 10 water years period, from water year 2008/9 to water year 2017/18, with the optimized model parameters of the same catchment with regards of streamflow magnitude and time of its occurring.

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Table 5-28: Numerical measures for optimized parameters for the study period -Pitabaddara watershed (unsorted FDC)

Gauging Station	RMSE (mm/day)	MRAE	Annual Water Balance Error (%)	Flow Duration Curve					
				High		Medium		Low	
				RMSE (mm/day)	MRAE	RMSE (mm/day)	MRAE	RMSE (mm/day)	MRAE
Pitabeddara	5.52	0.479	12.4	16.36	0.363	3.35	0.486	0.58	0.504

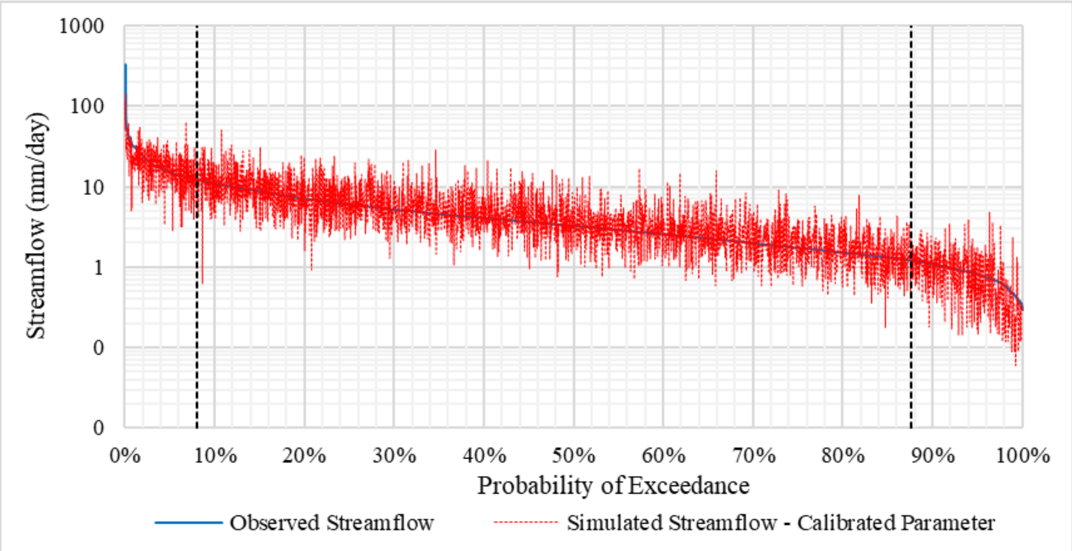

Figure 5-25: Unsorted flow duration curve for optimized parameters for the study period - Pitabeddara Catchment

Following Table 5-29 and Figure 5-26 illustrate streamflow simulation of Pitabadara catchment for total study period relevant to the streamflow magnitude and respective sequences.

`

Table 5-29: Numerical measures for optimized parameters for study period - Pitabaddara watershed (sorted FDC)

Gauging Station	RMSE (mm/day)	MRAE	Flow Duration Curve					
			High		Medium		Low	
			RMSE (mm/day)	MRAE	RMSE (mm/day)	MRAE	RMSE (mm/day)	MRAE
Pitabeddara	3.322	0.146	11.327	0.198	0.956	0.112	0.581	0.504

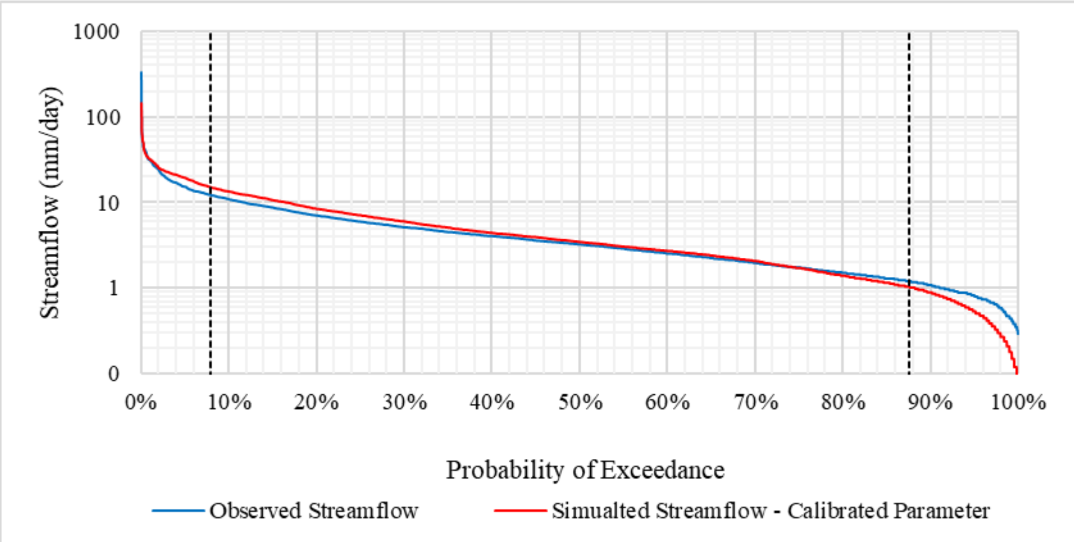

Figure 5-26: Unsorted flow duration curve for optimized parameters for the study period to Pitabeddara Catchment

5.11.1.2 Performance for optimized parameters for study period – Urawa catchment

Model performance with the assigned set of optimized parameters for the study period is shown in Table 5-30 and Figure 5-27 with sorted FDC and respective numerical measures.

`

Table 5-30: Numerical measures for optimized parameters for the study period - Urawa watershed (unsorted FDC)

Gauging Station	RMSE (mm/day)	MRAE	Annual Water Balance Error (%)	Flow Duration Curve					
				High		Medium		Low	
				RMSE (mm/day)	MRAE	RMSE (mm/day)	MRAE	RMSE (mm/day)	MRAE
Urawa	0.75	0.689	3.97	1.974	0.431	0.58	0.592	0.25	1.203

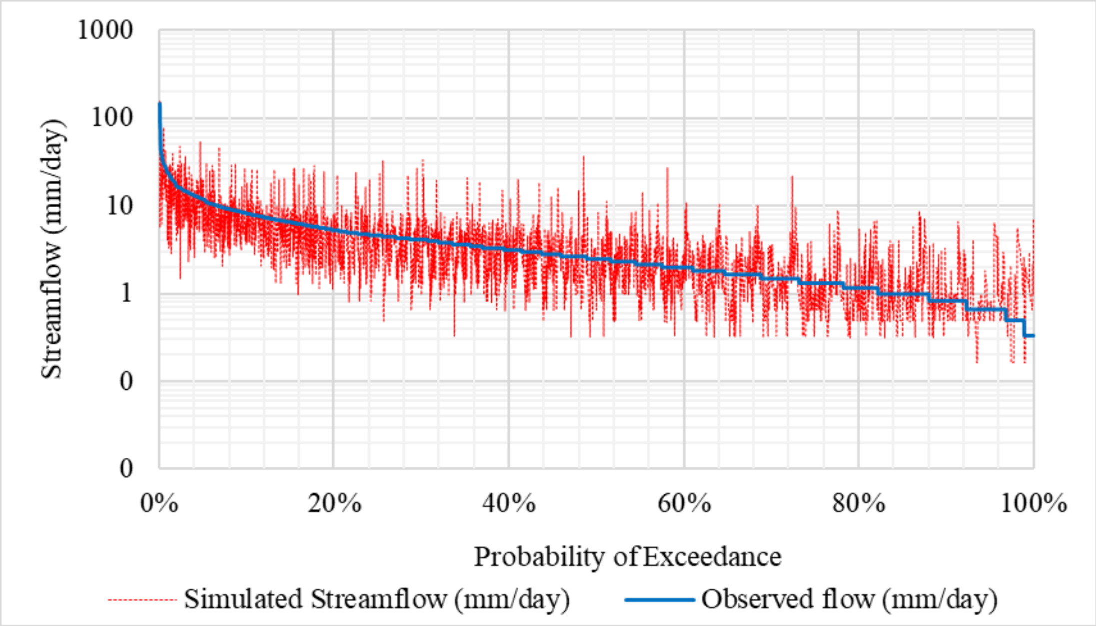

Figure 5-27: Unsorted flow duration curve for optimized parameters for the study period - Urawa Catchment

Table 5-31 and Figure 5-28 represent model performance with the streamflow magnitude and respective sequences.

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Table 5-31: Numerical measures for optimized parameters for study period – Urawa watershed (sorted FDC)

Gauging Station	RMSE (mm/day)	MRAE	Flow Duration Curve					
			High		Medium		Low	
			RMSE (mm/day)	MRAE	RMSE (mm/day)	MRAE	RMSE (mm/day)	MRAE
Urawa	1.200	0.107	4.253	0.078	0.198	0.081	0.190	0.231

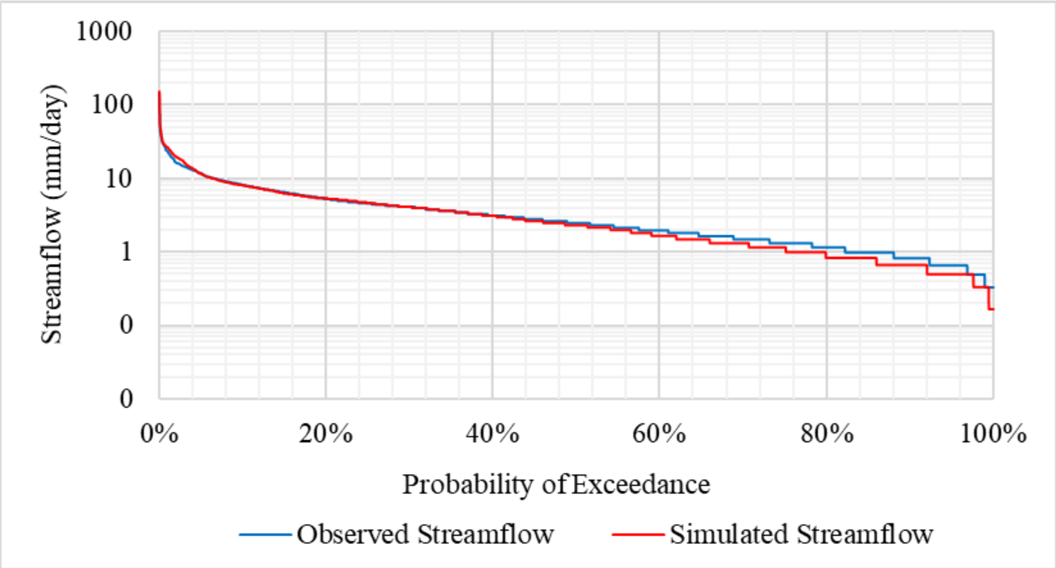

Figure 5-28: Unsorted flow duration curve for optimized parameters for the study period to Urawa Catchment

5.11.2 Parameter transferability from sub-catchment to the main catchment

Model performance criteria, used in model calibration and validation were applied in the assessment of parameter transformation.

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5.11.2.1 The goodness of fit measures for parameter transformation

5.11.2.1.1 Flow duration Curves

5.56 mm/day RMSE value and 0.445 MRAE value were reported as shown in Table 5-32 in parameter transformation. Respective non-sorted FDC is shown in Figure 5-29.

Table 5-32: Numerical measures for parameter transformation to Pitabaddara watershed – unsorted FDC

Gauging Station	RMSE (mm/day)	MRAE	Annual Water Balance Error (%)	Flow Duration Curve					
				High		Medium		Low	
				RMSE (mm/day)	MRAE	RMSE (mm/day)	MRAE	RMSE (mm/day)	MRAE
Pitabeddara	5.56	0.445	-19	17.77	0.463	2.64	0.448	0.62	0.419

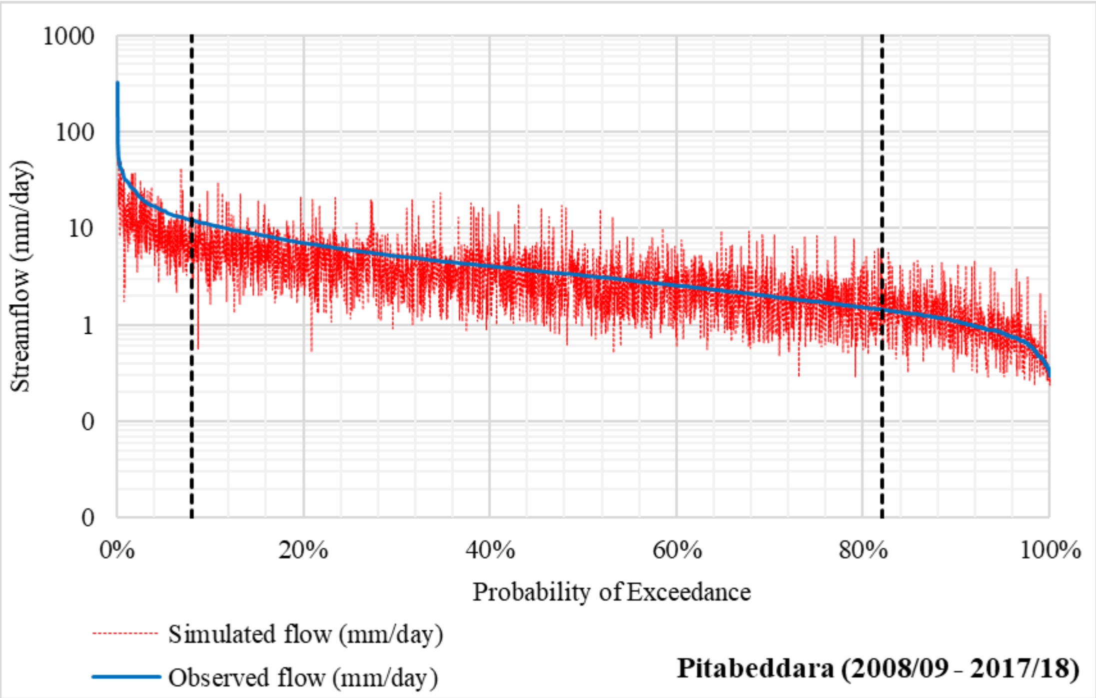

Figure 5-29: Unsorted flow duration curve for parameter transformation to Pitabeddara Catchment

Figure 5-30 illustrates sorted FDC and respective statistical presentation is shown in Table 5-33.

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Table 5-33: Numerical measures of flow duration curve for parameter transformation to Pitabaddara watershed – Sorted FDC

Gauging Station	RMSE (mm/day)	MRAE	Flow Duration Curve					
			High		Medium		Low	
			RMSE (mm/day)	MRAE	RMSE (mm/day)	MRAE	RMSE (mm/day)	MRAE
Pitabeddara	3.73	0.206	12.7	0.278	1.1	0.193	0.215	0.243

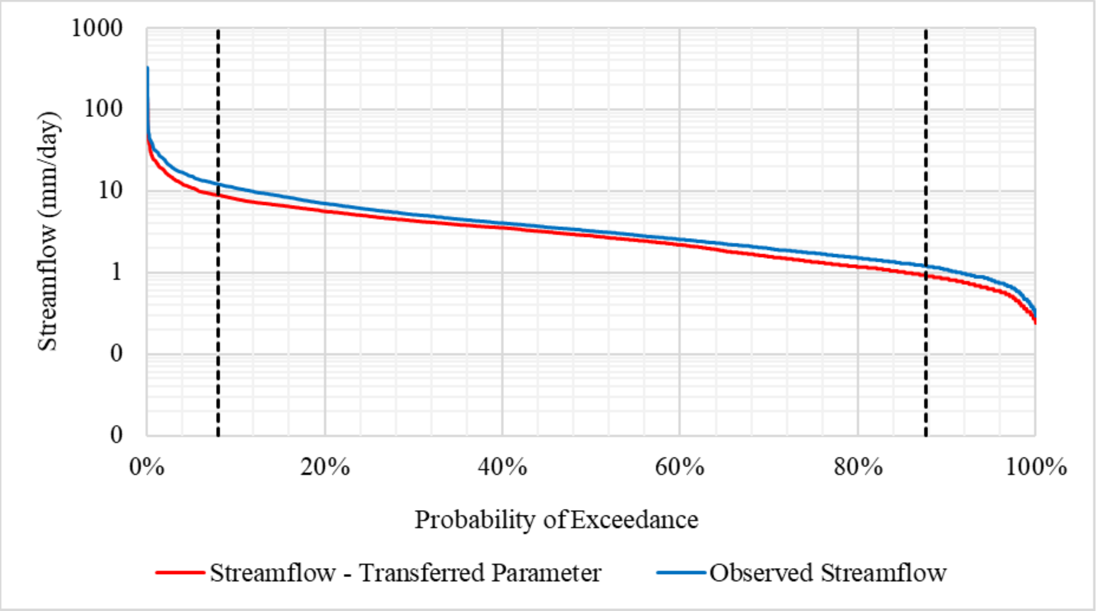
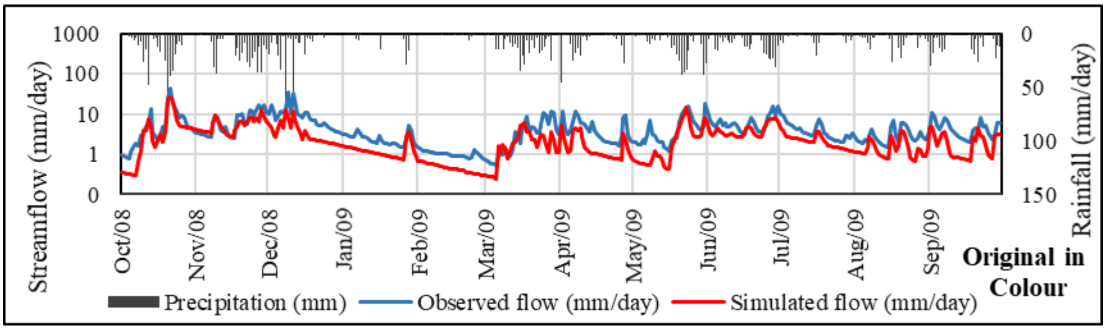
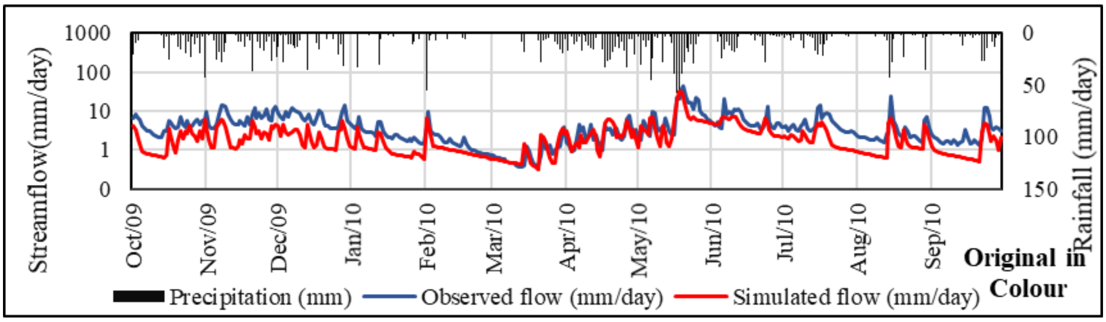


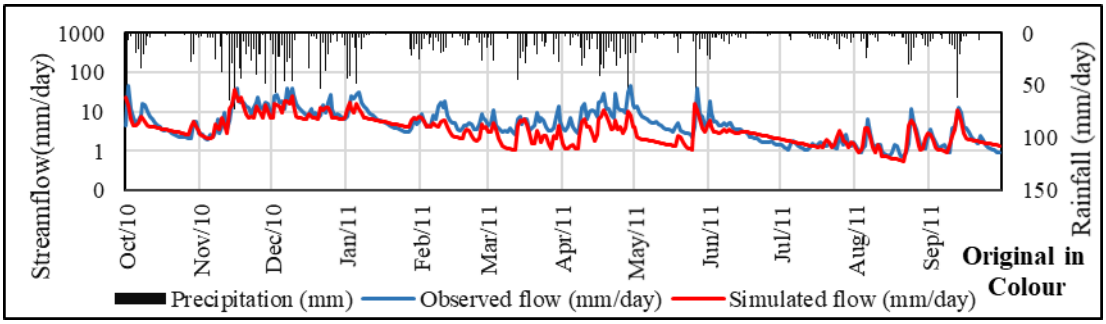
Figure 5-30: Flow Duration Curve for parameter transformation to Pitabaddara Watershed

5.11.2.1.2 Matching of Observed and Simulated hydrograph

The similarity of observed and simulated flow is shown in Figure 5-23. Each graph represents one water year.




Streamflow(mm/day)
1000
100
10
1
0
0
50
100
150
Rainfall (mm/day)
Oct/09
Nov/09
Dec/09
Jan/10
Feb/10
Mar/10
Apr/10
May/10
Jun/10
Jul/10
Aug/10
Sep/10
Precipitation (mm)
Observed flow (mm/day)
Simulated flow (mm/day)
Original in Colour


Streamflow(mm/day)
1000
100
10
1
0
0
50
100
150
Rainfall (mm/day)
Oct/10
Nov/10
Dec/10
Jan/11
Feb/11
Mar/11
Apr/11
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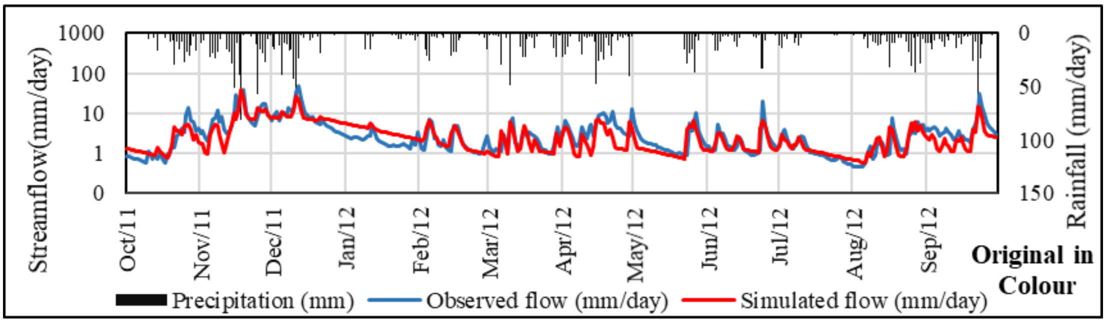
Jul/11
Aug/11
Sep/11
Precipitation (mm)
Observed flow (mm/day)
Simulated flow (mm/day)
Original in Colour


Streamflow(mm/day)
1000
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10
1
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50
100
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Rainfall (mm/day)
Oct/11
Nov/11
Dec/11
Jan/12
Feb/12
Mar/12
Apr/12
May/12
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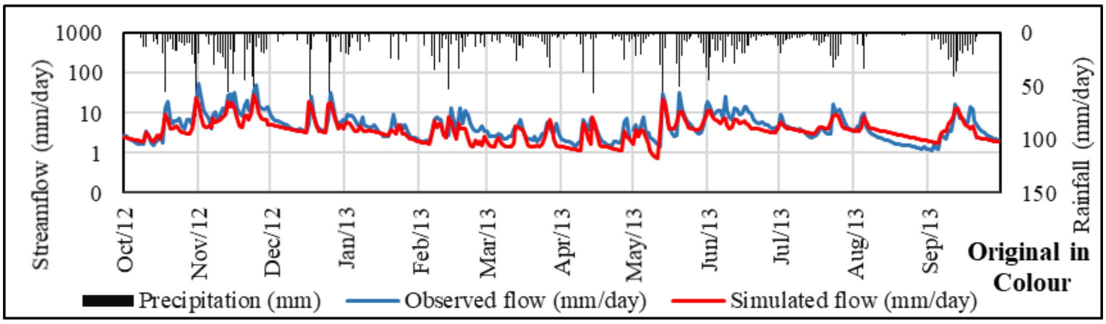
Jul/12
Aug/12
Sep/12
Precipitation (mm)
Observed flow (mm/day)
Simulated flow (mm/day)
Original in Colour


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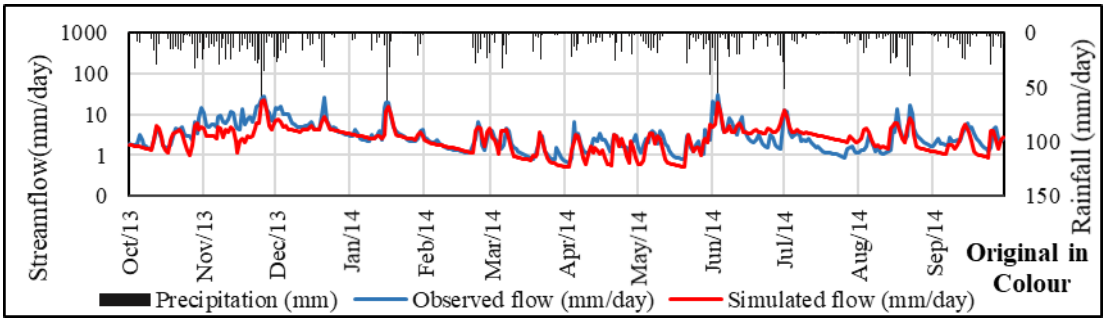
Rainfall (mm/day)
Oct/12
Nov/12
Dec/12
Jan/13
Feb/13
Mar/13
Apr/13
May/13
Jun/13
Jul/13
Aug/13
Sep/13
Precipitation (mm)
Observed flow (mm/day)
Simulated flow (mm/day)
Original in Colour


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

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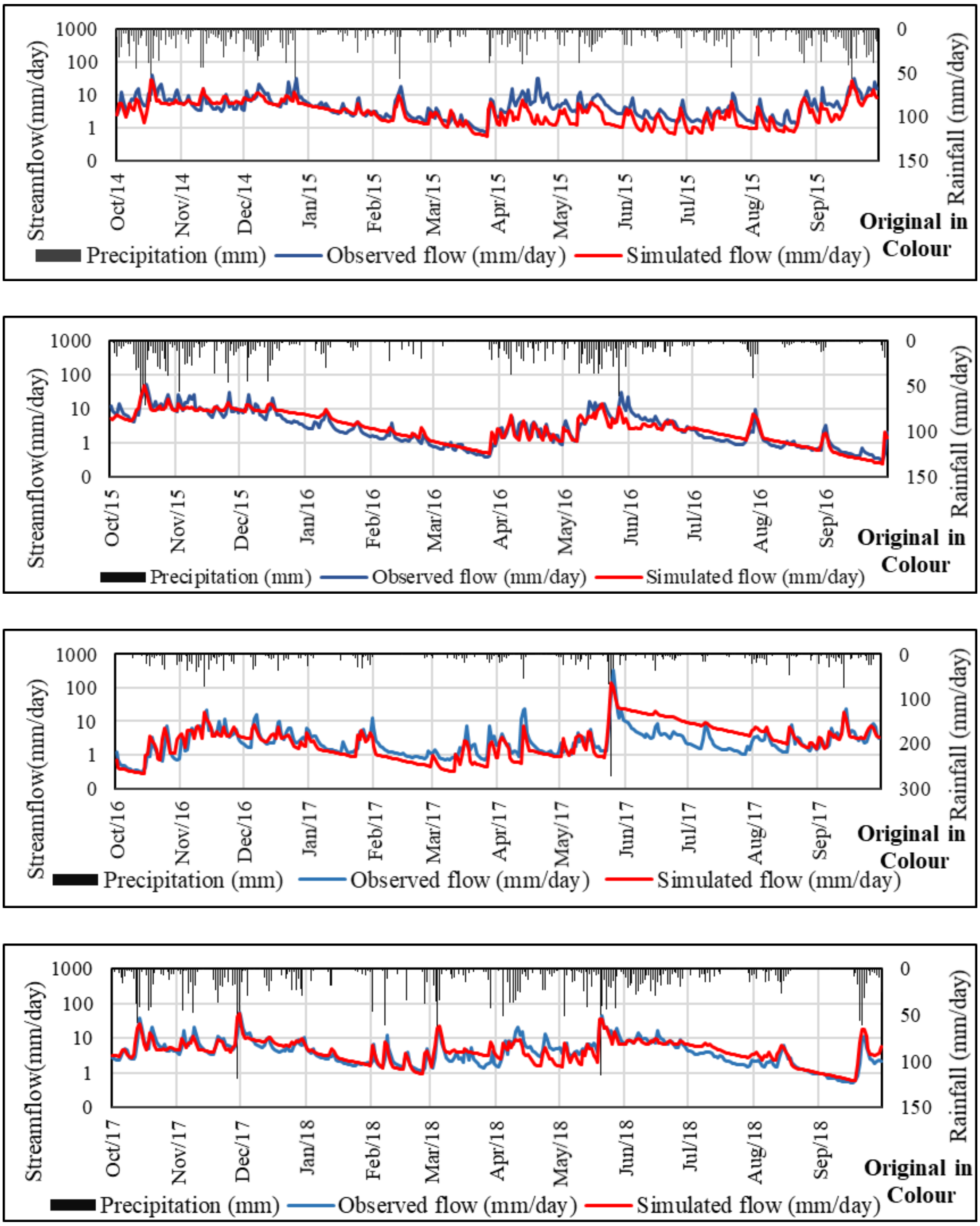

Figure 5-31: Parameter transformation for Pitabaddara Watershed – Hydrograph (Semi log plot)

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5.11.2.1.3 The Annual Water Balance

Table 5-34 and Figure 5-32 illustrate AWBE for the transferred parameter from sub-catchment (Urawa) to main catchment (Pitabaddara). The best prediction is noted for water year 2017/2018 as -0.28% which is -5.6 mm/year.

Table 5-34: Annual Water Balance for parameter transformation to Pitabaddara Watershed

Water Year	RF (mm/ year)	Sim. SF from Transferred Parameter (mm/year)	Obs. SF (mm/ year)	WB for Sim. SF (mm/y ear)	WB for Obs. SF (mm/ye ar)	AWBE - Transferred Parameter (mm/year)	Percent age error
2008/09	2749	1027	1818	1721	931	-790	-43%
2009/10	2653	916	1705	1736	947	-789	-46%
2010/11	3366	1670	2535	1696	831	-864	-34%
2011/12	2692	1212	1461	1480	1231	-248	-17%
2012/13	3351	1633	2265	1718	1086	-631	-27%
2013/14	2776	1129	1422	1646	1354	-292	-20.%
2014/15	3455	1401	2095	2053	1359	-694	-33%
2015/16	2718	1644	1803	1074	915	-158	-8%
2016/17	2761	1828	1646	932	1114	182	11%
2017/18	3482	2012	2018	1470	1464	-5	-0%
Average	3001	1447	1877	1553	1123	-429	-22%

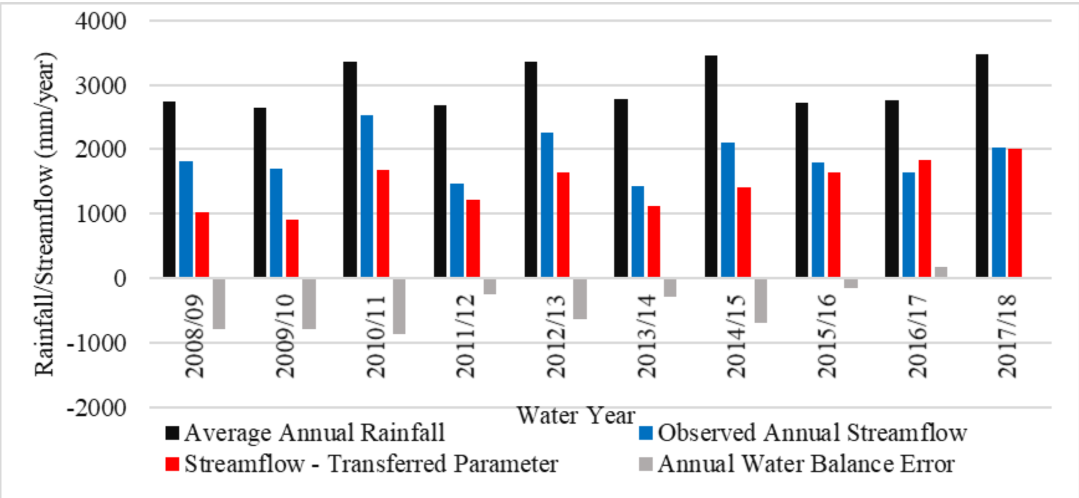

Figure 5-32: Annual Water Balance for Pitabaddara Watershed for Transferred model parameter

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5.11.3 Parameter transferability from main catchment to sub-catchment

Model performance criteria, hydrograph, sorted and unsorted FDCs and AWB were evaluated statistically and graphically.

5.11.3.1 The goodness of fit measures for parameter transformation

5.11.3.1.1 Flow duration Curves

The model performed with 5.29 mm/day RMSE value and 0.823 MRAE value as shown in Table 5-35 in parameter transformation to Urawa watershed. Respective non-sorted FDC is shown in Figure 5-33.

Table 5-35: Numerical measures for parameter transformation to Urawa watershed – unsorted FDC

Gauging Station	RMSE (mm/day)	MRAE	Annual Water Balance Error (%)	Flow Duration Curve					
				High		Medium		Low	
				RMSE (mm/day)	MRAE	RMSE (mm/day)	MRAE	RMSE (mm/day)	MRAE
Urawa	5.29	0.823	35.63	13.05	0.543	4.37	0.736	1.70	1.308

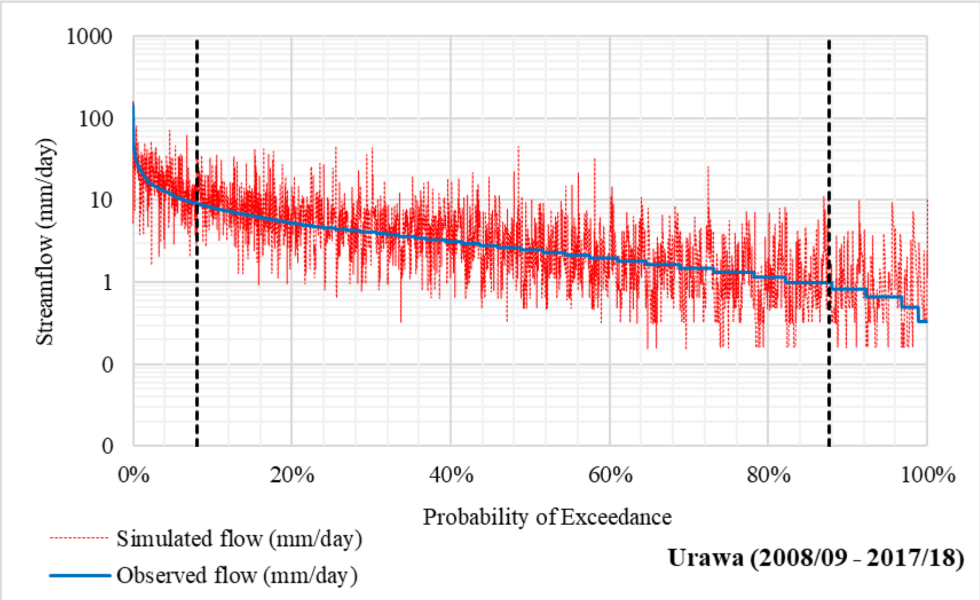

Figure 5-33: Unsorted flow duration curve for parameter transformation to Urawa Catchment

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Following Table 5-36 and Figure 5-34 show statistical and graphical measures in terms of sorted FDC in parameter transformation to Urawa Catchment.

Table 5-36: Numerical measures of sorted FDC for parameter transformation to Urawa watershed

Gauging Station	RMSE (mm/day)	MRAE	Flow Duration Curve					
			High		Medium		Low	
			RMSE (mm/day)	MRAE	RMSE (mm/day)	MRAE	RMSE (mm/day)	MRAE
Urawa	3.221	0.301	10.52	0.599	1.545	0.247	0.289	0.394

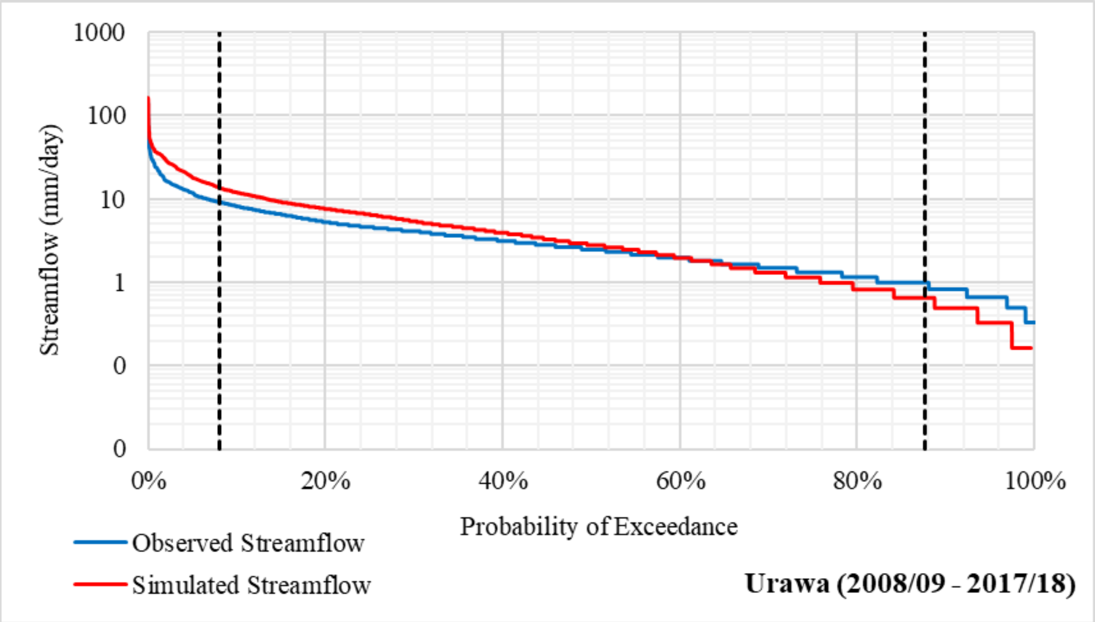

Figure 5-34: Sorted flow Duration Curve for parameter transformation to Urawa Watershed

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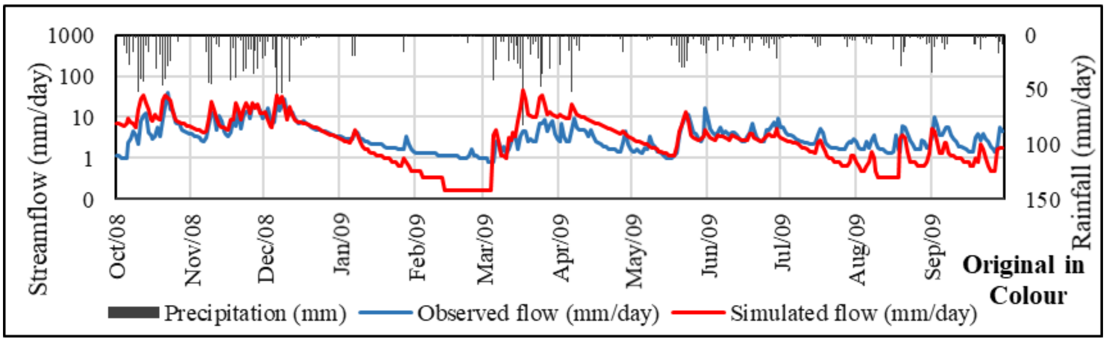
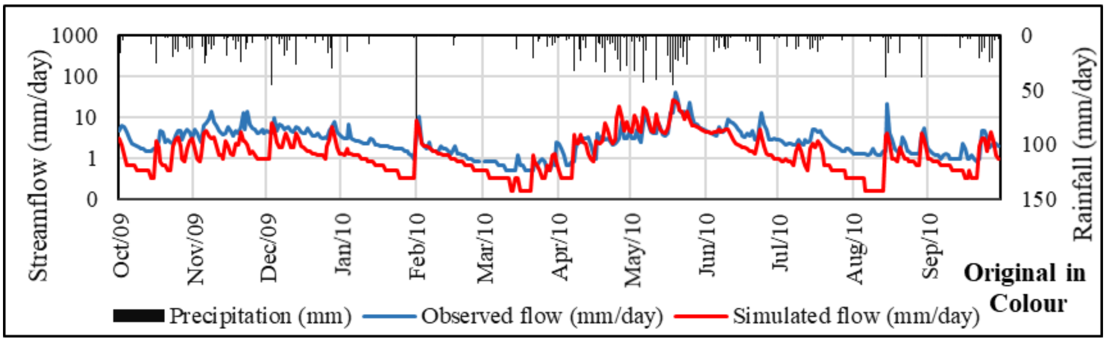
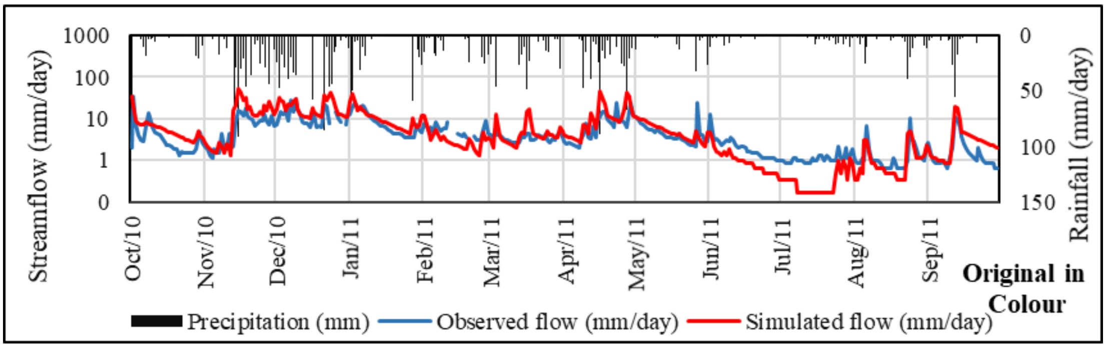
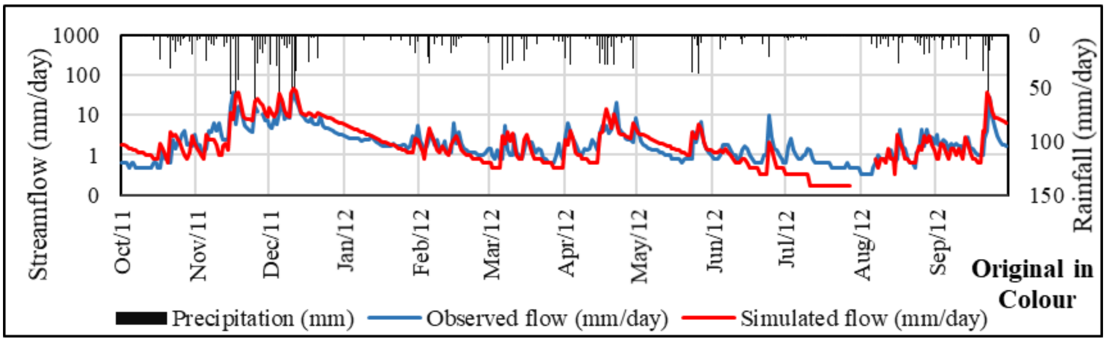
5.11.3.1.2 Matching of Observed and Simulated hydrograph

The similarity of measured and simulated flow is shown in Figure 5-35. Each graph represents one water year.









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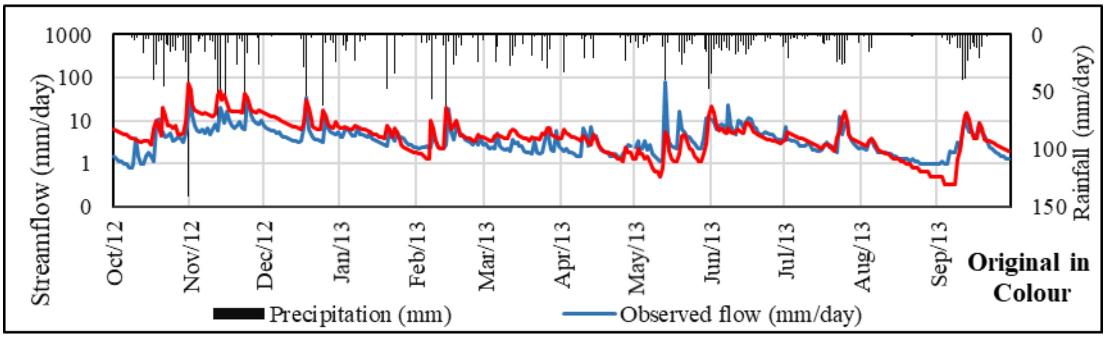
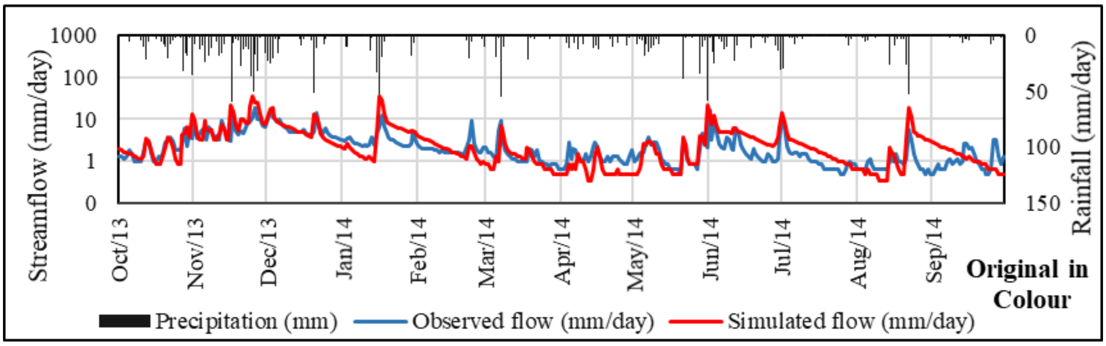

Streamflow (mm/day)
1000
100
10
1
0
Rainfall (mm/day)
0
50
100
150
Oct/12
Nov/12
Dec/12
Jan/13
Feb/13
Mar/13
Apr/13
May/13
Jun/13
Jul/13
Aug/13
Sep/13
Original in Colour
Precipitation (mm)
Observed flow (mm/day)


Streamflow (mm/day)
1000
100
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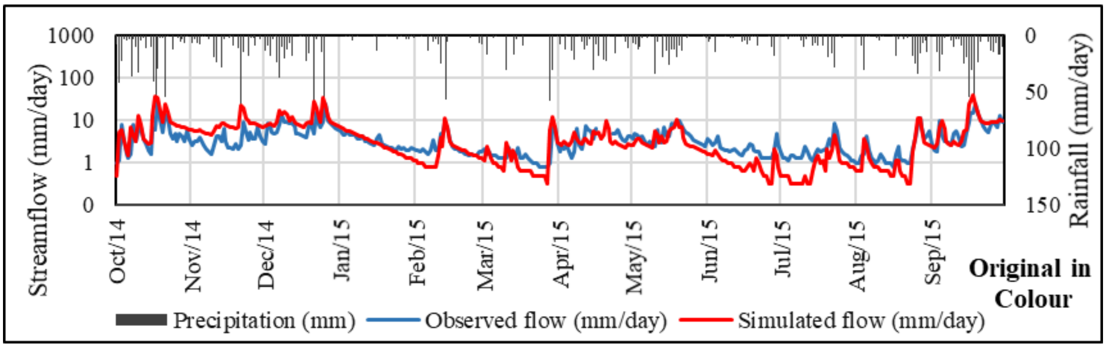
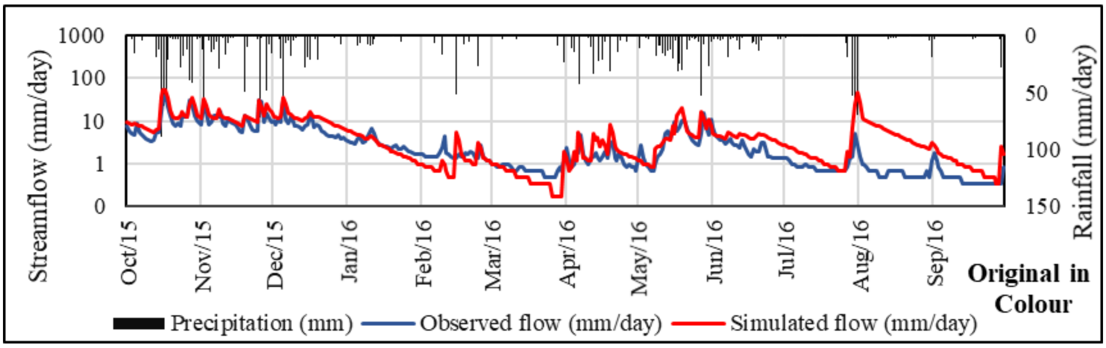
1
0
Rainfall (mm/day)
0
50
100
150
Oct/13
Nov/13
Dec/13
Jan/14
Feb/14
Mar/14
Apr/14
May/14
Jun/14
Jul/14
Aug/14
Sep/14
Original in Colour
Precipitation (mm)
Observed flow (mm/day)
Simulated flow (mm/day)


Streamflow (mm/day)
1000
100
10
1
0
Rainfall (mm/day)
0
50
100
150
Oct/14
Nov/14
Dec/14
Jan/15
Feb/15
Mar/15
Apr/15
May/15
Jun/15
Jul/15
Aug/15
Sep/15
Original in Colour
Precipitation (mm)
Observed flow (mm/day)
Simulated flow (mm/day)


Streamflow (mm/day)
1000
100
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1
0
Rainfall (mm/day)
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Oct/15
Nov/15
Dec/15
Jan/16
Feb/16
Mar/16
Apr/16
May/16
Jun/16
Jul/16
Aug/16
Sep/16
Original in Colour
Precipitation (mm)
Observed flow (mm/day)
Simulated flow (mm/day)

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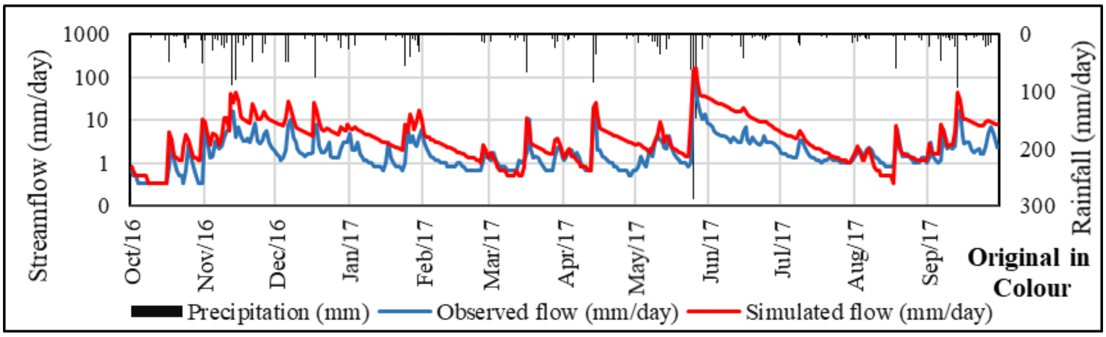

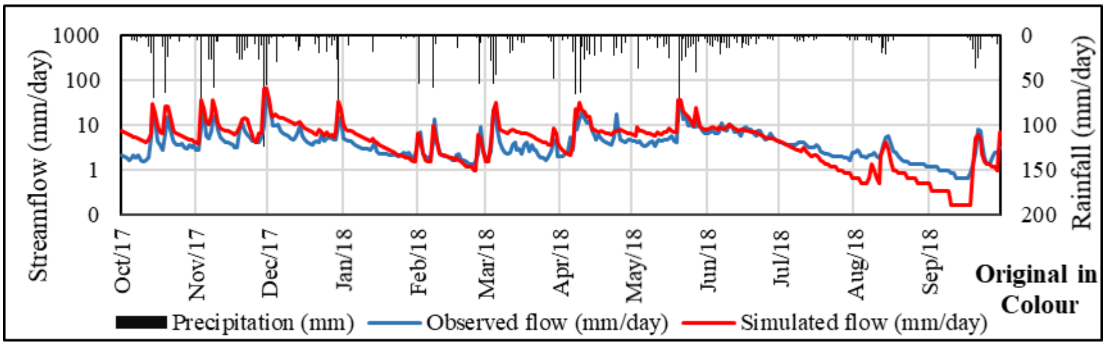

Figure 5-35: Parameter transformation to Urawa Watershed – Hydrograph (Semi log plot)

5.11.3.1.3 The Annual Water Balance Error

Performance of transferred model parameter from main catchment (Pitabaddara) to Urawa in term of AWBE is shown

Table 5-37 and Figure 5-36. On average 35.63 %, which is 502.8 mm/year annual water balance error was noted.

Table 5-37: Annual Water Balance for parameter transformation to Urawa Watershed

Water Year	RF (mm/year)	Sim. SF from Transferred Parameter (mm/year)	Obs. SF (mm/year)	WB for Sim. SF (mm/year)	WB for Obs. SF (mm/year)	AWBE - Transferred Parameter (mm/year)	Percentage error
2008/09	2525	1969	1564	556	961	405	25%
2009/10	1968	838	1277	1130	691	-438	-34%
2010/11	2856	2473	1816	383	1040	657	36%

Water Year	RF (mm/year)	Sim. SF from Transferred Parameter (mm/year)	Obs. SF (mm/year)	WB for Sim. SF (mm/year)	WB for Obs. SF (mm/year)	AWBE - Transferred Parameter (mm/year)	Percentage error
2011/12	2097	1303	1064	793	1032	239	22%
2012/13	2666	2303	1683	363	982	619	36%
2013/14	2029	1288	978	740	1050	309	31%
2014/15	2559	1705	1404	854	1154	300	21%
2015/16	2252	2167	1449	85	803	717	49%
2016/17	2771	2614	1105	157	1666	1508	136%
2017/18	2847	2480	1770	367	1077	710	40%
Average	2457	1914	1411	543	1046	502	35%

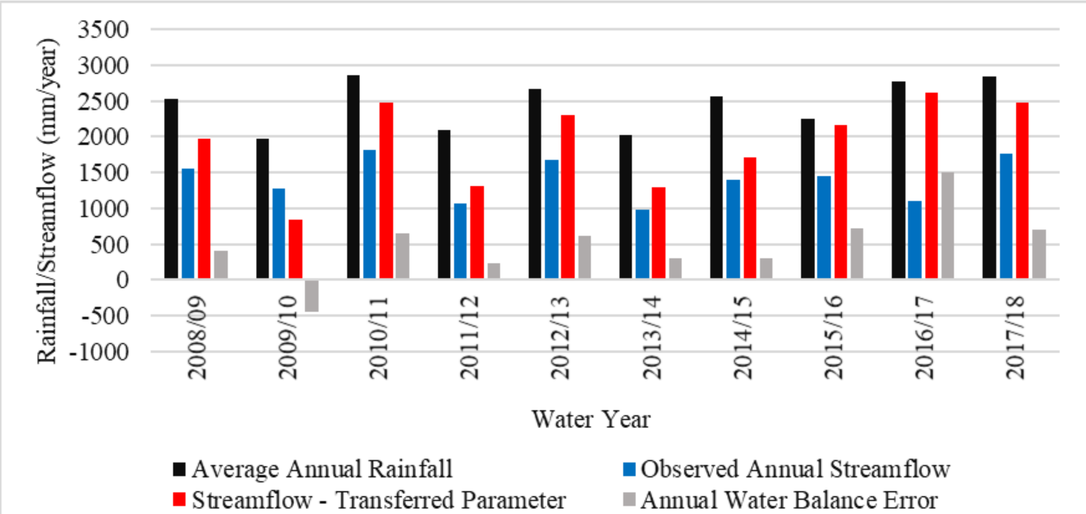

Figure 5-36: Annual Water Balance for Urawa Watershed for Transferred model parameter

5.11.4 Transferability of model parameters in spatial and temporal and spatiotemporal

In addition to the transformation of optimal parameters in the full study period, the performance of model transferability with respect to the spatial and temporal variation was assessed. Results are shown in Appendix G.

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6 DISCUSSION

6.1 Hydro metrological data selection

6.1.1 Selection of gauging stations

The ample literature review reveals the necessity of the identification of reliable and sufficient data periods in hydrologic modelling. The Nilwala river basin has four hydrometric stations called Pitabeddara, Urawa, Bopagoda and Panadugama. Out of these four stations in the present context, only Pitabeddara and Urawa is well-functioning and could obtain reliable data from responsible government organizations (Department of Irrigation). The Bopagoda hydrometric station has been terminated in the year 2010 which was commenced in the year 1940. Panadugama stations have not been calibrated and the reliability of the data is uncertain as per received information of the Department of Irrigation. Accommodating all circumstances, Pitabaddara and Urawa gauging stations were the available reliable river gauging station for the study.

6.1.2 Selection of data period

Information retrieval implies five to ten years' series of hydrologic data is sufficient to have a continuous lumped hydrologic model for accurate daily streamflow, with adequate representation of hydrologic processes in catchments. Accordingly, data for 10 years were selected from the water year 2008/09 to 2017/18 as it correlated existing characteristics of the catchment to the model to get reliable results for streamflow simulations to accomplish sustainable water resource management and planning in future.

The data series included long sequences of parallel diurnal data, moderate and extreme hydrological variability (flood and drought) and highest Spatio-temporal data density. Juraj and Slobodan (2004) identified these requirements as the main criteria to be considered in the selection of data and the data period in continuous hydrologic modelling.

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6.1.3 Data errors

The data was checked in visual to assess the correlation of streamflow and rainfall, and consistency of the data series by double mass curve and accuracy of data from annual water balance. Streamflow at Pitabaddara highly response precipitation of gauging stations at Hulandawa and streamflow at Urawa is highly sensitive for precipitation of gauging station at Urawa Rotumba. Nevertheless, the overall response of streamflow to the Thiessen weighted rainfall was adequate for model simulation with respect to the visual performance of rainfall and streamflow.

Water years 2013/14, 2014/15, 2016/17 and 2017/18 had an annual water balance which was higher than potential evaporation, (Figure 4-3) caused by either error of hydro-meteorological data or non-representational of Thiessen rainfall to the actual situation and those were insignificant. Only one significant deviation could be identified in AWB in Urawa catchment for water year 2016/17 as shown in Figure 4-6. Streamflow at Urawa of this specific year is very low compared to similar rainfall in recent years, having a runoff coefficient as 0.4 which was 0.58 on average. Consistency of data was at a level of acceptance as a correlation of the double mass curve is straight with a constant ratio as shown in Figure 4-9 and Figure 4-10. In brief other than the prescribed specific situation, the conclusion is that the data series are at a level of satisfaction to be applied to the model.

6.2 Determination of flow regimes

Streamflow thresholds of a watershed vary with the temporal resolution of data used for the study and also it is considered as watershed specific. Therefore, the derivation of flow threshold through a flow duration curve is a reasonable approach due to the ability of FDC to corporate catchment specific characteristics to determine the flow threshold. Wijesekera (2018) presented methodology through FDC slope and that can be seen in the logarithmic plots.

6.3 Model selection

The selection of appropriate hydrologic models with respect to the intention is a challenge faced by hydrological communities. The hydrologic problem to be addressed

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and its complexity, data availability and accuracy needed influence on choosing the hydrological modelling approach (Chandra et al., 2000). Table 2-3 shows a list of hydrologic models used in hydrologic modelling and parameter transformation to quantify streamflow in the ungauged catchment. However, many researchers have nominated, process-based hydrological models as the best representative of the catchment since its capability to incorporate a spatial and temporal variation of the catchment to the model by its logical structure and model parameter (Sitterson et al., 2017). Hence, process-based hydrologic models are appropriate to derive the model parameter to assess the possibility of parameter transferability.

Freely available and accessible hydrologic modelling software is generally used by hydrologists. Among them, software with proper technical guidance and assistance are prominent in the modelling. Therefore, HEC-HMS is one of the software, satisfied all the aforesaid requirements.

6.4 Hydrological process model selection

Application of lump model increased simplicity of the model concurrently achieving the intended objective of the study, reducing the uncertainty of model with excessive parameters. In addition to that, the lumped model is proficient to model the streamflow just at the outlet of the catchment (Moradkhani & Sorooshian, 2008).

The selection of appropriate models for hydrologic processes was carried out evaluating subjective criteria derived for the objective as described in chapter 2.9.1. Figure 6-1 illustrates a schematic diagram of hydrologic processes according to the selected process models for canopy model, surface model, loss model, transform model and baseflow model for this study.

Simple canopy and surface models were capable to symbolize the catchment characteristic linked to rainfall interception due to canopy and surface depression, to a sufficient level rather than complex dynamic behaviors. The HEC-HMS model has two precipitation loss models to simulate continuous hydrologic modelling. Out of these two models, one-layer deficit and constant model have been recommended for simple continuous modelling whereas five layers' soil moisture accounting (SMA)

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model is suggested for environments with complex infiltration and evaporation (Juraj & Slobodan, 2004). The data scare situation is one of the main problems in hydrologic modelling in this region. Therefore, the application of the deficit and constant model was appropriate which has fewer parameters. SCS unit hydrograph method was selected as the transform method. Also, the recession method was applied as the baseflow model and it was capable to reset baseflow automatically after each storm event simulating the behavior of the continuous hydrological process.

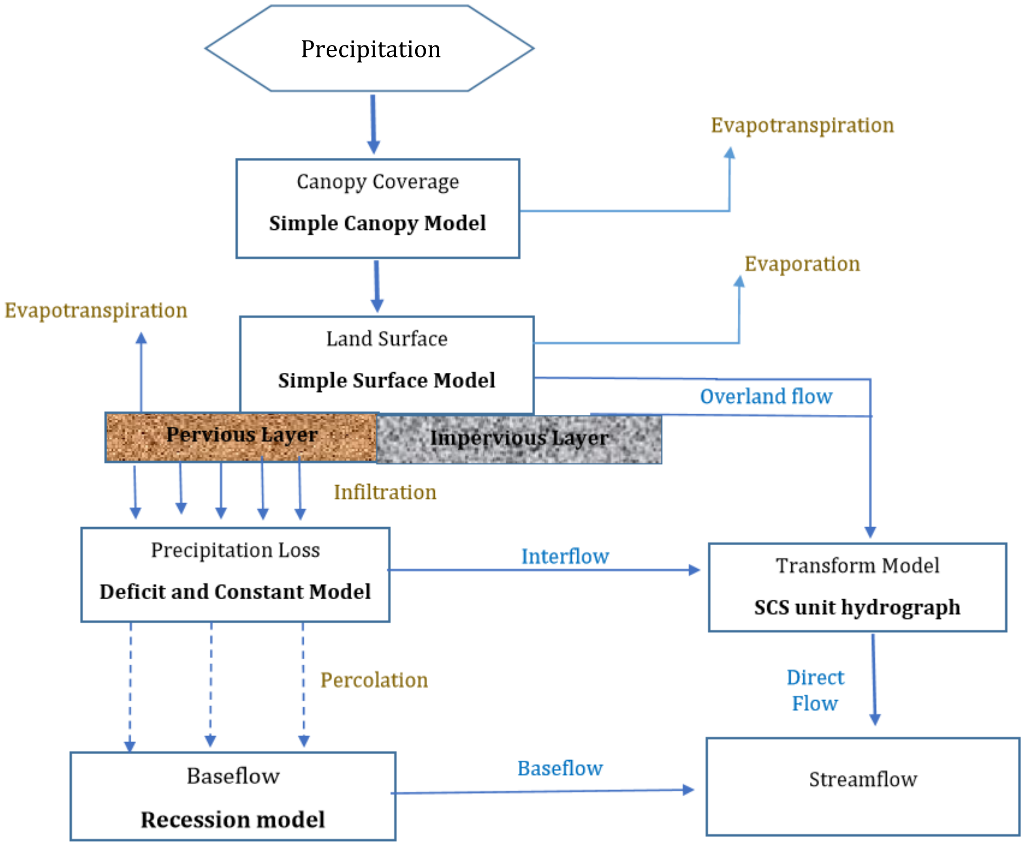

Figure 6-1: Schematic diagram for developed HEC-HMS model

Respective catchment parameters for process models were assigned related to catchment characteristics such as river length, slope, land use, soil type, etc. Combination of all process models simulated streamflow at Urawa and Pitabeddara, with adequate performance in high and medium flow regimes where in some situations model could not capture low flows properly as shown in Figure 5-7 and Figure 5-13. Deficiency of layers of precipitation loss method and incapability to continue that routine through baseflow model caused low performance in low flows. Therefore,

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selecting a precipitation loss model with more layers would capable to predict groundwater flow in a high level of accuracy with the participation of more parameter associate for respective layers. Nevertheless, targeted flow regimes were high and medium flows in the flow spectrum to manage water resources sustainably. Accordingly expected objective could be achieved by identifying model parameters which define catchment characteristics a comprehensible way.

6.5 Model Optimization

The comprehensive literature review reveals three types of approaches to model calibration as manual, automatic and combination of manual and automatic. In model calibration, the HEC HMS model had introduced two searching approaches to identify minimum value for objective function as deterministic and stochastic. The deterministic search method was selected following the comprehensive literature review, which consists of two algorithms as the univariate gradient and the Nelder and Mead.

Automatic calibration with the univariate gradient algorithm led to a local minimum for initially assigned model parameters. In the case of automatic calibration with the Nelder and Mead method kept crashing the model due to the inability to converge model to optimized initial model parameters. Manual calibration had no systematic approach to optimized initial parameters and had a high probability to converge to a local minimum. Therefore, a systematic model calibration method was followed with both manual and automatic calibration procedures.

HEC-HMS had pre-established hard constraints by which model parameters were limited within an acceptable range to avoid numeric instabilities or error in model computations. Also, it facilitated modeler to define soft constraints depend on physically measured and estimated model parameters. Therefore, at first soft constraints were defined to model in manually ensuring model represents catchment with physically meaningful initial parameters. In the next step, parameter values were changed systematically, keeping some parameters in constant and some parameters were allowed to calibrate automatically with Nelder and Mead search algorithms. After several trials, a monotonical reduction of value of objective function could be notified

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and Juraj and Slobodan (2004) introduced that as a global minimum of the objective function. A convergence of the value of model parameters to constant values against several iterations also could observe simultaneously with pre-defined behavior of the objective function. Finally, the model was fine-tuned manually adjusting received optimized parameters.

6.6 Model Performance Evaluation Criteria

Model performance evaluation criteria were depended on the objective of the study. The selection of criteria is described in chapter 5.6. According to the summary of the literature, basic required criteria recommended to be applied in the model performance evaluation are one dimensionless statistic, one absolute error-index statistic and one graphical technique (Legates & Jr, 1999; Moriasi et al., 2007). Therefore, assessment of sorted and unsorted FDCs graphically and numerically (RMSE, MRAE) for flow spectrum and flow regimes, matching of flow hydrograph and AWB were selected as performance evaluation criteria.

The goodness of fit of the model in daily resolution for a continuous period was assessed through unsorted FDC and numerically evaluated by RMSE and MRAE values. Further, matching of pattern and magnitude of observed streamflow and simulated streamflow was measured through flow hydrographs. However, the purpose of the study was water resource management in which the spectrum of flows was the main concern, concerning high and medium flow and shifting of the flows did not matter on the purpose. Therefore, sorted FDC illustrates the flow spectrum within the considered a long period graphically and, RMSE and MRAE values were capable to provide a numerical representation of the performance. Moreover, in model performance in calibration, it could identify a reduction of RMSE value from high flow to low flow and converse behavior in MRAE value. Therefore, it highlights that the RMSE function mainly focuses on high and medium flow and MRAE function on low flow to minimize its error value. Annual water balance denoted the performance of the model concerning the conservation of mass within the project area.

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6.7 Model Calibration

6.7.1 Methodology for Model Calibration

The model parameters, which closely represent the hydrological behavior of the interested catchment is identified through model calibration (Wagener, Wheater, & Gupta, 2004; Moore & Doherty, 2005). As stated in chapter 6.5 model was optimized in a semi-automatic optimization method. In addition to that, optimized parameters were verified applying fully automatic optimization with deterministic, Nelder and Mead search algorithms, assigning optimized parameters as initial parameters to the model.

According to the result, there were minor differences in MRAE value and RMSE value for flow spectrum and flow regimes for Pitabeddara watershed as shown in Table 5-13. Nevertheless, sorted FDC (Figure 5-9) underestimated observed flow with -16.71 % of annual water balance error in fully automatic optimization and which was -1.65 % in semi-automatic optimization. Further, low flow simulation was poor in fully automatic calibration as shown in hydrographs in

Figure 5-10. The model result of Urawa watershed indicated better performance in fully automatic calibration, for RMSE and MRAE values as shown in Table 5-19. Nevertheless,

Figure 5-16 illustrates poor performance of simulating streamflow pattern, peak flows and flow fluctuation of the model is fully automatic calibration compared to the result of semi-automatic model optimization (Figure 5-13). Gyawali and Watkins (2013) also have noted that a better fitting hydrograph can be achieved through manual calibration rather than automatic optimization. Also as per the results of the full optimization approach, the model was unable to predict the low flow regime in the flow spectrum as in sorted FDC (Figure 5-15).

In the case of fully automatic optimization, model mainly targets on reduction of RMSE value by giving priority to high and medium flows, since their contribution to the objective function is higher than low flows. Further, sudden fluctuation of flows was not reflected in simulated flows in automatic calibration in some situations, as streamflow was averaged to get low value for RMSE. Accordingly, semi-automatic optimization is the best approach for the considered model performance evaluation criteria.

6.7.2 Model Calibration for Pitabaddara watershed

The model was calibrated for 6 years from water years 2008/09 to 2013/14 which included extreme events such as floods and droughts and also seasonal variations. The spectrum of observed streamflow at Pitabaddara was varied from 0.36 mm/day to 53.2 mm/day within the calibrated period and respective simulated streamflow variation was from 0.11 mm/day to 41.2 mm/day. The model exhibited 3.2 mm/day RMSE value with 60 % of streamflow prediction accuracy.

Table 5-9, Table 6-1, Figure 5-7 and Figure 5-5 illustrate the degree of model performance of predicting streamflow accomplishing best fit of agreement with regards to magnitude and time of occurrence of streamflow. The model simulated high and intermediate flow by 70% and 60% of accuracy level, which is reflected by streamflow hydrographs (Figure 5-7), especially in October, November, and December of each water year excluding water year 2009/10. Nevertheless, the model was unable to simulate no or less rainy season at a satisfactory level and also flow was underestimated within this period. This limitation could be noted in hydrographs from January to March in the year 2008/09 and 2011/12. Therefore, plotted hydrographs depicted that optimized model parameters are most appropriate to simulate streamflow for the catchment in wet conditions rather than dry conditions.

RMSE value was reduced from high flow to low flow and contrary behavior could be noted for MRAE value as shown in Table 5-9. It reflected that RMSE value was converging on high and intermediate flow while MRAE was towards low flow.

Table 5-10 and Figure 5-6 exhibit model capacity to capture the streamflow spectrum with emphasis on its sequences. High and medium flow signatures could be obtained with an accuracy level of 98% and which was a greater performance in modelling. Nevertheless, underestimation of low flow in no or less rainfall situation led to a decrease accuracy level to 72% on predicting low flow regimes.

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Performance evaluation in aggregated annually and seasonally resolution provides a better indicator for the application of results for water resource management and designs. Accumulated annual RMSE values into annual resolution were varied between 2.35 mm/day and 4.28 mm/day as shown in Table 6-1. -1.65% of AWBE was countered for the calibration period as shown in Figure 5-8.

Table 6-1: Comparison of Annual RMSE and MRAE value for Pitabaddara watershed

Year	2008/09	2009/10	2010/11	2011/12	2012/13	2013/14
RMSE (mm/day)	2.85	3.10	4.28	2.49	3.68	2.35
MRAE	0.41	0.45	0.36	0.35	0.37	0.43

Seasonal and annual streamflow prediction was adequate level with lower annual and seasonal water balance error (Table 5-11, Figure 5-8 and Figure F- 1), excluding identified irregular hydro-meteorological period. The highest rainfall in Maha season in the studied period has been reported for the water year 2010/11 (Figure F- 1) and concurrently the highest annual RMSE value and the highest annual water balance error, 240.5 mm/day also obtained for this year. Extreme rainfall events of this year contributed to high RMSE value since the model was incapable to capture extreme events. Further, the underestimation of extreme rainfall events has been revealed by the obtained lower runoff coefficient for simulated streamflow.

Water year 2009/10 had higher rainfall in the Yala season than Maha season as 1605.1 mm/season and 1137.5 mm/season in respectively. As a result of this contradicted behavior of regular seasonal rainfall patterns, reported no or low rain period was higher in Maha season than other water years. Therefore, the model was incapable to model this dry period as shown in Figure 5-7 and which led to the highest annual MRAE value for year 2009/10 as summarized in Table 6-1**.**

6.7.3 Model calibration for Urawa watershed

Initially, the model was calibrated for a period of 6 water years from 2008/09 to 2013/14. According to the results, the model performance in both calibration and validation was not at an acceptable level for supplementary applications. However, Patil and Stieglitz (2015) stated the representation of the hydrological model can be

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varied in the equal watershed for dissimilar calibration period. Also, the highest rainfall has been recorded in May 2017 as 289.1 mm/day. Therefore, the model was excited incorporating the extreme event in calibration, changing the calibration period from water year 2012/13 to 2017/18.

The model exhibited a RMSE value of 4.36 mm/day and a MRAE value of 0.746 within the calibrated period. The goodness of fit measures of predicted and recorded streamflow with regards to magnitude and time of occurrence has been illustrated in Table 5-15, Figure 5-13 and Table 6-2. According to the result, the model performed acceptable level as presented in Table 6-2 for water year 2013/14, 2014/15, 2015/16 and 2017/18 maintaining the RMSE values less than 3.08 mm/day. In addition to that, 54% of streamflow prediction accuracy could be noted in annual MRAE value in water year 2012/13, 2013/14, 2014/15 and 2017/18. The reduction of RMSE value has been exhibited from high flow to low and reverse behavior concerning MRAE value.

Table 6-2: Comparison of Annual RMSE and MRAE value for Urawa watershed

Water Year	2012/13	2013/14	2014/15	2015/16	2016/17	2017/18
RMSE (mm/day)	5.58	2.33	2.57	3.54	6.97	3.08
MRAE	0.44	0.44	0.46	1.17	1.63	0.33

Poor model performance in water year 2016/17 contributed to high error values in both RMSE and MRAE. As per Figure 5-13, observed streamflow has not responded to the respective rainfall at the end of July 2016. This disagreement has been extended for 6 months accumulating error value. In addition to that, the model was unable to predict the recession of the extremist rainfall event of the calibration period. In this situation, observed streamflow reduced by 80% in the following day, after the extreme rainfall event at the end of May 2017 and the respective decline for simulated flow was 49%. This mismatch of streamflow and observed flow has been extended for the end of August 2017 contributing to higher error.

Presentation of simulated streamflow in terms of magnitude and its sequences had a higher accuracy level of about 92% as shown in Table 5-16. The model captured both high and intermediate streamflow in 82% and 92% of precision in respectively.

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Therefore, the model provided better illustration on the streamflow spectrum for calibration period though there is a deviation of time of occurrence.

Annual and seasonal resolution streamflow data provides better indication for the suitability of simulated streamflow for design and management of water resources. The average AWBE was 11% and each year's AWBE varied between -22% and 12% excluding water year 2016/17 (Table 5-17 and Figure 5-14). However, as per Figure 5-14 annual observed flow of water year, 2016/17 was in lower value concerning the water years with approximately similar annual precipitation. In regards to seasonal water balance, lower error values were reported for Maha season as illustrated in Figure F- 2. Further, seasonal water balance error of Yala season also was at an acceptable level excluding water year 2012/13 and 2016/17.

6.7.4 The Validity of Calibration Result

As described in chapter 6.7.2 and chapter 6.7.3, models for both Urawa and Pitabaddara catchments had similarities and as well as unique behaviors in some situations in model calibrations. It could note that the reduction of RMSE value from high flow to low flow and converse behavior in MRAE value as shown in Table 5-9 and Table 5-15. Those responses imply convergence to high flow with regards to RMSE value and for low flow respect to MRAE value which was specific to the studied catchment.

Optimized parameters for both catchments were unable to simulate streamflow in both seasons with the same accuracy. Especially, the model had low competence in capturing no or low rainfall periods which was expected in selecting a one-layer model for precipitation loss model. According to the result, model parameters were most suitable for Maha season which implies the better representation of the wet condition of the catchment. Juraj and Slobodan (2004) revealed that variation of seasonal behavior can be encountered due to disagreement between the nonlinear rainfall-runoff reaction of the catchment and linear structure of the developed model. Further, they defined a semiannual parametrization methodology to overcome the issue.

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The Urawa catchment spread over 54 km^2 area and it is the origination of the Nilwala river located in the hilly mountain area. Due to the geographical characteristic and speedy and extreme behavior of hydrological and meteorological conditions, sudden fluctuation of observed streamflow could be notified and which was not replicated by the model. Similarly, Juraj and Slobodan (2004) experienced improvement of replicated hydrograph when contribution area is increased to the HEC-HMS model.

In general, the model was not able to reproduce the entire form of streamflow hydrograph for the calibration period. Imprecise representation of rainfall by applied aerial average method, the Thiessen polygon over the catchment was one reason for this discrepancy.

Though the overall model performance was reliable, there were some situations with higher error value in simulating streamflow. Irregular behavior of hydro-meteorological condition (such as higher rainfall in Yala season than Maha season) deviated the simulated behavior of the catchment from the physical catchment response. Also, low flow in extreme drought period and recession of extreme flood event could not be captured by the model.

Both catchment models performed in high prediction accuracy when the main concern was the magnitude of streamflow and its sequences rather than the time of occurrence. In another way, this behavior can be utilized accumulating daily resolution data to annual or seasonal scale to have the precise level of performance which can be recommended to obtain data for the application of water resource planning and management.

6.8 Model Verification

Chapter 2.8.5 revealed 4 approaches for model verification as presented by Bathurst et al. (2004). For the study simple split sample test was selected which is being applied by many hydrological modellers and concluded for an acceptable level of performance. Accordingly selected study period, 10 water years (from water year 2008/09 to 2017/18) divided into two parts as 6 years for calibration and 4 years for validation.

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6.8.1 Model verification for Pitabaddara watershed

Pitabaddara watershed was validated accounting observed streamflow for four years from water year 2014/15 to 2017/18. Table 6-3 shows the comparison of numerical measures for the goodness of fit for the model simulation in terms of streamflow magnitude and its time of occurrence. Accordingly, both RMSE and MRAE values have increased to 7.79 mm/day and 0.604 respectively compared to the calibration period (Table 6-3). This increment could notify not only the flow spectrum, simultaneously in high, medium and low flow regimes.

Table 6-3: Comparison of Validation and calibration goodness of fit measures of unsorted FDC – Pitabaddara watershed

Gauging Station	RMSE (mm/day)	MRAE	Annual Water Balance Error (%)	Flow Duration Curve - Unsorted					
				High		Medium		Low	
				RMSE (mm/day)	MRAE	RMSE (mm/day)	MRAE	RMSE (mm/day)	MRAE
Calibration	3.2	0.39	-1.65	8.07	0.30	2.49	0.39	0.58	0.46
Validation	7.79	0.60	32	23.92	0.44	4.33	0.62	0.63	0.58

There was a significant increment in RMSE in the high flow regime compared to other regimes which are clearly illustrated in Table 6-3. The extremist rainfall event, 273 mm/day in the study period has been reported at the end of May 2017. Figure 5-19 depicts the incapability of the model to predict the streamflow of this extremist event. Observed flow recessed by 77% within one day after the event, but a relative reduction of simulated flow is 55%. Therefore, the mismatch prevailed for two months' period accumulating error value, presenting the highest annual RMSE value, 12.99 mm/day for water year 2016/17 (Table 6-4). Not only the RMSE value but also the highest annual MRAE value also has been reported for the water year 2016/17 as shown in Table 6-4 and Figure 5-19. In most cases, the model underestimated low flows producing high MRAE.

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Table 6-4: Annual MRAE and RMSE value for the validation period – Pitabaddara watershed

Water Year	2014/15	2015/16	2016/17	2017/18
RMSE	3.55	4.10	12.99	5.52
MRAE	0.49	0.58	0.69	0.65

Although the model performance was poor in the validation as described previously, the model exhibits satisfactory behavior in the evaluation of streamflow magnitude with its sequences. The model was able to capture the high flow and medium flow in 60% and 69% accuracy level respectively (Table 5-21).

Figure 5-19 and Figure 5-18 reveal streamflow overestimation in high and medium flow regimes. This situation was reflected by annual and seasonal water balance and amplified runoff coefficient as shown in Table 5-22, Figure 5-20 and Figure F- 3. The average AWBE was 33%. Moreover, there was a variation of seasonal rainfall patterns in the validation period compared to the calibration period. Water years 2014/15 and 2017/18 have approximately equal rainfall for both seasons while water year 2016/17 has higher precipitation in the Yala season. Both scenarios exhibited contradictory behavior to typical seasonal rainfall patterns. Therefore, the annual average rainfall in the validation period is higher than the calibration period by 170 mm/season.

6.8.2 Model validation for Urawa watershed

The model for Urawa watershed was calibrated for a period of four water years from 2008/09 to 2011/12. The model exhibited better performance than calibration by reduced RMSE and MRAE value as 3.25 mm/day and 0.523 respectively as illustrated in Table 6-5.

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Table 6-5: Comparison of Validation and calibration goodness of fit measures of unsorted FDC – Urawa watershed

Gauging Station	RMSE (mm/day)	MRAE	Monthly Water Balance Error (%)	Flow Duration Curve - Unsorted					
				High		Medium		Low	
				RMSE (mm/da	MRAE	RMSE (mm/da	MRAE	RMSE (mm/da	MRAE
Calibration	4.36	0.746	11	13.5	0.28	3.3	0.60	1.62	1.47
Validation	3.25	0.523	-17	9.30	0.44	2.6	0.52	0.70	0.56

Model performance was evaluated concerning streamflow magnitude and its time of incidence as shown in Table 5-23 and Figure 5-23. Accordingly, the model captured high and intermediate and flow regimes with 55% and 48% precision level.

The lowest seasonal rainfall has been recorded in the water year 2008/09. As per Figure 5-23, the low flows were underestimated leading to the higher MRAE value for this year as 0.58 (Table 6-6). This behavior was reflected by higher error value (66.8%) of seasonal water balance as well as the reduction of runoff coefficient from 0.71 to 0.51.

Table 6-6: Annual MRAE and RMSE value for the validation period – Urawa watershed

Water Year	2008/09	2009/10	2010/11	2011/12
RMSE	3.55	3.30	4.25	2.99
MRAE	0.58	0.55	0.44	0.50

However, the model performed 72% of accuracy for the prediction of streamflow spectrum in regards to streamflow magnitude with its sequences of occurrence as shown in Table 5-24. Similarly, high and intermediate flow regimes could be predicted by 90% and 73% of precision. According to Figure 5-22, related consequences have been reflected by sorted FDC with the growth of correctness of replicated and observed streamflow from low flows to high flows.

Annual and seasonal water balance implies a better indication of water resource management. According to Table 5-25, annual water balance error is less than 17%, excluding the water year 2009/10. The water year 2009/10 has behaved in contradict

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way to the normal seasonal rainfall pattern as 37% of annual rainfall in Maha and 63% in the Yala season (Figure F- 4). The model underestimated the streamflow in Maha season with 159.8% seasonal water balance error and also it is revealed by the reduced runoff coefficient from 0.74 to 0.32 and respective hydrograph in Figure 5-23. Further, 51% of annual water balance error was encountered for this year.

6.8.3 The validity of the verification result

Model verification was processed applying the optimized model parameters in the calibration process for a different period and the agreement of recorded and simulated flow was evaluated with regards to selected evaluation criteria. As described in the previous chapter 6.8.1 and chapter 6.8.2, Pitabaddara catchment underperformed in validation compared to calibration and Urawa catchment had better performance in the validation with the consideration of streamflow magnitude with the time it occurred. Verma et al. (2010) also surprisingly presented a better performance in his HEC-HMS model in the validation than calibration for Upper Blue Nile Basin, since in general calibration results are deteriorated in the validation. Accordingly, they concluded, "There are relatively unique input-output relations and that the runoff formation is dominated by the only mechanism"

Similarly, the non-sensitiveness of observed flow to the aerial average rainfall could be identified in some situations. Verma et al. (2010) stated this ambiguity might be due to the nonrepresentation of spatial rainfall distribution over the catchment. The uncertainty of observed data also encountered in the model as errors. Juraj and Slobodan (2004) suggested incorporating error based weighting for observations as a formal mechanism to address the issue.

However, regarding the study objective, simulated streamflow magnitude and its sequences were important to future applications. According to that requirement, both catchments had an adequate level of performance.

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6.9 Model Parameters transferability

Potential of parameter transferability was evaluated using two gauged catchments by at a time one gauged catchment was considered as if ungauged and optimized set of parameters of candidate donor catchment was assigned to the ungauged catchment. Zelelew and Alfredsen (2014) cited this approach as the Jackknife procedure.

6.9.1 Selection of model parameter transferability approach

Chapter 2.3 reveals the state of the art of parameter transferability approaches and their limitations. However, in brief, most researcher's conclusion of their studies was that in general, there is a probability to get better performance with spatial proximity and catchment attribute similarity approach for parameter transferability (Shrestha et al., 2007; Parajka et al., 2005). Shrestha et al., (2007) stated that the rationale for these approaches is that representation of similar runoff regimes of close catchments as the variation of hydro-meteorological conditions and catchment attribute is smoothy in space. Therefore, the transformation of model parameters from the main catchment to sub-catchment and vice versa is one of the cases of the prescribed domain.

There are various methodologies to transfer optimized parameters to the ungauged catchment. Among those methods, one which easily understandable and simply operational by hydrologic communities would be preferred for application. Accordingly, the transformation of all the optimized parameters directly to the ungauged catchment was the appropriate method in this regard. It could be verified by the conclusion of Bárdossy (2007b) that model parameters should be regionalized on concerning them to compatible sets or vectors without adapting as individual parameters.

6.9.2 Parameter transferability from sub-catchment to main catchment

The set of the optimized parameters of Urawa (sub-watershed) was transferred to Pitabadara (main watershed) for the 10 years. Predicted streamflow had 55% accuracy to capture streamflow considering both its magnitude and time of taking place (Table 5-32). The result presented an insignificant difference in terms of evaluated error value for flow spectrum as shown in Table 5-28 and Table 5-32. Although, simulated

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streamflow with transferred parameter had better performance in medium and low flow regime which has been reflected in Figure 5-30 and Figure 5-31.

As shown in Figure 5-30 and Table 5-33 the predicted flow was able to capture all three flow regimes, high, intermediate and low with 71% of satisfactory accuracy level with regards to the scale of streamflow and its sequences. However, according to the annual RMSE and MRAE values, water years 2014/15, 2015/16, and 2017,18 had better-simulated streamflow than with calibrated parameters as shown in Table 6-7.

Table 6-7: Comparison of annual MRAE and RMSE value of Pitabaddara catchment with transferred model parameter

Water Year	Simulated Streamflow - Transferred Parameter		Simulated Streamflow - Calibrated Parameter	
	RMSE (mm/day)	MRAE	RMSE (mm/day)	MRAE
2008/09	3.566	0.480	2.85	0.41
2009/10	3.664	0.508	3.100	0.450
2010/11	5.614	0.389	4.280	0.360
2011/12	3.075	0.397	2.490	0.350
2012/13	4.503	0.337	3.680	0.370
2013/14	2.695	0.398	2.350	0.430
2014/15	4.476	0.396	5.230	0.490
2015/16	3.548	0.375	4.100	0.580
2016/17	13.114	0.779	12.990	0.690
2017/18	3.261	0.391	5.520	0.650

As per Figure 5-31, the model has captured fluctuation of streamflow with respect to rainfall events, but there was a shift of magnitude of the respective streamflow and it has been prevailed for significant time accumulating relevant error values. Incapability to capture the recession of streamflow after rainfall under various catchment conditions could be identified. However, model behavior in no or less rainfall situation was stable compared to streamflow hydrograph with calibrated model parameters. A further significant number of mismatch could be identified in the early water year of study period like 2008/09, 2009/10 and 2010/11, and which has been reduced in latter water years. The average AWBE was 22.8%, with underestimation of streamflow as shown in

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Table 5-34. The lowest AWBE has been recorded for water year 2017/18 when the extremist rainfall event of the study period is recorded.

6.9.3 Parameter transferability from main catchment to sub-catchment

An optimal set of parameters of Pitabaddara catchment were transferred to the Urawa sub-catchment for 10 years. According to the result shown in Table 5-35 and Figure 5-35 prediction of streamflow complying to both streamflow magnitude and time it occurred was in unsatisfactory level. Similarly, model performance in the calibrated parameter for the Urawa catchment also did not show a high satisfactory level. Annual RMSE and MRAE values for the study period are shown in Table 6-8. According to that, incapability of model to capture low flows could be noted with high MRAE value and which has been noticeably reflected in Figure 5-35.

Table 6-8: Comparison of annual MRAE and RMSE value of Pitabaddara catchment with transferred model parameter

Water Year	Simulated Streamflow - Transferred Parameter		Simulated Streamflow - Calibrated Parameter	
	RMSE (mm/day)	MRAE	RMSE (mm/day)	MRAE
2008/09	5.14	0.81	3.55	0.58
2009/10	2.95	0.57	3.30	0.55
2010/11	6.09	0.66	4.25	0.44
2011/12	4.02	0.63	2.99	0.50
2012/13	7.07	0.70	5.58	0.44
2013/14	3.31	0.70	2.33	0.44
2014/15	3.93	0.55	2.57	0.46
2015/16	4.57	1.29	3.54	1.17
2016/17	8.28	1.68	6.97	1.63
2017/18	4.99	0.61	3.08	0.33

However, Table 5-36 and Figure 5-34 illustrate model capacity to predict streamflow for magnitude and its occurrences. Accordingly, streamflow at Urawa has been predicted 41%, 75% and 60% level of accuracy for the high, intermediate and low flow regimes. Predicted streamflow could capture streamflow response related to rainfall events. Nevertheless, there were shifts in streamflow with magnitude and it caused due

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to the inability to reproduce streamflow behavior in low or no rain period as shown in Figure 5-35.

In brief, the transferred set of optimized parameters overestimated streamflow at Urawa watershed. Annual average water balance error was 25.2% excluding water year 2016/17 which has lower observed streamflow compared to water year with similar precipitation.

6.9.4 Parameter transferability approaches with temporal, spatial and spatio-temporal variations

Comprehensive literature review revealed mainly three model parameter transferability schemes defined as temporal, spatial and spatiotemporal (Patil & Stieglitz, 2015b). Accordingly developed parameter transferability schemes with regards to spatial and temporal variation have been assessed and respective results are shown in Appendix H and Appendix I for Pitabaddara and Urawa catchment respectively. Evaluation of performance in these three schemes facilitates the decision-maker to select appropriate schemes with respect to the data availability and the objective of the catchment.

6.9.4.1 Performance of model parameter transfer schemes for Pitabaddara catchment

As per Table 5-27, optimized parameters were transferred forming spatial and temporal variation to predict streamflow at Pitabaddara. According to the results, the spatial transferability scheme had better performance compared to the other two approaches, concerning streamflow magnitude, its time of occurrence and sequences as shown in Table 6-9 and Table 6-10. Yet, the spatial transferability approach predicted streamflow with 58% accuracy for the total flow spectrum, while spatiotemporal approach captured streamflow with 56% accuracy. Hence spatial transferability had slightly better performance in flow spectrum and as well as flow regimes compared to spatiotemporal transferability. However, simulated streamflow with both spatial and spatiotemporal transferability method exhibited better

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performance than temporal transferability, although it was modelled with the optimized set of parameters in the same catchment, Pitabaddara.

Table 6-9: Model performance for parameter transferability schemes for Pitabaddara watershed – Unsorted FDC

Transferability Scheme	Period	RMSE (mm/day)	MRAE	Annual Water Balance Error (%)	Streamflow magnitude with the date of occurrence					
					High		Medium		Low	
					RMSE (mm/day)	MRAE	RMSE (mm/day)	MRAE	RMSE (mm/day)	MRAE
Temporal	4 years	7.79	0.60	32	23.92	0.45	4.33	0.62	0.63	0.58
Spatial	6 years	3.97	0.42	-13	11.66	0.47	2.45	0.41	0.63	0.43
Spatiotemporal	4 years	4.10	0.44	-35	11.89	0.48	2.60	0.45	0.57	0.40

All three approaches could replicate streamflow with 65% accuracy with the consideration of streamflow magnitude and its frequency as shown in Table 6-10.

Table 6-10: Model performance for parameter transferability schemes for Pitabaddara watershed – Sorted FDC

Transferability Scheme	Period	RMSE (mm/day)	MRAE	Streamflow magnitude with its sequences					
				High		Medium		Low	
				RMSE (mm/day)	MRAE	RMSE (mm/day)	MRAE	RMSE (mm/day)	MRAE
Temporal	4 years	5.60	0.33	18.53	0.40	2.21	0.31	0.27	0.42
Spatial	6 years	2.73	0.29	8.15	0.38	1.62	0.28	0.29	0.30
Spatiotemporal	4 years	2.81	0.35	8.15	0.39	1.78	0.35	0.26	0.30

In addition to that predicted streamflow from spatial transferability could capture streamflow in low and no rainfall conditions than the temporal parameter transferability approach as illustrated in Figure H- 3 and Figure H- 7. Further, the

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spatial parameter transferability approach capable to bounce back after extremist rainfall event in May 2017 than the temporal transferability approach as shown in streamflow hydrograph and respective AWBE was 0.3% and 50% for both conditions (Table H- 4 and Table H- 8).

Streamflow was overestimated in the temporal parameter transferability approach and streamflow was underestimated in both spatial and spatiotemporal approaches. In summary, the spatial parameter transferability scheme performed better than the other two approaches.

6.9.4.2 Performance of model parameter transfer schemes for the Urawa catchment

Spatial and temporal variations have cooperated with the respective approaches as mentioned in Table 5-27. On the subject of streamflow magnitude and the time of it occurred, temporal parameter transferability performed better than the other two schemes with 48% of accuracy on the prediction of streamflow (Table 6-11). Spatial and spatiotemporal approached exhibited performance in the second and third level respectively.

Table 6-11: Model performance for parameter transferability schemes for Urawa watershed – Unsorted FDC

Transferability Scheme	Period	RMSE (mm/day)	MRAE	Annual Water Balance Error (%)	Streamflow magnitude with the date of occurrence					
					High		Medium		Low	
					RMSE (mm/day)	MRAE	RMSE (mm/day)	MRAE	RMSE (mm/day)	MRAE
Temporal	4 years	3.25	0.52	-17	9.30	0.45	2.62	0.52	0.70	0.56
Spatial	6 years	5.00	0.68	53	12.43	0.55	4.10	0.66	1.08	0.84
Spatiotemporal	4 years	5.70	1.03	62	13.47	0.52	4.76	0.85	2.50	1.99

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However, referring to the streamflow magnitude with its frequency, the spatial parameter transferability approach performed better than the other two at a significant level concerning corresponding MRAE value (Table 6-12). Accordingly, the spatial parameter transferability scheme captured medium and low flow with 95% and 91% of accuracy for streamflow prediction. This situation was reflected by relevant sorted FDC for three transferability approaches as shown in Figure I- 2, Figure I- 6 and Figure I- 10. The spatial transferability scheme was capable to capture both intermediate and low flows in high accuracy level (Figure I- 6) while spatiotemporal transferability replicate low flow regimes in high accuracy (Figure I- 10). However, the best match for the peak flows could be obtained by temporal parameter transferability as 89% of the accurate prediction level.

Table 6-12: Model performance for parameter transferability schemes for Urawa watershed – Sorted FDC

Transferability Scheme	Period	RMSE (mm/day)	MRAE	Streamflow magnitude with its sequences					
				High		Medium		Low	
				RMSE (mm/day)	MRAE	RMSE (mm/day)	MRAE	RMSE (mm/day)	MRAE
Temporal	4 years	0.78	0.28	1.76	0.11	0.74	0.26	0.33	0.41
Spatial	6 years	1.80	0.07	6.20	0.25	0.43	0.05	0.08	0.09
Spatiotemporal	4 years	4.33	0.42	13.75	0.75	2.22	0.46	0.10	0.10

In regards to annual water balance for three approaches, temporal transferability performed with a lower value for annual water balance error as 17% with underestimation of streamflow (Table 5-21 and Figure I- 4). However, both spatial and spatiotemporal transferability approaches overestimated streamflow as shown in Table I- 8 and Table I- 12.

6.9.5 The reliability of results in model parameter transferability

The simulation inconsistencies encountered in model calibration were similarly associated with model parameter transferability approaches. Hydro-meteorological

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data consists of systematic errors that are uncorrectable (Duan, Schaake, & Koren, 2011). In addition to that, the application of areal averaging for estimation of rainfall over catchment associated uncertainties on the representativeness of the actual rainfall (Gumindoga et al., 2017). Therefore, optimal parameters obtained from model optimization contain uncertainties and errors (Gan & Biftu, 1996). Gan and Burges (2006) explained the possibility of those uncertainties and errors to be influenced in simulated streamflow from the transferred model parameter to the recipient catchment.

Parameter transfer credibility was varied when the characteristics of donor and receiver catchments are different. According to the result, when sub-catchment model parameters were transferred to the main catchment, the spatial transfer scheme performed better and for contrariwise application, the temporal transfer scheme performed better. However, the selected water years for calibration for both catchments were dissimilar and in which main catchment (Pitabaddara) was calibrated for the early 6 years of the study period and sub-catchment (Urawa) for later 6 years. According to the simulated trials, it could note that there was an overestimation of streamflow in later years compared to the early years for the selected study period. Therefore, there is a doubt about changes in catchment physical attributes in later years or deviations of observed streamflow at two catchment outlets.

According to the conclusion of pre-studies, deterioration in streamflow prediction was expected following spatial and spatiotemporal parameter transfer schemes (Patil & Stieglitz, 2015a). In general, the temporal parameter transfer method was outperformed than other methods (Patil & Stieglitz, 2015a; Parajka et al., 2005; Y. Zhang & Chiew, 2009), since the model parameters have been calibrated for the same catchment. Nevertheless, as described in the above paragraph spatial transfer approach performed better, where sub-catchment model parameters were transferred to the main catchment. In view of that, it implies selection of transfer scheme is unique to the catchment and also it can be varied for the same catchment, according to the selected model, deployed objective function and used data for the model calibration (Gupta, Sorooshian, & Yapo, 1998; Madsen, 2003).

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Application of parameter transferability between main catchment (Pitabaddara) and sub-catchment (Urawa) in the same river basin is formed similarity with regards to hydrological behavior, physical characteristics and spatial proximity for the significant extent. This is constructive because most of the studies revealed better streamflow simulation transferring model parameters to the neighbor catchment complying basin similarity and spatial proximity (Parajka et al., 2005; Heuvelmans et al., 2004). Accordingly, Simulated streamflow from the transferred parameter had performed differently, depending on its evaluation criteria. For instance, though there was poor performance in streamflow for magnitude and the time it occurred, it had exhibited better performance to streamflow magnitude, its sequences, and annual water balance. Therefore, the selection of the parameter transfer scheme is mainly depending on the objective of the deployment of simulated streamflow.

Optimal parameters of both catchments had catchment specific physical characteristics such as lag time, initial discharge which were mainly depend on catchment size. This fact is reflected by the set of optimal parameters given in Table 5-26. However, when the spatial and spatiotemporal parameter transfer scheme is deployed, the disagreement of model parameters to the catchment characteristics was not modified. This equifinality has been discussed by Beven and Freer (2001) that parameters are not unique and there are a diverse set of parameter values that exhibit similar model performance. Complying to this Bárdossy (2007b) stated changes of one parameter of a set of parameters can be compensated by one or more other parameters due to their interdependence and concluded recommending the transformation of the set of parameters as complementary parameter vectors.

However, finally, the set of transferred model parameters able to simulate streamflow at a satisfactory level for the application of water resource management without representing ungauged catchment attributes trough model parameters.

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6.10 Model Performance for Water Resource Management

Water resource engineers and managers are managing water resources generally in seasonal and monthly scale. Therefore, the performance of parameter transfer schemes to that temporal scale is important to assess their credibility for application on water resource management and designs. Appendix J and Appendix K consist of relevant results for model performance in Pitabaddara and Urawa catchments respectively.

Among the various hydrologic model performance evaluation criteria, the ability of flow duration curve method to separate streamflow in regards to streamflow magnitude and its sequences qualifies its application for suitable and flexible water resource management practices (Mohamoud, 2008). Therefore, annual FDC, match of seasonal and monthly streamflow volume was used as model performance evaluation key indicators.

All three transfer schemes were capable to predict streamflow more than 65% of accuracy level as shown in Table J- 1, Table J- 4, Table J- 7, Table K- 1, Table K- 4 and Table K- 7 excluding the water years with recorded extreme events such as flood and prolonged drought. This situation is reflected by annual sorted FDC as illustrated in Figure J- 1, Figure J- 4, Figure J- 7, Figure K- 1, Figure K- 4 and Figure K- 7. Though there was significant disagreement between measured and predicted daily streamflow, conferring to the annual FDC those could consolidate to streamflow magnitude and its frequency provided reliable data for water resource planning and management.

Estimation of streamflow quantity in Yala season was accurate in many transfer schemes than Maha season as shown in Table 6-13. Similar to the overall annual streamflow prediction, temporal transfer approach overestimated streamflow for both seasons in every year and streamflow underestimated in other two transfer schemes, spatial and spatiotemporal (Table J- 2, Table J- 5 and Table J- 8). Contradict behavior was exhibited in Urawa catchment as shown in Table K- 2, Table K- 5 and Table K- 8.

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Table 6-13: Summary of estimated seasonal streamflow for parameter transfer schemes

Catchment	Season	Accuracy on streamflow prediction (%)		
		Temporal	Spatial	Spatiotemporal
Pitabaddara	Maha Season	61	84	68
	Yala season	74	88	60
Urawa	Maha Season	91	64	39
	Yala season	71	99	49

Spatiotemporal transfer scheme at Pitabaddara catchment presented 91% of accuracy on predicting streamflow volume as shown in Table 6-14. Nevertheless, temporal and spatial transfer methods capable to estimate average monthly streamflow volume with 83% accuracy at Urawa. However, as per Table J- 3, Table J- 6 and Table J- 9, the month of January, April, May, and August captured streamflow at Pitabaddara with an accuracy level of more than 80% for all three parameter transfer schemes. Though spatiotemporal scheme had poor estimation on monthly streamflow quantity (Table K-9) at Urawa other two approaches, temporal and spatial, had obtained more than 80% accuracy for five months (Table K- 3 and Table K- 6).

Table 6-14: Summary of estimated monthly streamflow for parameter transfer schemes

Catchment	Accuracy on predicting streamflow		
	Temporal	Spatial	Spatiotemporal
Pitabbadara	70%	77%	91%
Urawa	83%	83%	43%

According to the above-discussed results, parameter transfer schemes performed differently with regards to dissimilar time resolutions. Therefore, the selection of time resolution and model parameter transfer scheme is a subjective decision of the application.

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7 CONCLUSIONS

1. Transformation of sub-catchment model parameters to the main catchment exhibits high performance than transferring of main catchment model parameters to sub-catchment. The high flow regime is the most accurately predicted streamflow regime with 58% and 46% accuracy level respectively for Pitabaddara and Urawa catchment with respect to streamflow magnitude with its occurred time. Transferred sub-catchment parameter predicts streamflow in the main catchment with 81% accuracy of annual water balance and vice versa scenario 64% level of accuracy.

2. For the application of streamflow magnitude with its sequences, prediction of intermediate flow regime outperforms in both catchments with 80% and 72% accuracy level respectively for Pitabaddara and Urawa catchment. Pitabaddara catchment is capable to capture low and high flow regime with 72% of accuracy and Urawa catchment predicts 60% and 40% of accuracy level.

3. Spatial transfer scheme is the best approach to estimate streamflow at both catchments considering streamflow magnitude and its sequences. The intermediate flow regime is prominently predicted streamflow in Pitabaddara and Urawa catchments with 95% and 82% of accuracy and prediction of the low flow regime also is significant with 91% and 70% of accuracy respectively.

4. Spatial and Temporal transfer schemes are the suitable approaches to predict daily streamflow respectively at Pitabaddara and Urawa catchments with regards to streamflow magnitude and its respective occurred time. Greatly predicted flow regimes are intermediate and high flow regimes with 59% and 55% accuracy respectively for Pitabaddara and Urawa watersheds with 87% and 83% accuracy for annual water balance.

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5. Spatial transfer scheme capable to capture streamflow for 84% and 88% of average accuracy level in Maha & Yala season respectively for seasonal water resource management in Pitabaddara catchment and Urawa catchment, temporal transfer scheme can provide 91% and 71% of average accuracy level in predicting streamflow volume for Yala and Maha season respectively.

6. The best approach to get a highly reliable estimation for monthly streamflow quantity at Pitabaddara is the spatiotemporal transfer with an average accuracy of 91% and for Urawa, temporal and spatial transfer schemes with an average accuracy of 83%.

7. The credibility of parameter transfers schemes, spatial, temporal and spatiotemporal is subjective to the objective of the application and temporal resolution such as annual, seasonal, monthly and signature of the catchment.

8. Selected one-layer precipitation loss model is incapable to capture low flow in model calibration due to fewer number of parameters to optimize the model to simulate low flows and it leads to error value of more than 46% for low flows in both catchments becoming the flow regimes with the highest error value.

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8 RECOMMENDATIONS

1. It is necessary to explore the potential of predicting low flow (environmental flow) by model parameter transfer deploying precipitation loss model with more soil layers using HEC-HMS
2. It is important to develop a framework to select objective function and model performance evaluation criteria with respect to the objectives to identify the suitable set of optimal parameters.

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APPENDIX A : SUMMARY OF LITERATURE REVIEW

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Table A- 1: Selection of model performance evaluation criteria

Reference	Region	Performance evaluation function
(Meenu et al., 2012)	Tunga–Bhadra river basin, India	Coefficient of determination Nash–Sutcliffe model efficiency Percent deviation
(Plesca et al., 2012)	Upper Blue Nile Basin, Ethiopia	Relative bias error functions Nash–Sutcliffe Efficiency Coefficient of determination
(Ouédraogo et al., 2018)	Mkurumudzi River Catchment in Kenya	The Percentage Error in Volume The percentage Error in Peak Flow The Coefficient of correlation Index of agreement Nash-Sutcliffe model Efficient Root Mean Squared Error - standard deviation ratio (RSR)
(Gumindoga et al., 2017a)	Upper Manyame catchment, Zimbabwe	Nash-Sutcliffe efficiency Relative Volume Error (RVE)
(Fleming & Neary, 2004)	Cumberland River basin (Tennessee)	Mean absolute error (MAE) Root mean square error (RMSE)
(W. R. Singh & Jain, 2015)	Vamsadhara River Basin, India	Percentage Error in simulated volume Percentage error in simulated peak Coefficient of determination Index of agreement Nash-Sutcliffe Efficiency percentage error in simulated peak
(Razmkhah et al., 2016)	Karoon III River basin	Minimum error in peak discharges and volumes Nash-Sutcliffe The peak weighted root mean square
(Gebre, 2015)	upper Blue Nile River Basin, Ethiopian	Coefficient of determination Nash-Sutcliffe efficiency

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APPENDIX B :VISUAL DATA CHECKING

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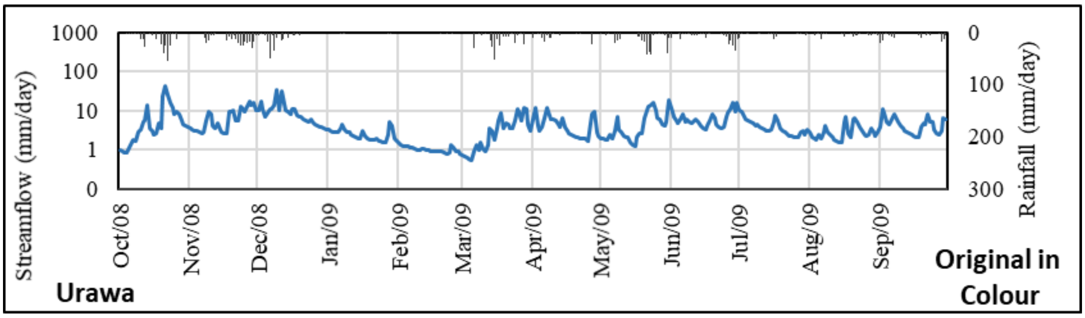
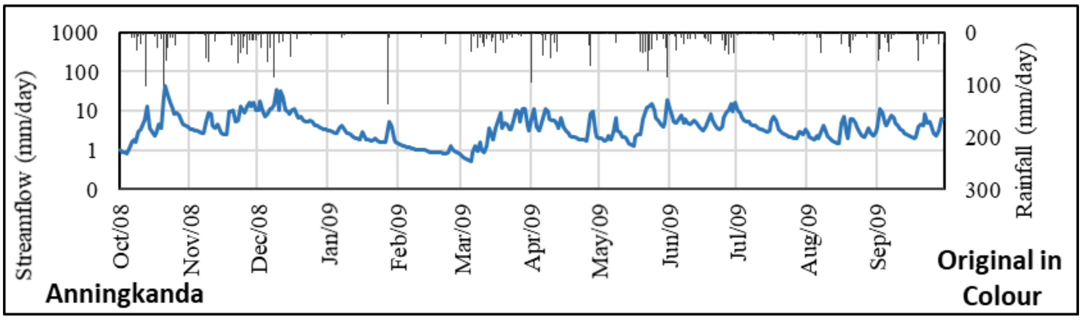
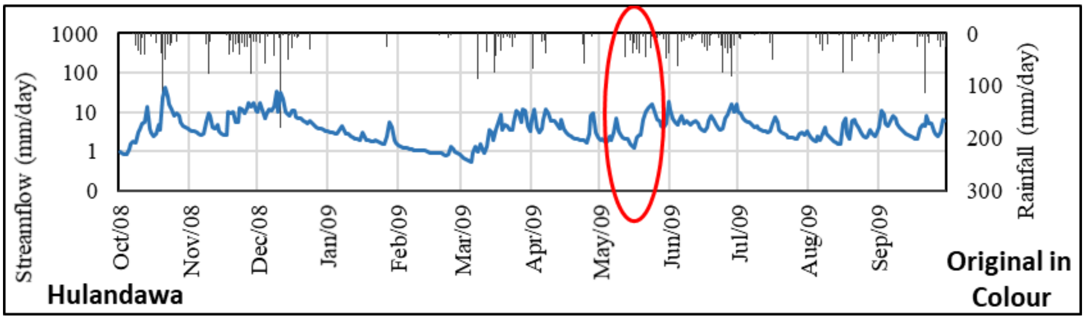


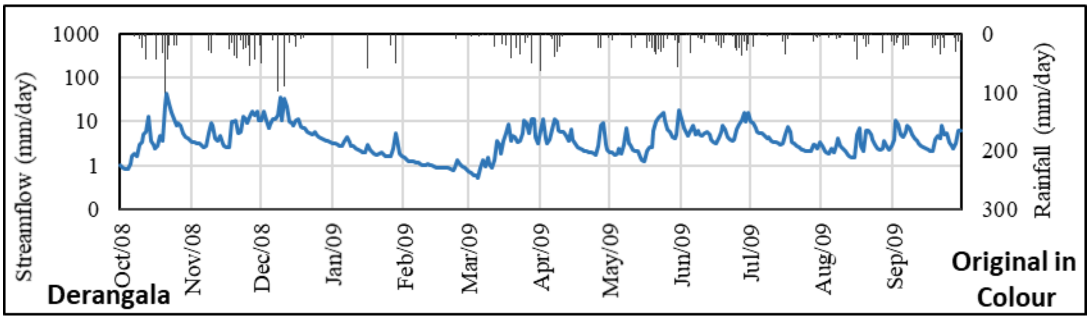
Streamflow (mm/day)
1000
100
10
1
0
Oct/08
Nov/08
Dec/08
Jan/09
Feb/09
Mar/09
Apr/09
May/09
Jun/09
Jul/09
Aug/09
Sep/09
0
100
200
300
Rainfall (mm/day)
Urawa
Original in Colour



Streamflow (mm/day)
1000
100
10
1
0
Oct/08
Nov/08
Dec/08
Jan/09
Feb/09
Mar/09
Apr/09
May/09
Jun/09
Jul/09
Aug/09
Sep/09
0
100
200
300
Rainfall (mm/day)
Anningkanda
Original in Colour



Streamflow (mm/day)
1000
100
10
1
0
Oct/08
Nov/08
Dec/08
Jan/09
Feb/09
Mar/09
Apr/09
May/09
Jun/09
Jul/09
Aug/09
Sep/09
0
100
200
300
Rainfall (mm/day)
Hulandawa
Original in Colour



Streamflow (mm/day)
1000
100
10
1
0
Oct/08
Nov/08
Dec/08
Jan/09
Feb/09
Mar/09
Apr/09
May/09
Jun/09
Jul/09
Aug/09
Sep/09
0
100
200
300
Rainfall (mm/day)
Derangala
Original in Colour

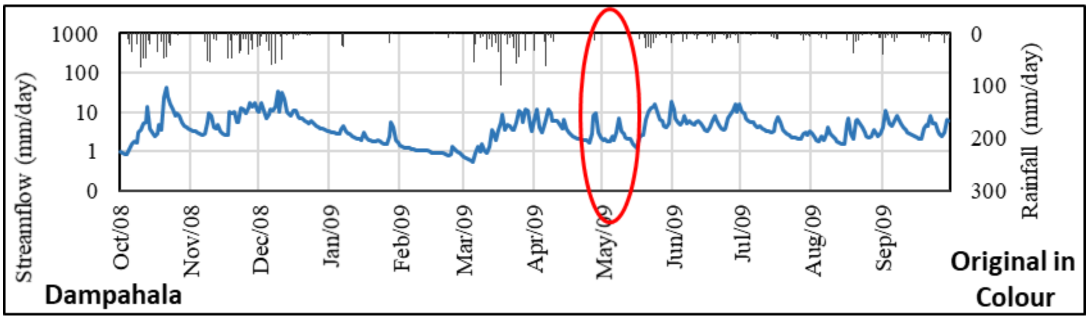
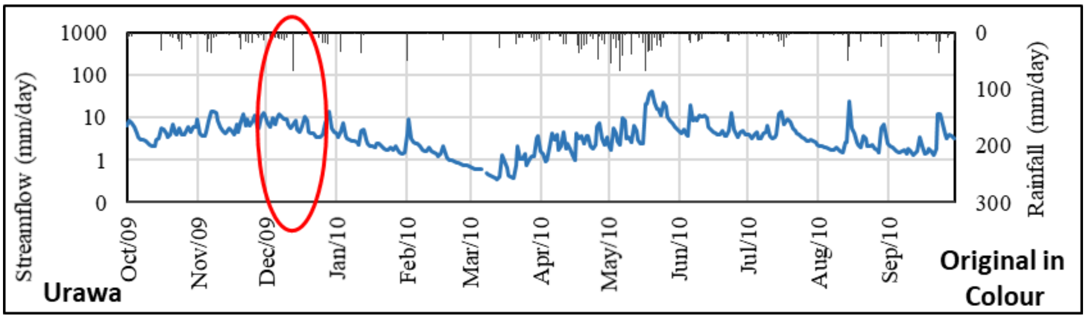
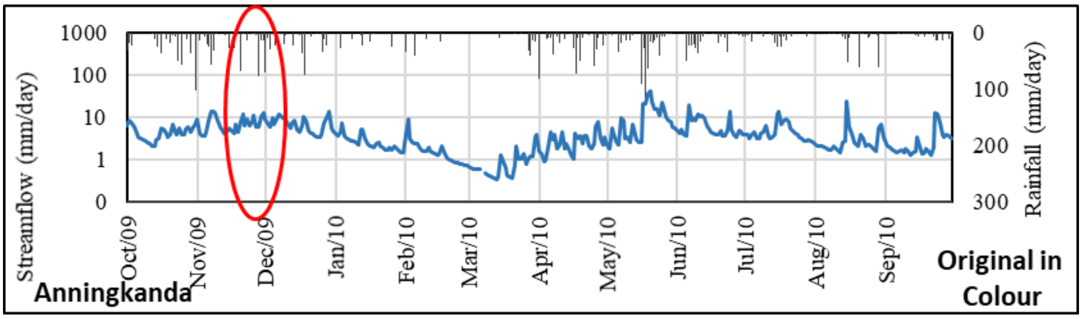
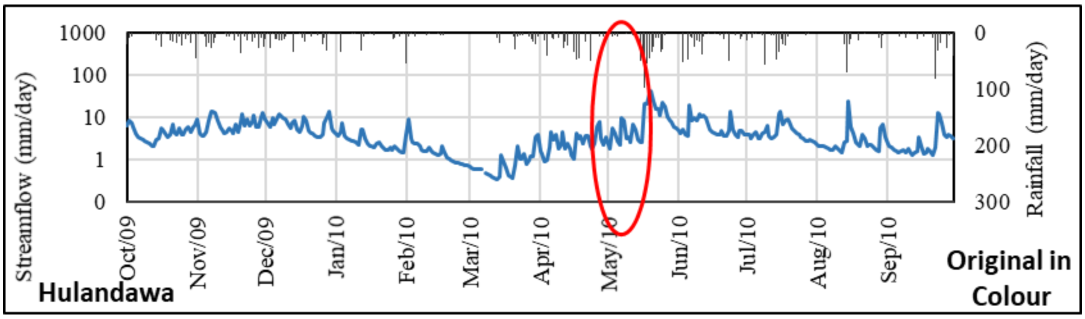


Figure B- 1: Streamflow response at Pitabaddara for year 2008/2009







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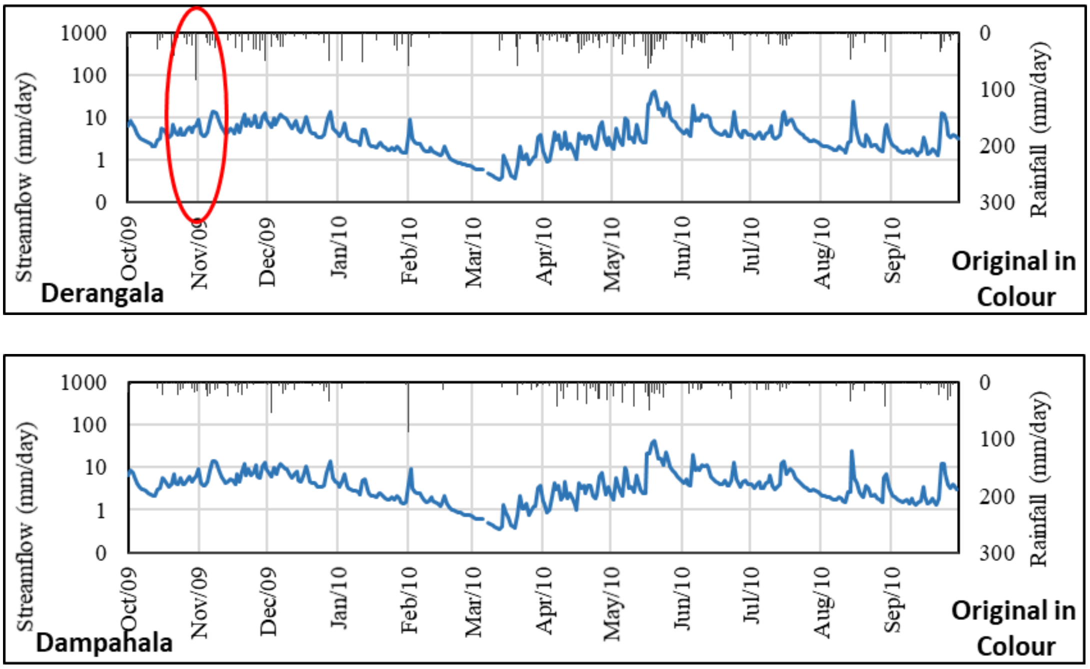
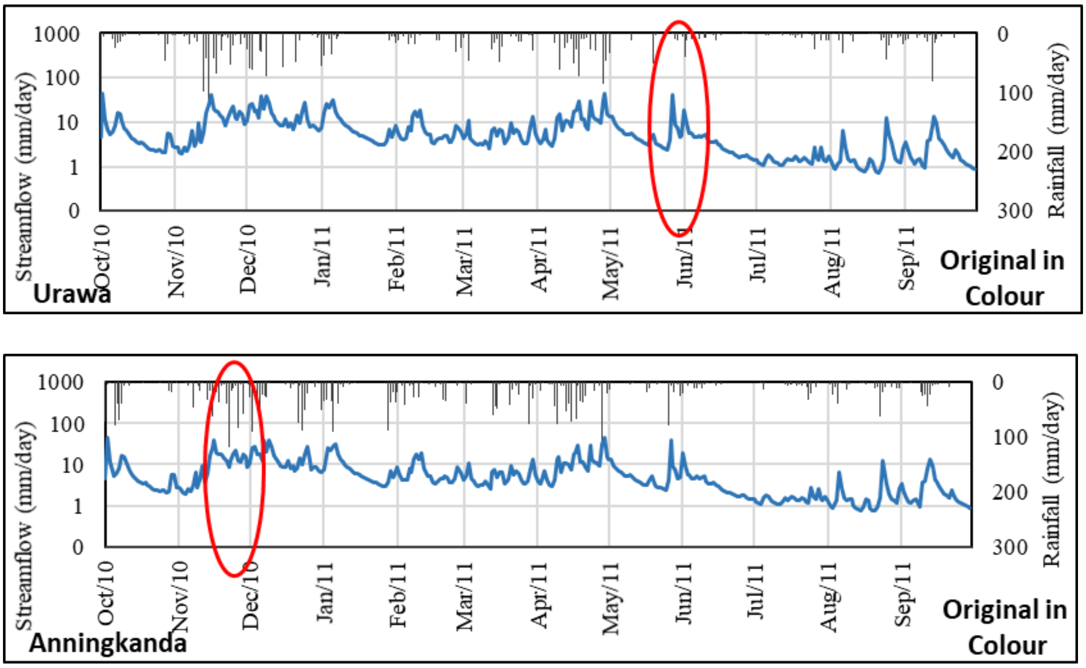


Figure B- 2: Streamflow response at Pitabaddara for year 2009/2010



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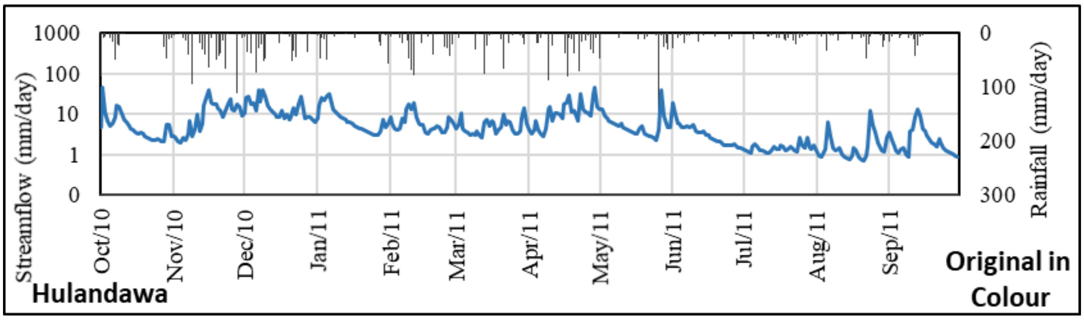
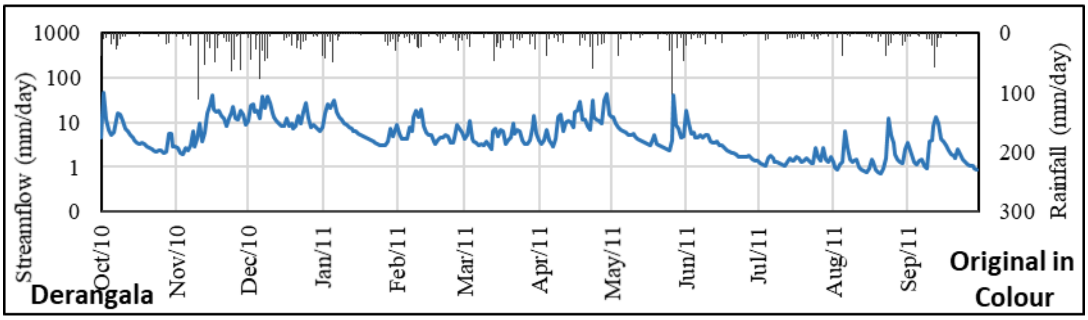




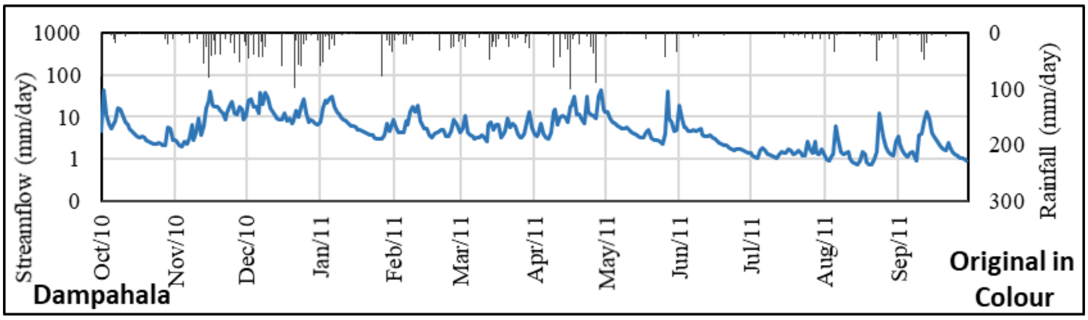
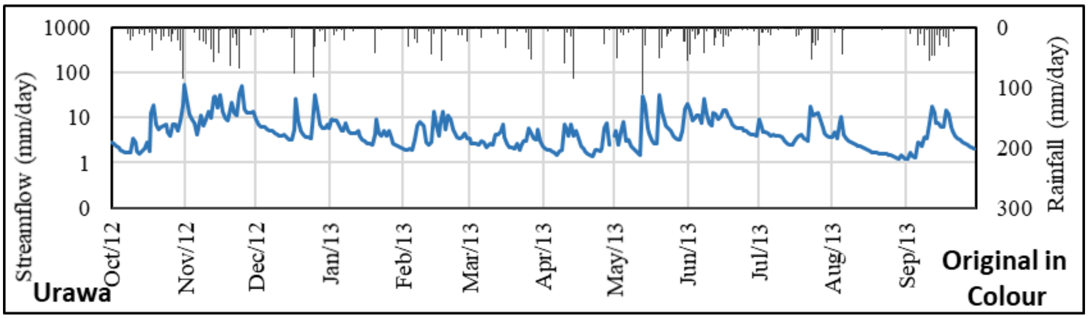


Figure B- 3: Streamflow response at Pitabaddara for year 2010/2011



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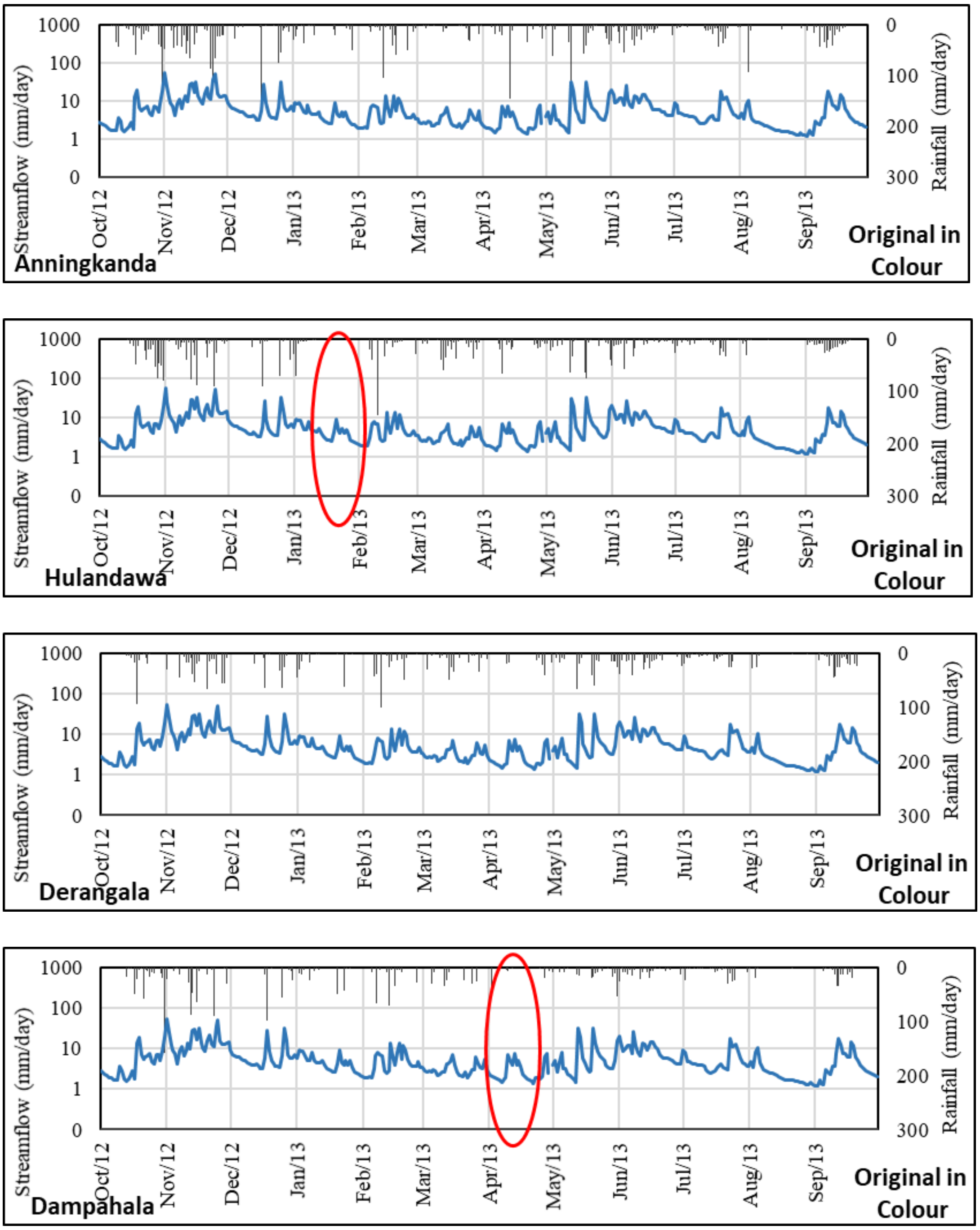

Figure B- 4: Streamflow response at Pitabaddara for year 2012/2013

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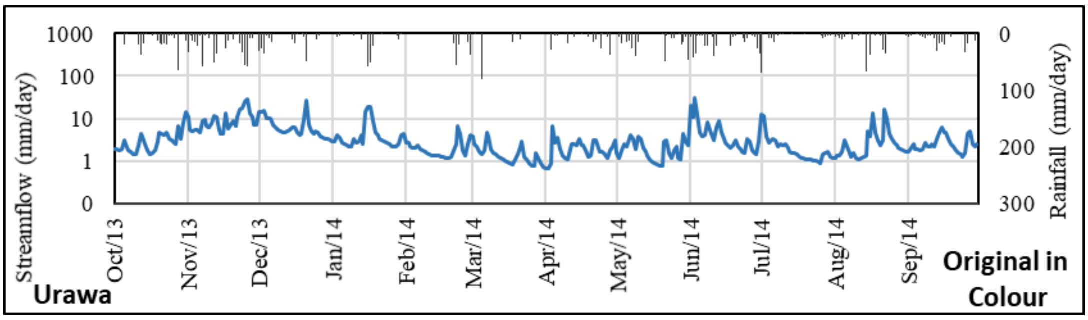
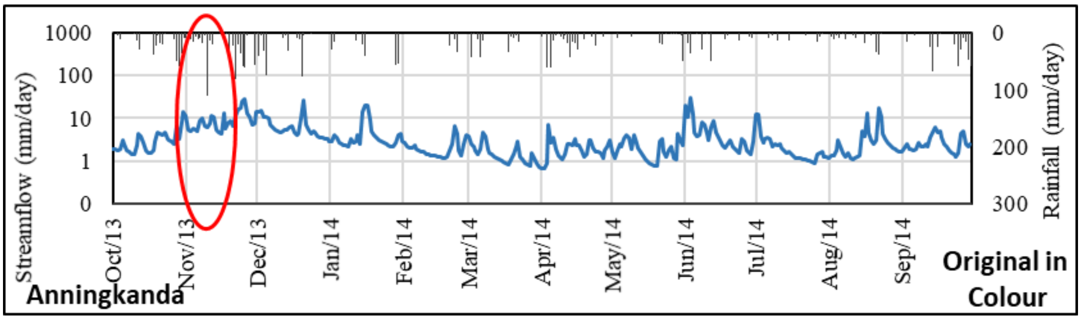
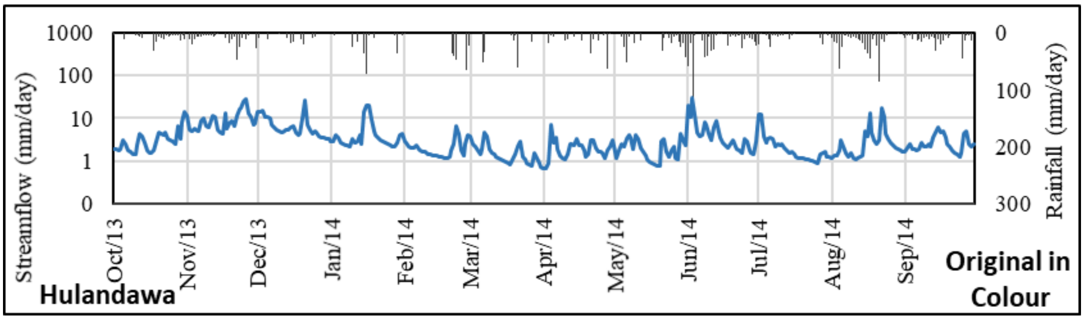
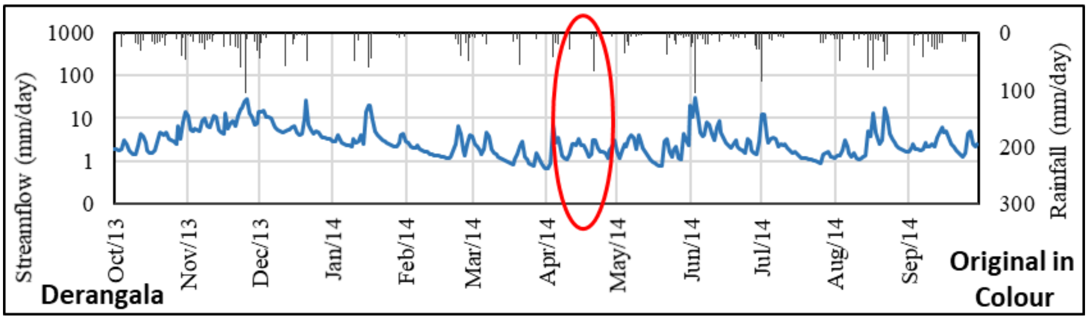

Streamflow (mm/day)
1000
100
10
1
0
Oct/13
Nov/13
Dec/13
Jan/14
Feb/14
Mar/14
Apr/14
May/14
Jun/14
Jul/14
Aug/14
Sep/14
0
100
200
300
Rainfall (mm/day)
Urawa
Original in Colour


Streamflow (mm/day)
1000
100
10
1
0
Oct/13
Nov/13
Dec/13
Jan/14
Feb/14
Mar/14
Apr/14
May/14
Jun/14
Jul/14
Aug/14
Sep/14
0
100
200
300
Rainfall (mm/day)
Anningkanda
Original in Colour


Streamflow (mm/day)
1000
100
10
1
0
Oct/13
Nov/13
Dec/13
Jan/14
Feb/14
Mar/14
Apr/14
May/14
Jun/14
Jul/14
Aug/14
Sep/14
0
100
200
300
Rainfall (mm/day)
Hulandawa
Original in Colour


Streamflow (mm/day)
1000
100
10
1
0
Oct/13
Nov/13
Dec/13
Jan/14
Feb/14
Mar/14
Apr/14
May/14
Jun/14
Jul/14
Aug/14
Sep/14
0
100
200
300
Rainfall (mm/day)
Derangala
Original in Colour

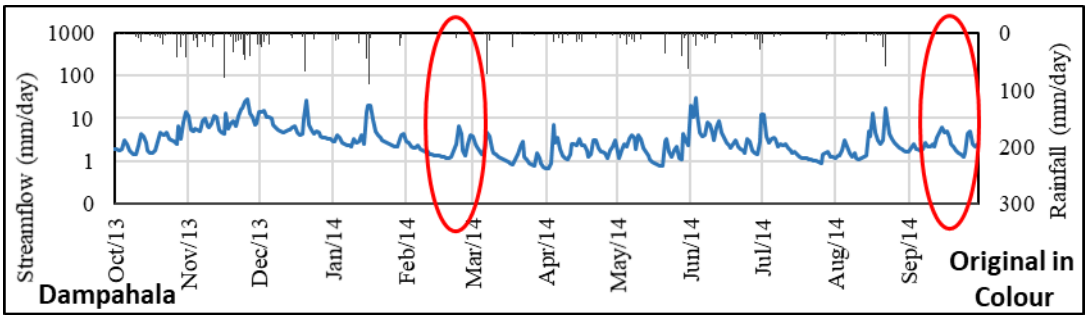
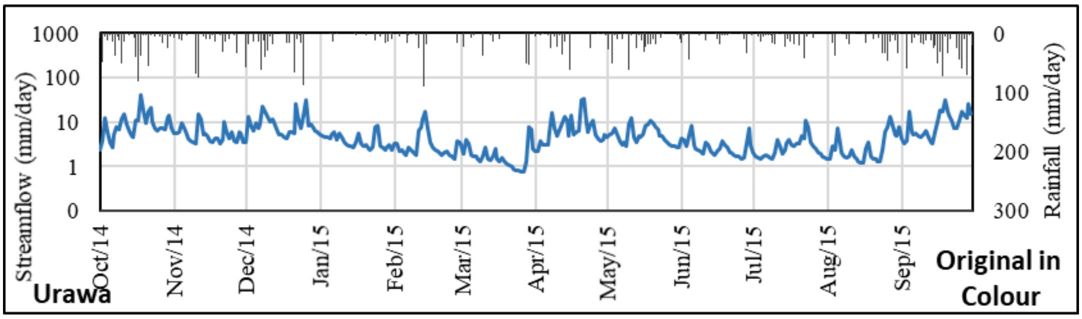
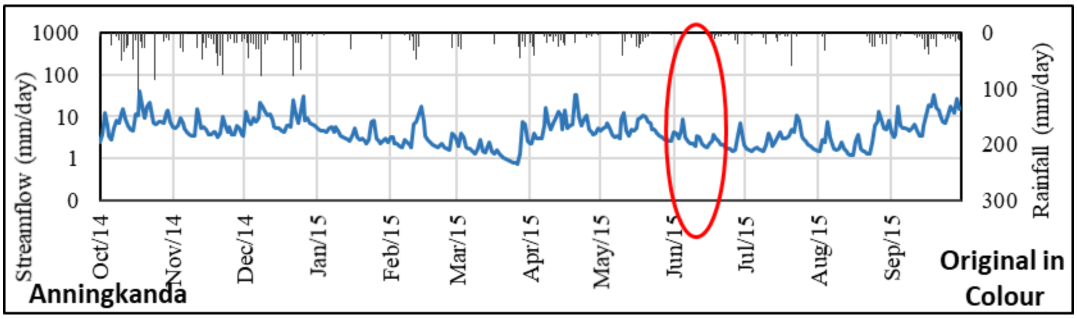
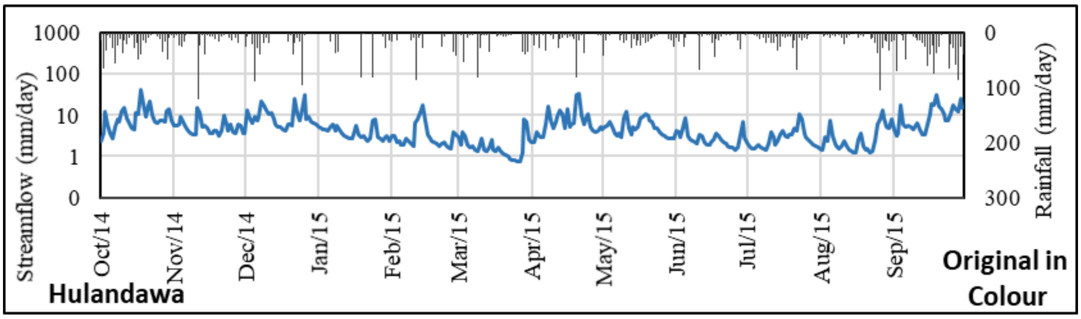


Figure B- 5: Streamflow response at Pitabaddara for year 2013/2014







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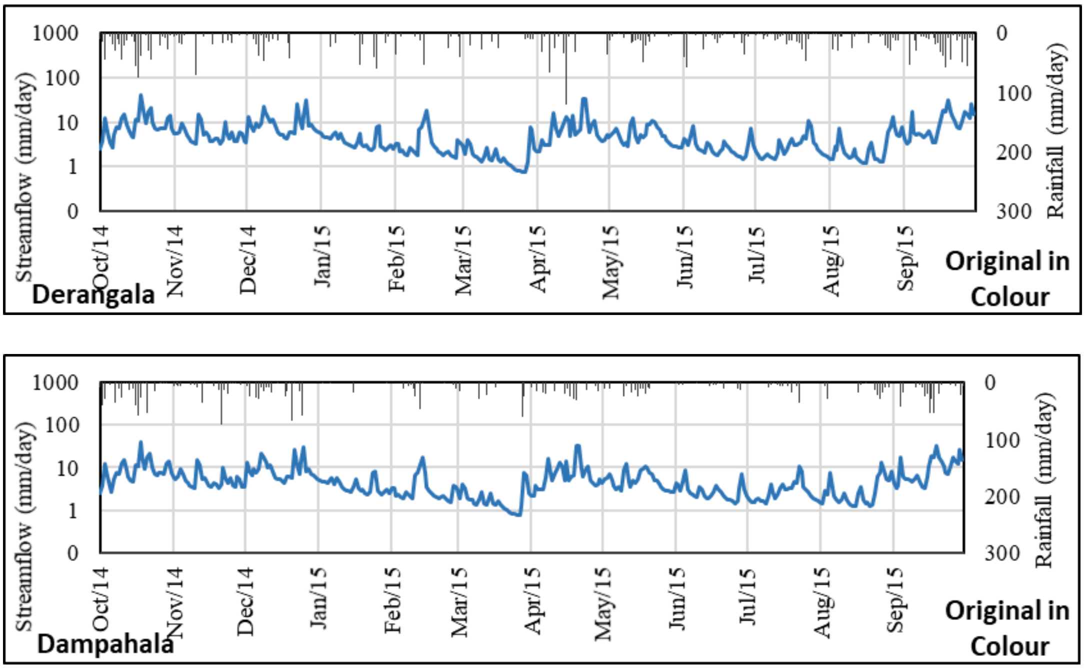
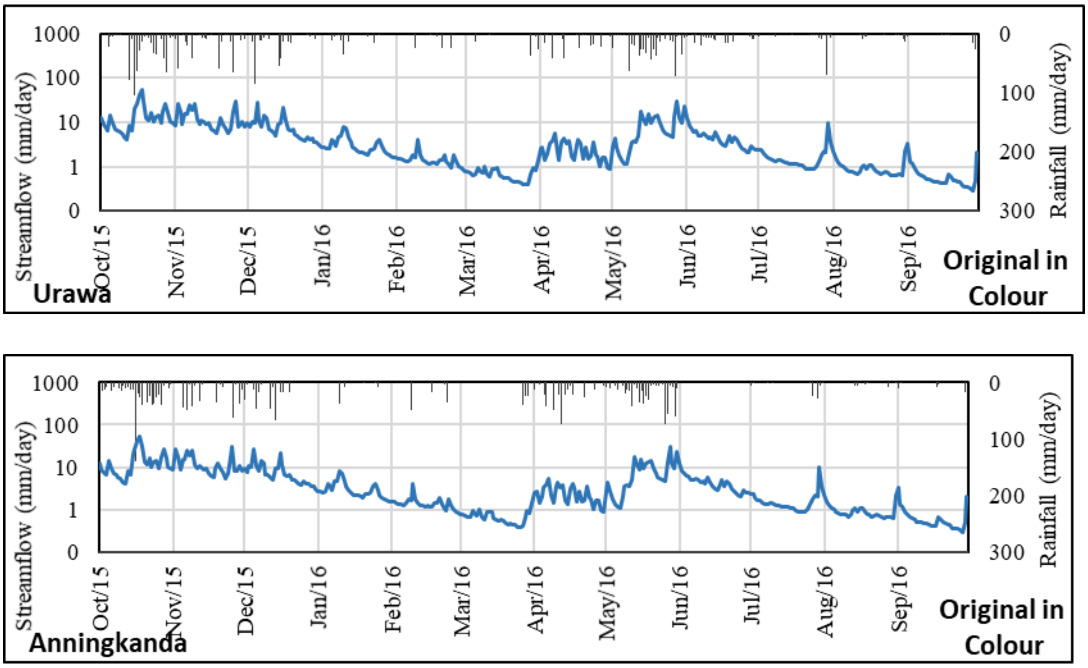


Figure B- 6: Streamflow response at Pitabaddara for year 2014/2015



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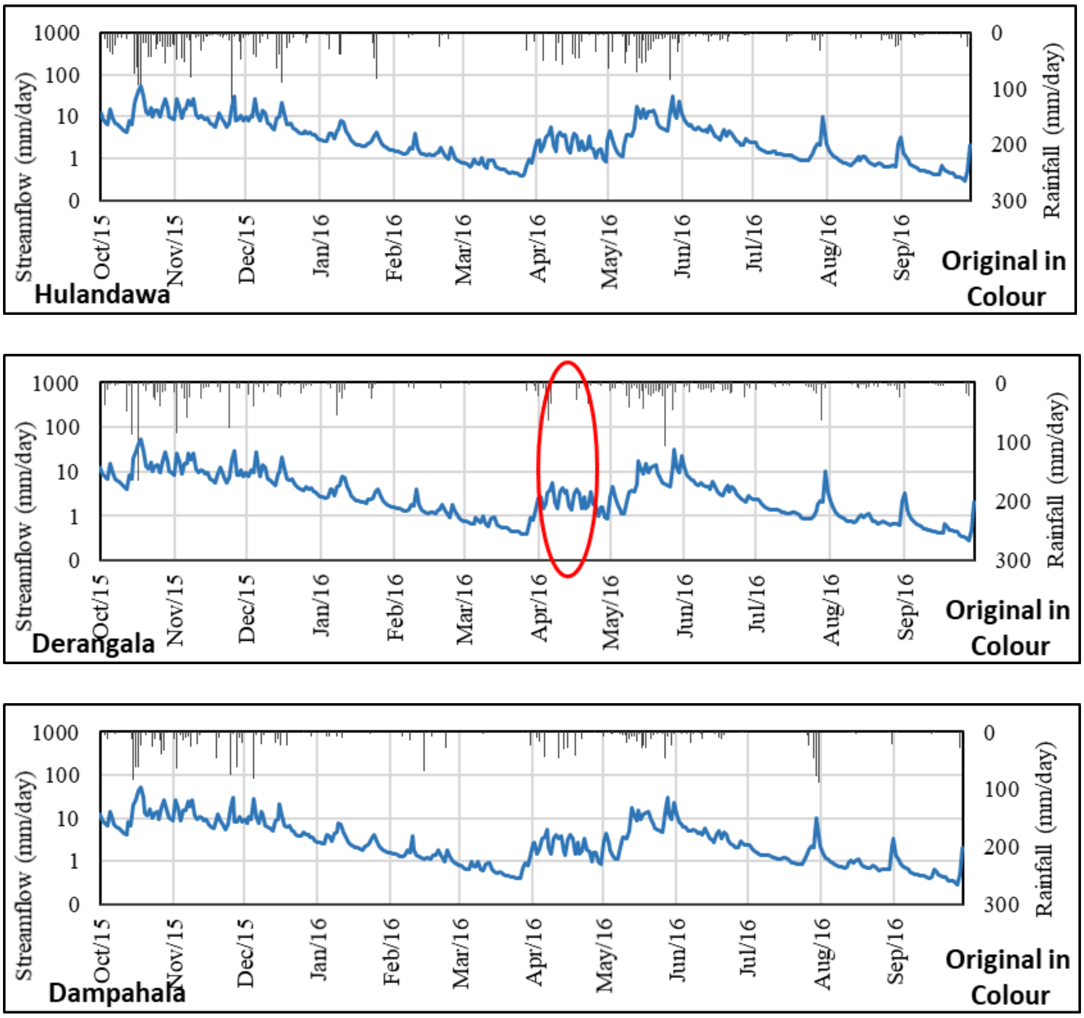
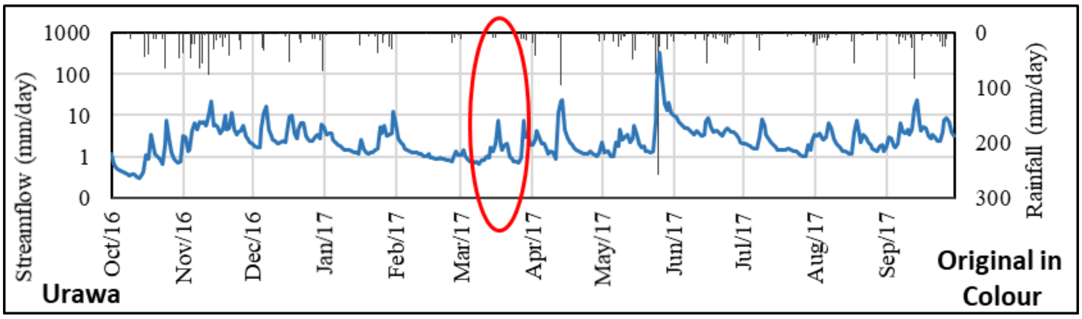


Figure B- 7: Streamflow response at Pitabaddara for year 2015/2016



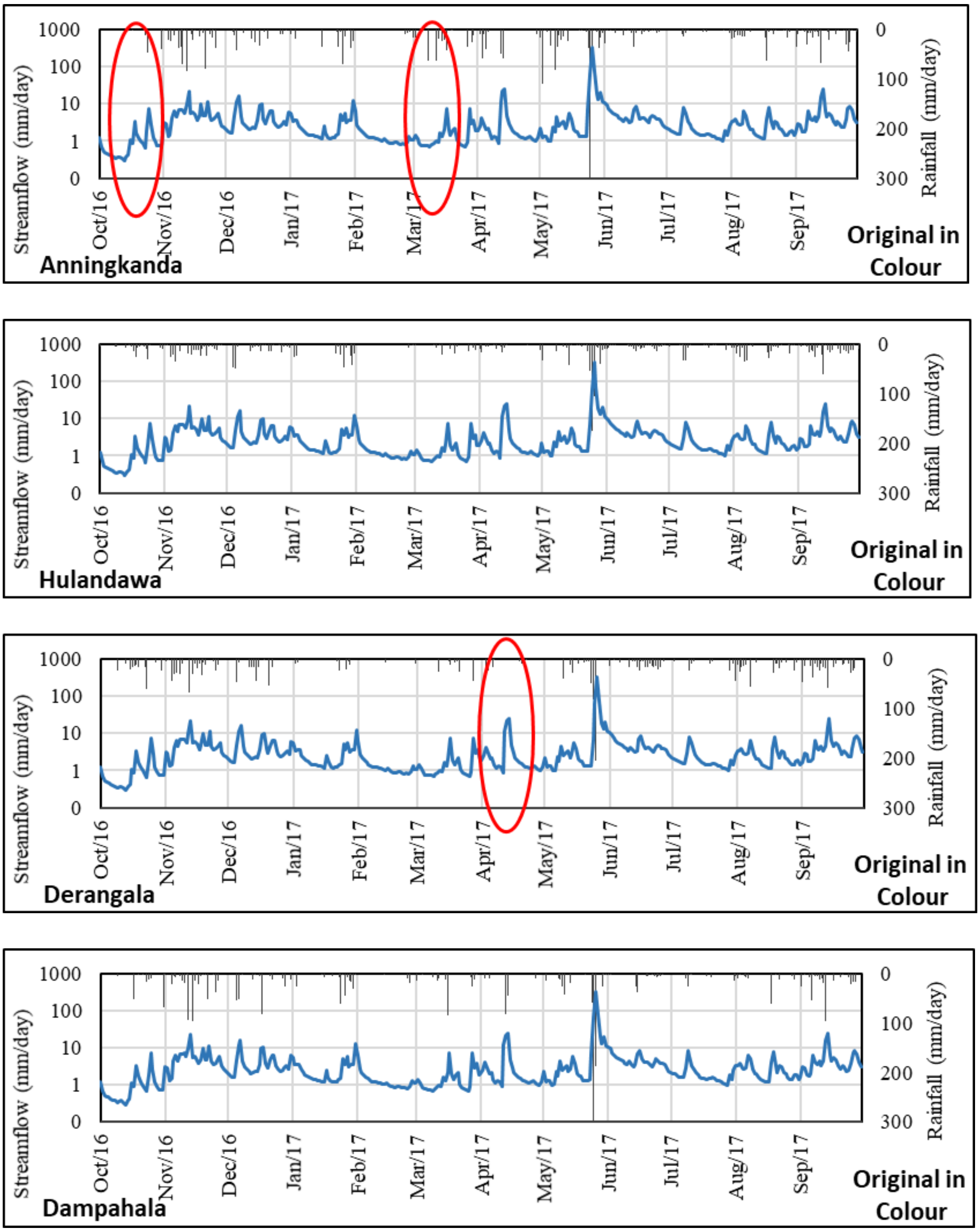


Figure B- 8: Streamflow response at Pitabaddara for year 2016/2017

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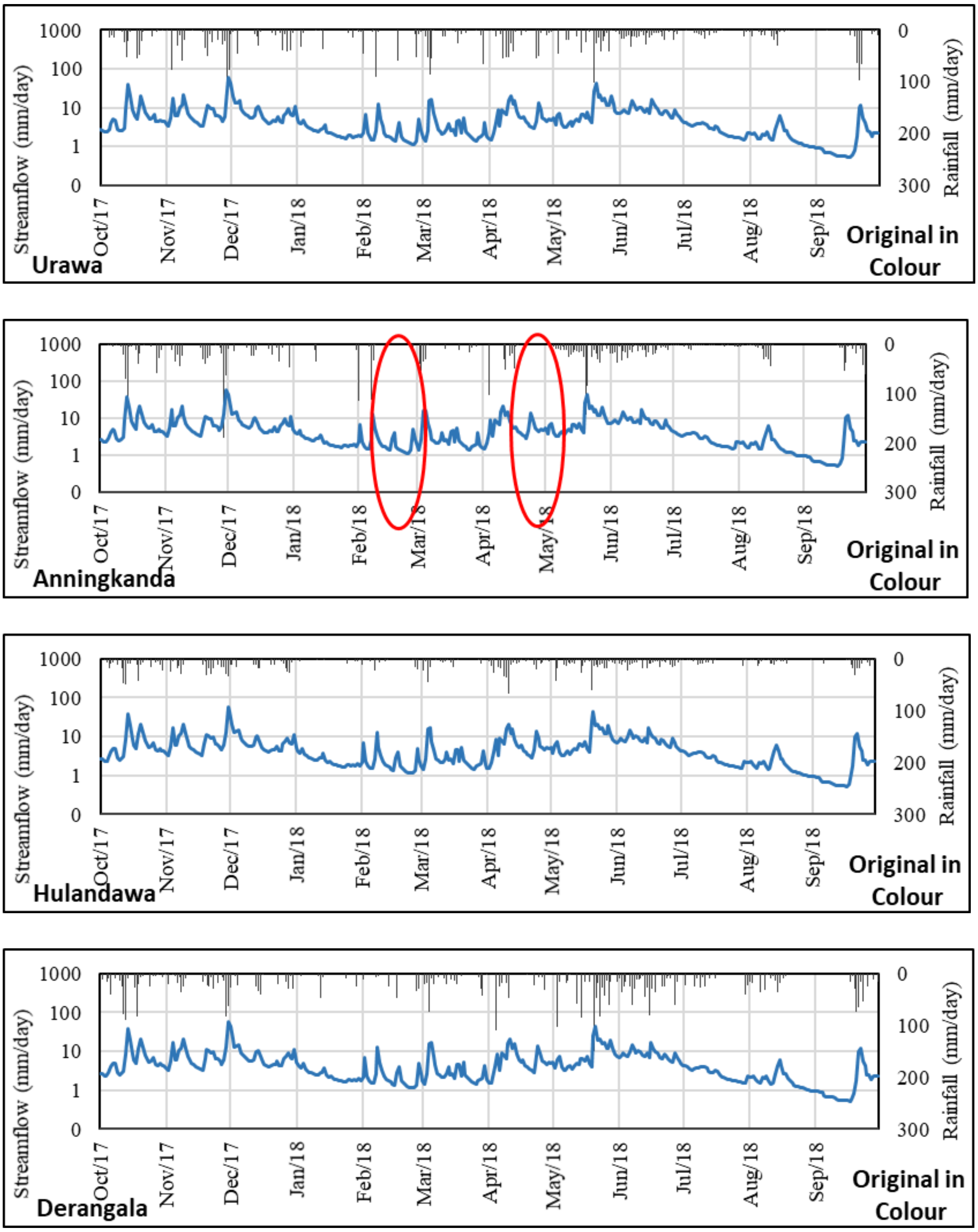

Urawa
Anningkanda
Hulandawa
Derangala
Streamflow (mm/day)
Rainfall (mm/day)
1000
100
10
1
0
300
200
Oct/17
Nov/17
Dec/17
Jan/18
Feb/18
Mar/18
Apr/18
May/18
Jun/18
Jul/18
Aug/18
Sep/18
Original in Colour

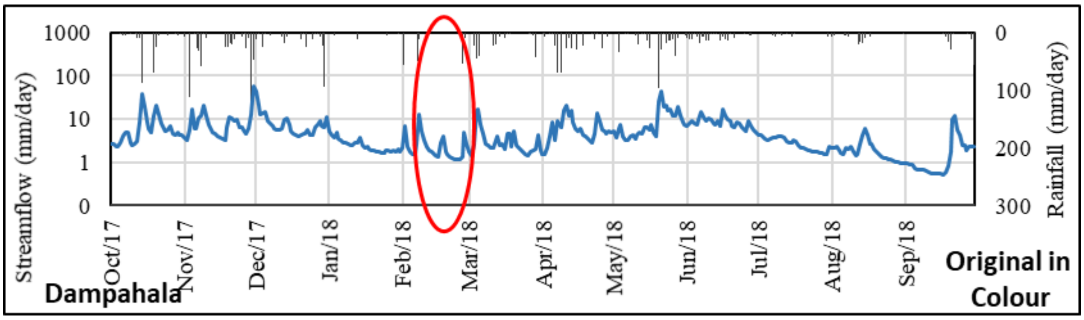


Figure B- 9: Streamflow response at Pitabaddara for year 2017/2018

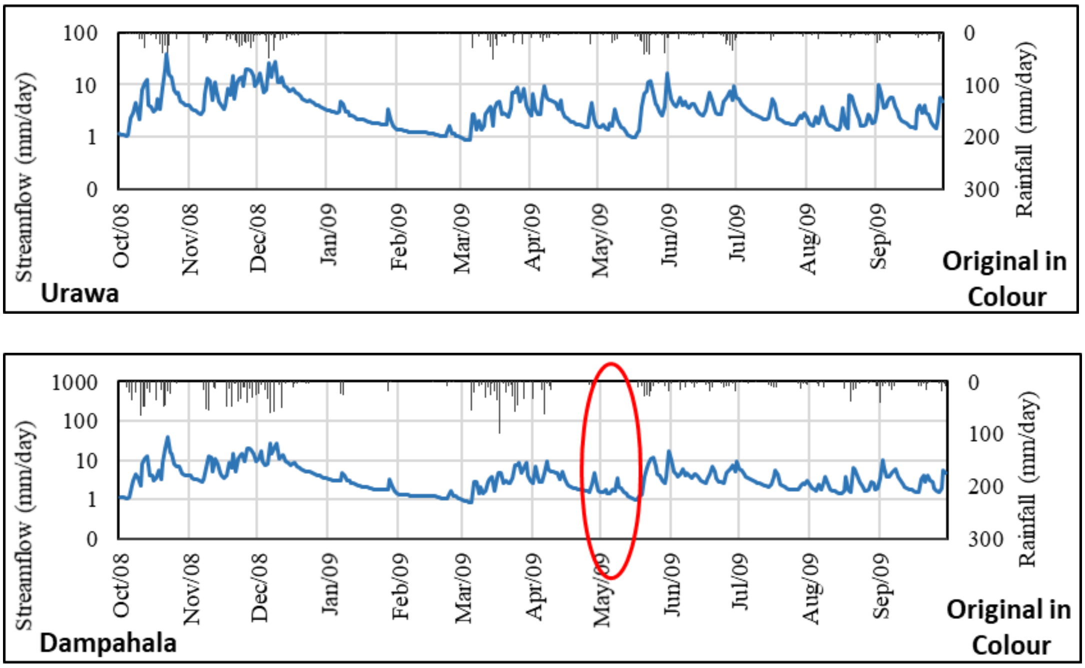
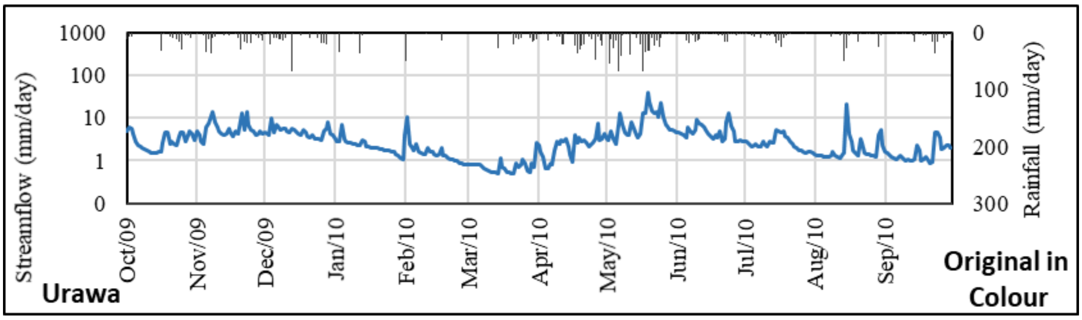


Figure B- 10: Streamflow response at Urawa for year 2008/2009



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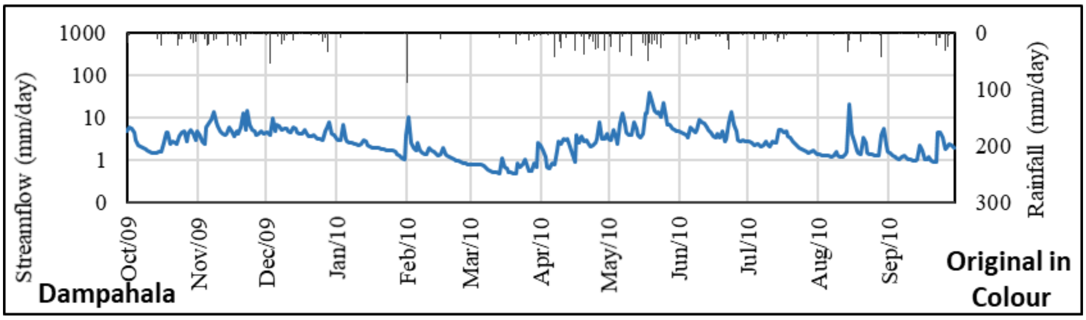
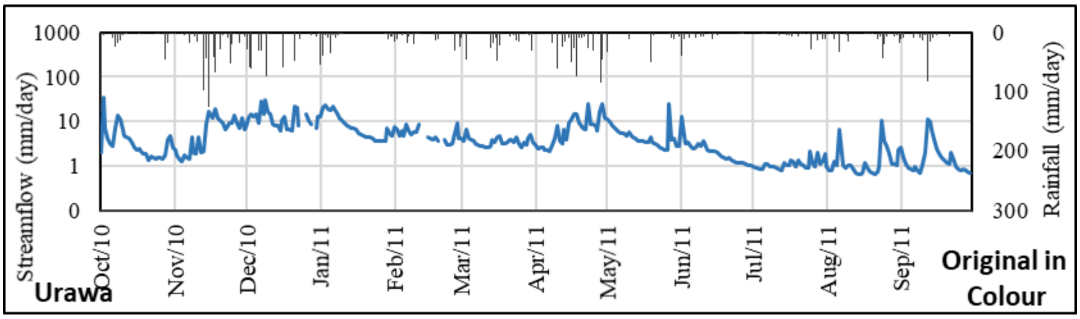


Figure B- 11: Streamflow response at Urawa for year 2009/2010



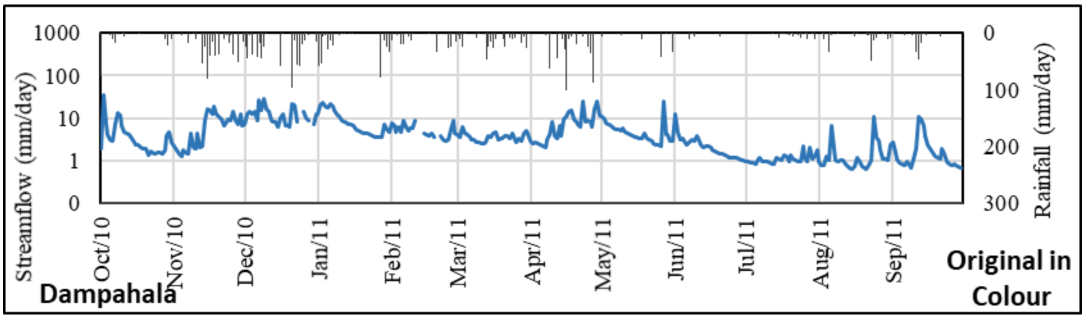
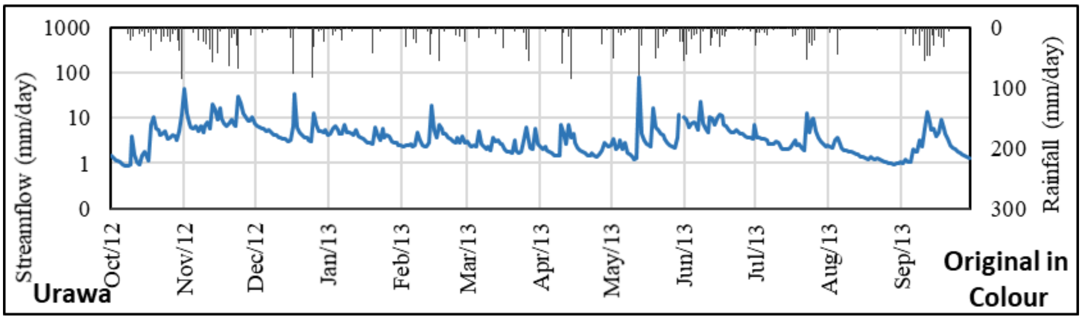


Figure B- 12: Streamflow response at Urawa for year 2010/2011



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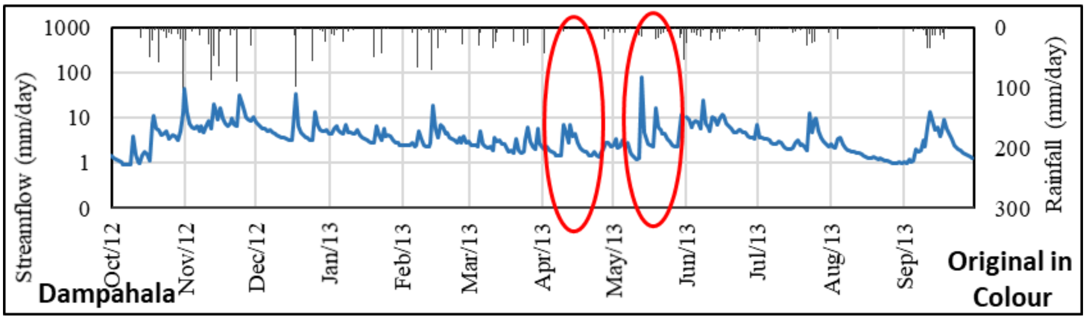


Figure B- 13: Streamflow response at Urawa for year 2012/2013

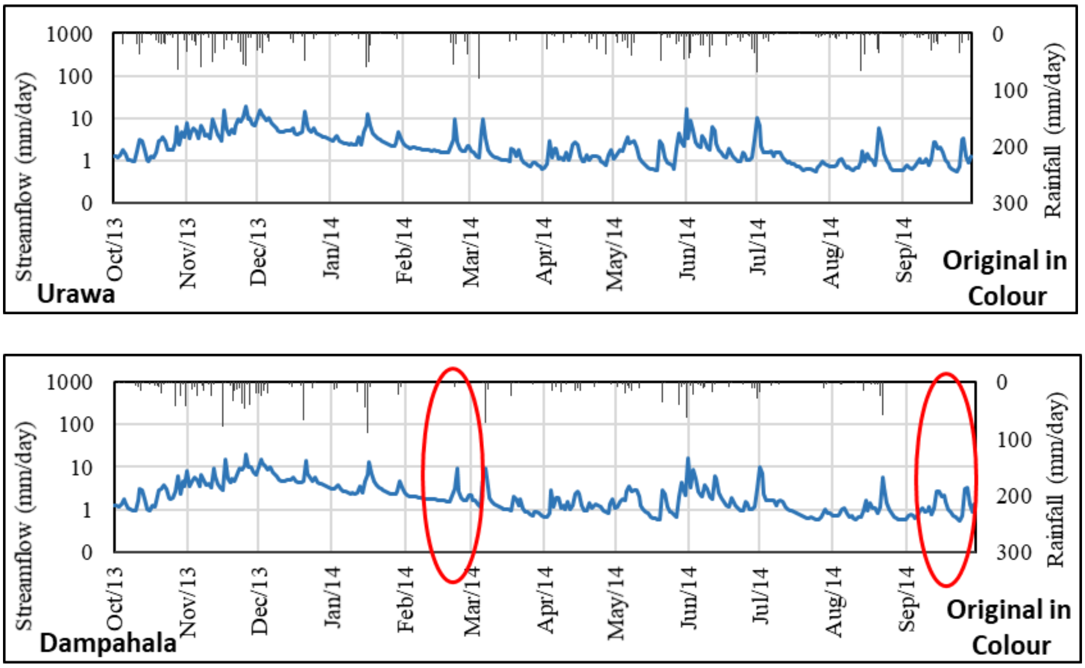
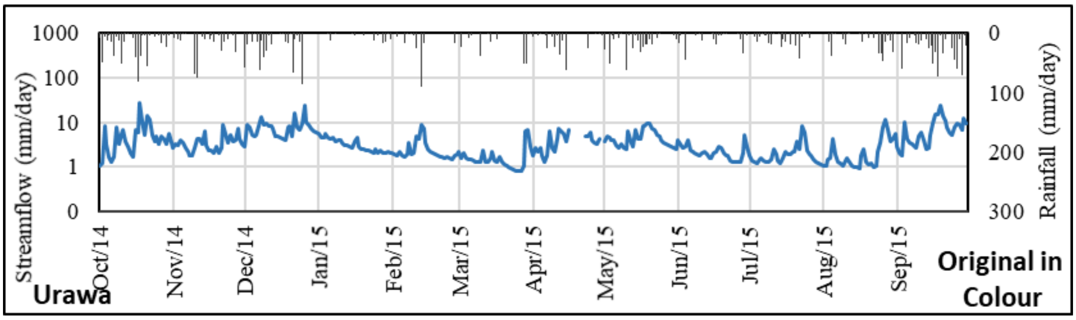


Figure B- 14: Streamflow response at Urawa for year 2013/2014



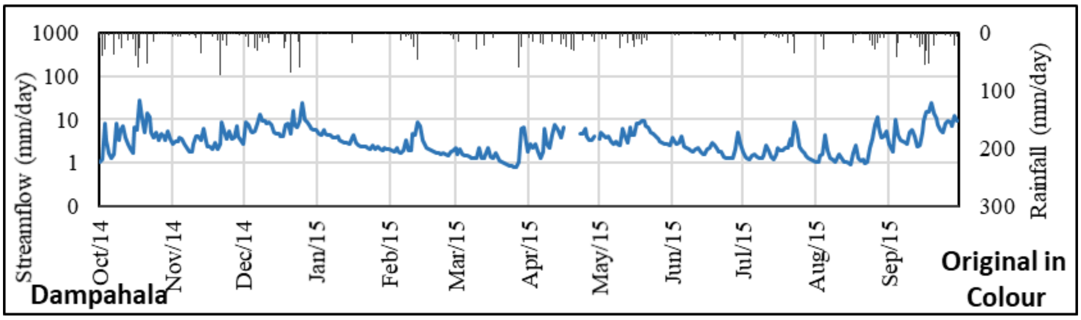


Figure B- 15: Streamflow response at Urawa for year 2014/2015

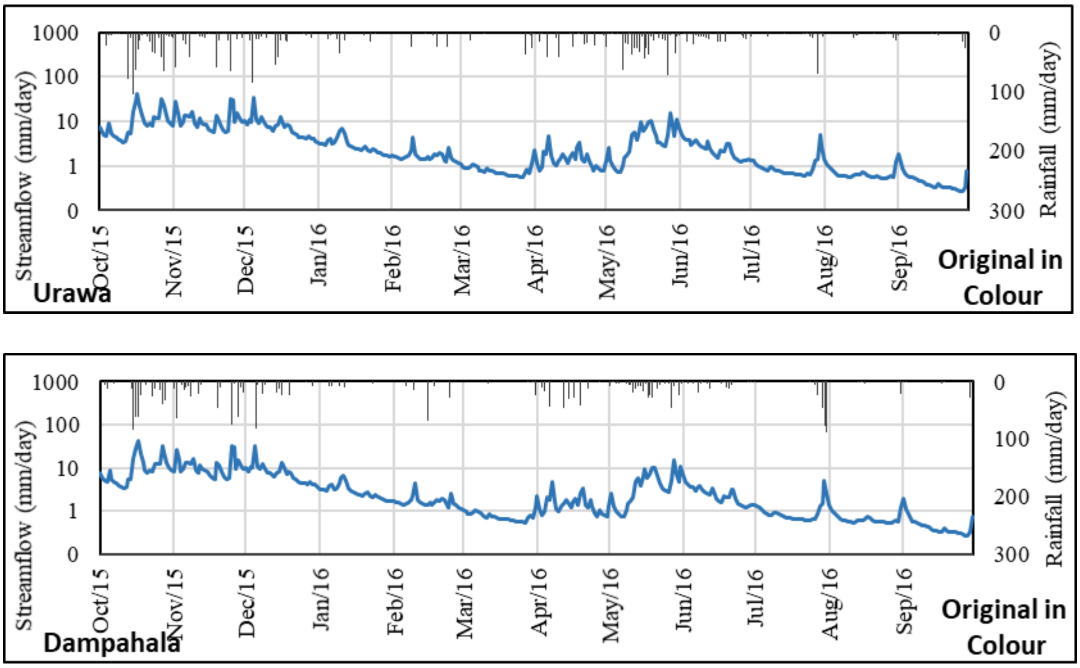
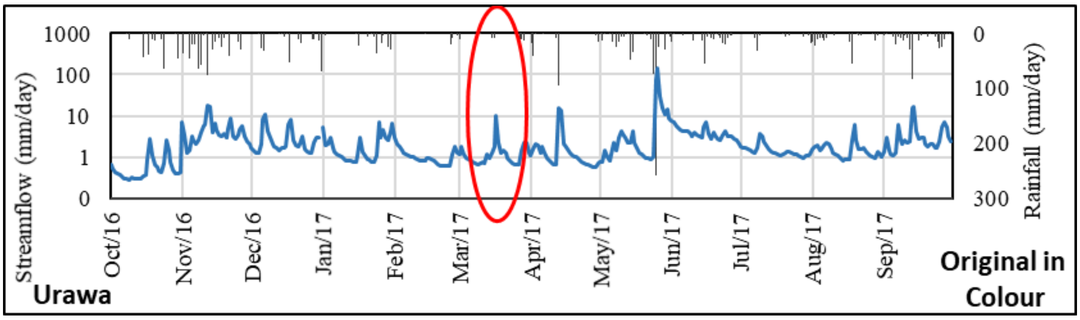


Figure B- 16: Streamflow response at Urawa for year 2015/2016



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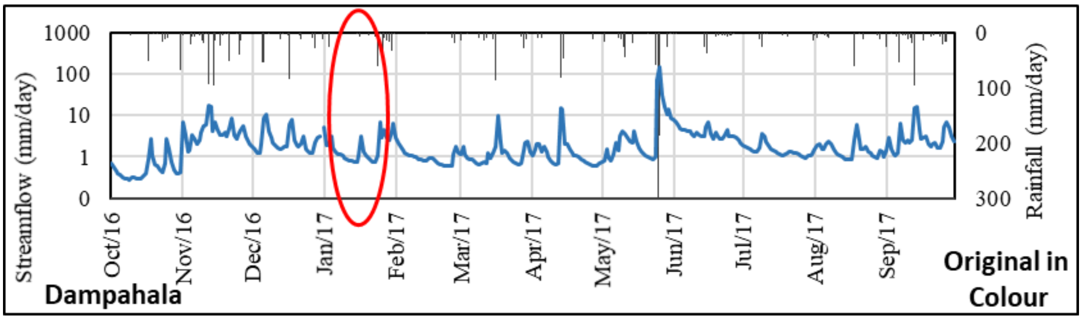

Figure B- 17: Streamflow response at Urawa for year 2016/2017

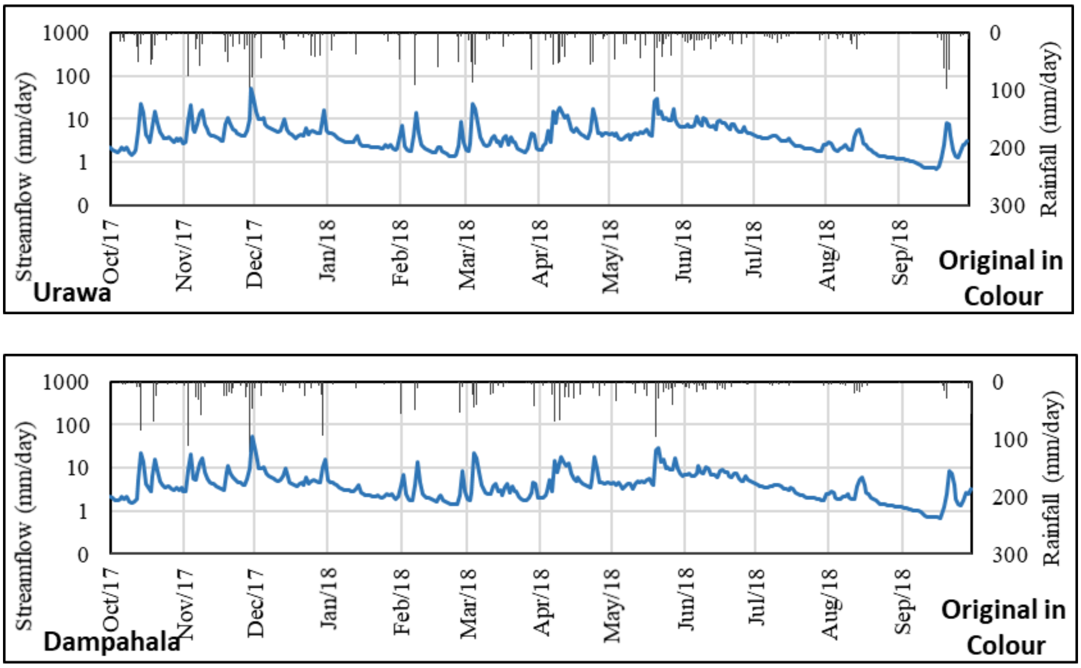

Figure B- 18: Streamflow response at Urawa for year 2016/2017

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APPENDIX C : MODEL CALIBRATION RESULTS

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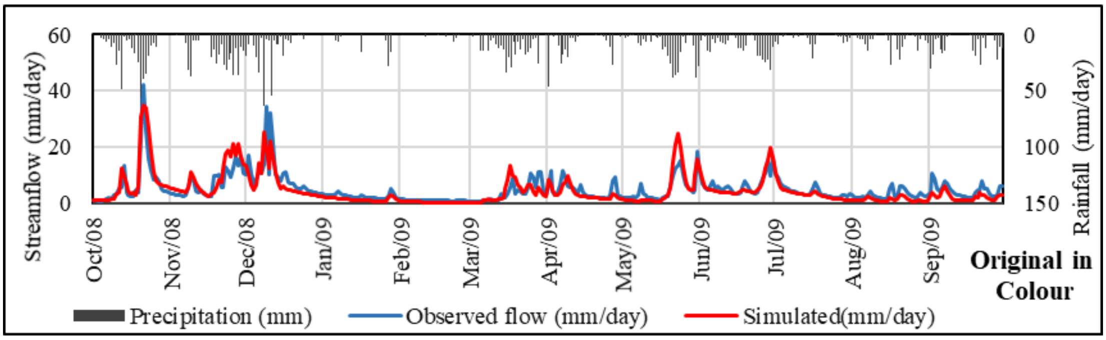
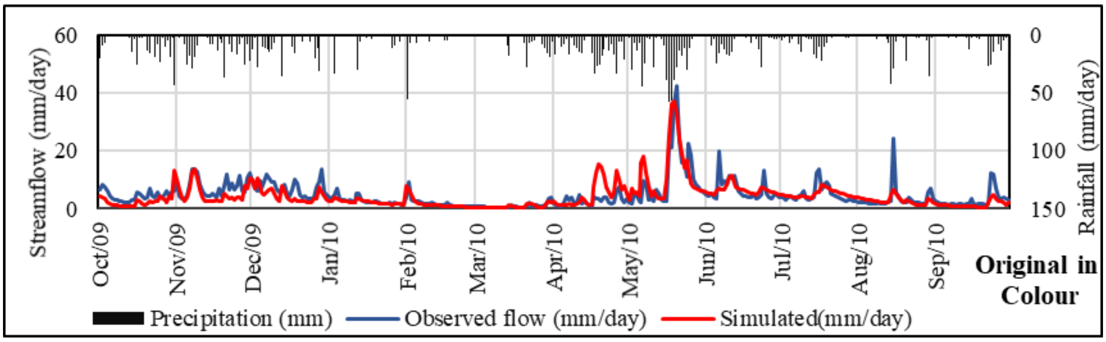
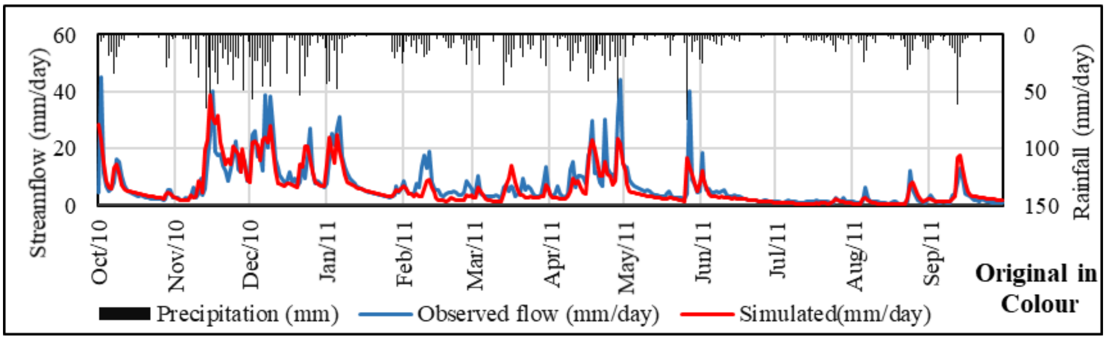
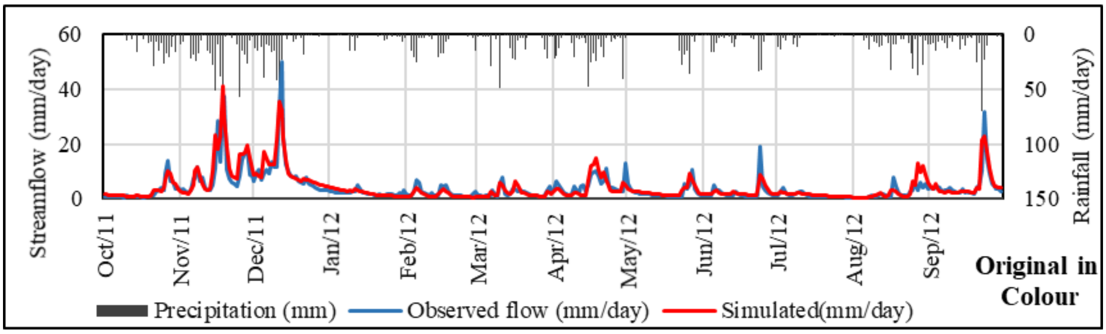

Streamflow (mm/day)
60
40
20
0
0
50
100
150
Rainfall (mm/day)
Oct/08
Nov/08
Dec/08
Jan/09
Feb/09
Mar/09
Apr/09
May/09
Jun/09
Jul/09
Aug/09
Sep/09
Original in Colour
Precipitation (mm)
Observed flow (mm/day)
Simulated(mm/day)


Streamflow (mm/day)
60
40
20
0
0
50
100
150
Rainfall (mm/day)
Oct/09
Nov/09
Dec/09
Jan/10
Feb/10
Mar/10
Apr/10
May/10
Jun/10
Jul/10
Aug/10
Sep/10
Original in Colour
Precipitation (mm)
Observed flow (mm/day)
Simulated(mm/day)


Streamflow (mm/day)
60
40
20
0
0
50
100
150
Rainfall (mm/day)
Oct/10
Nov/10
Dec/10
Jan/11
Feb/11
Mar/11
Apr/11
May/11
Jun/11
Jul/11
Aug/11
Sep/11
Original in Colour
Precipitation (mm)
Observed flow (mm/day)
Simulated(mm/day)


Streamflow (mm/day)
60
40
20
0
0
50
100
150
Rainfall (mm/day)
Oct/11
Nov/11
Dec/11
Jan/12
Feb/12
Mar/12
Apr/12
May/12
Jun/12
Jul/12
Aug/12
Sep/12
Original in Colour
Precipitation (mm)
Observed flow (mm/day)
Simulated(mm/day)

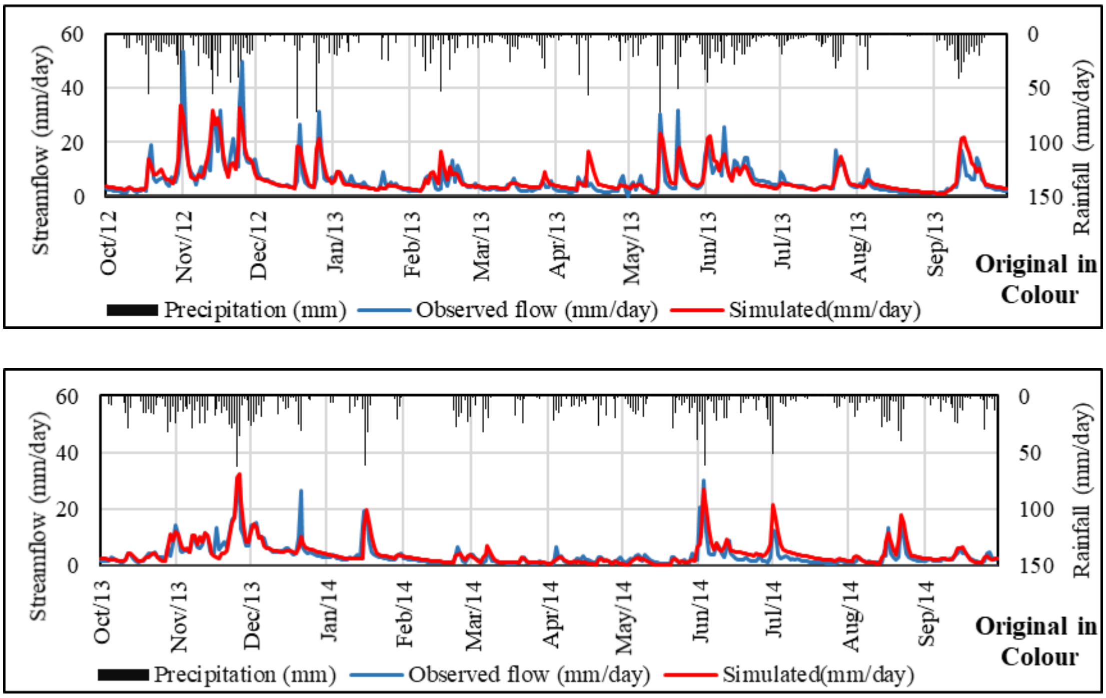
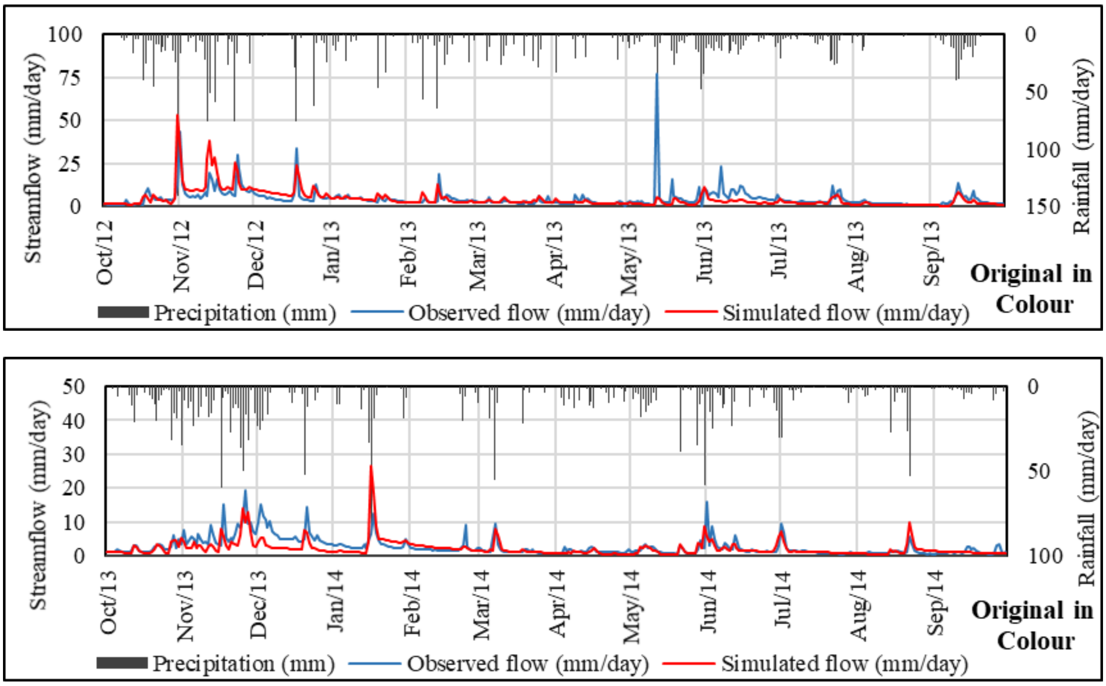


Figure C- 1: : Calibration Result of Pitabaddara Watershed - Normal Plot



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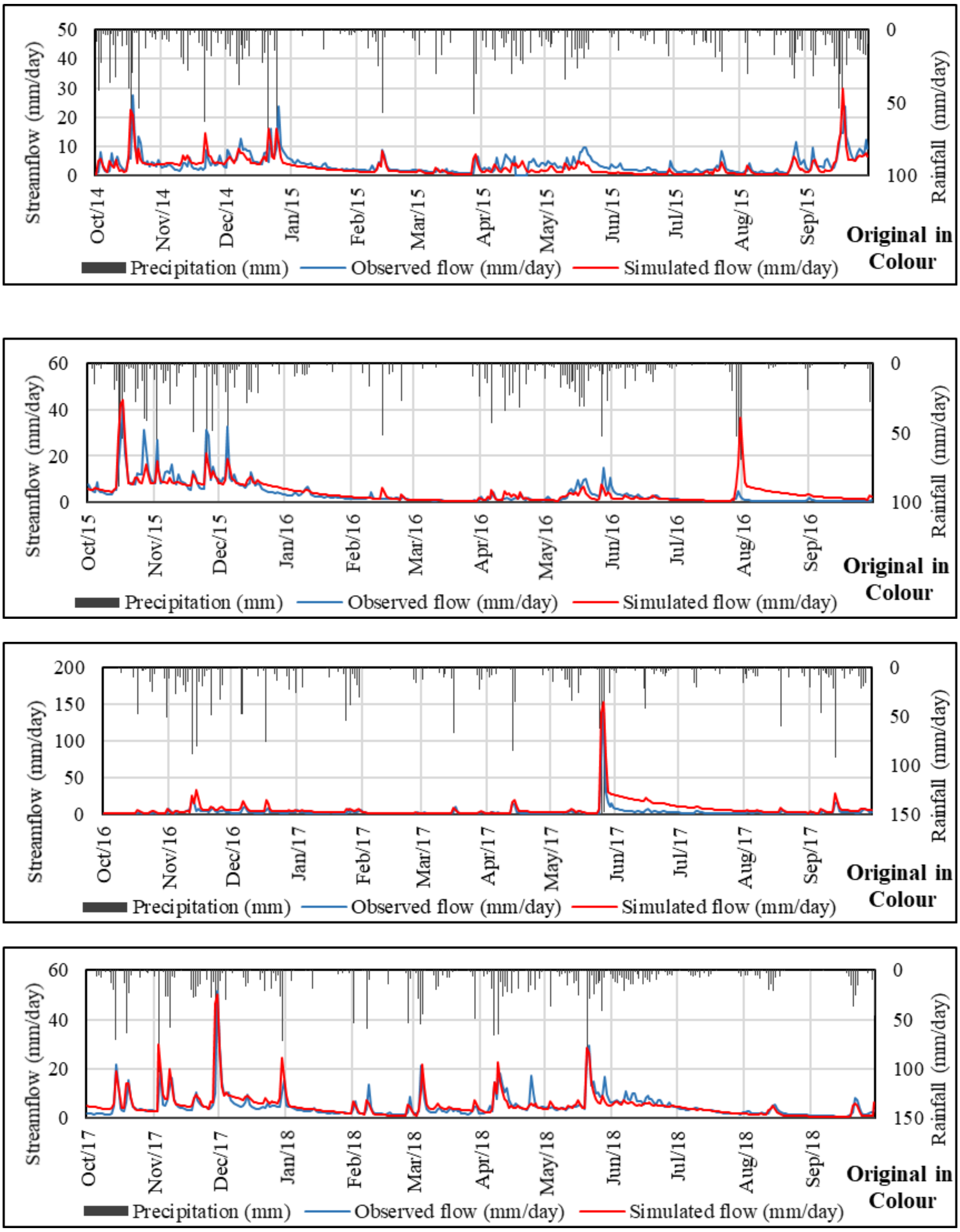

Figure C- 2: Calibration Result of Urawa Watershed - Hydrograph (Normal Plot)

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APPENDIX D :MODEL FULLY AUTOMATIC CALIBRATION

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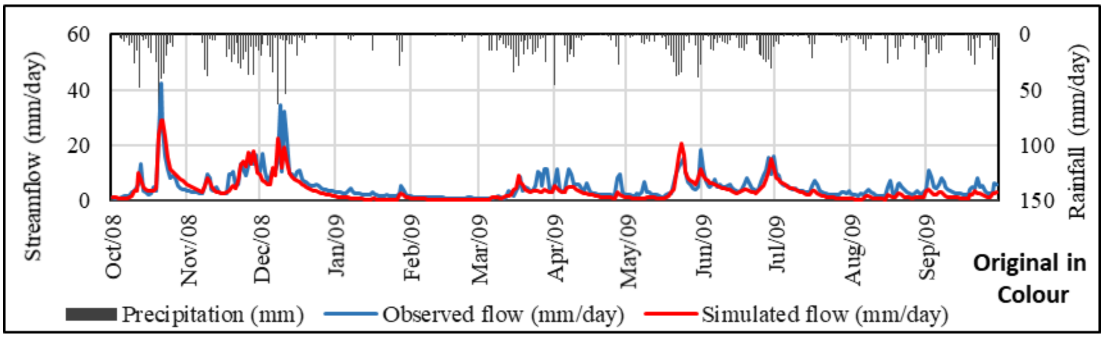
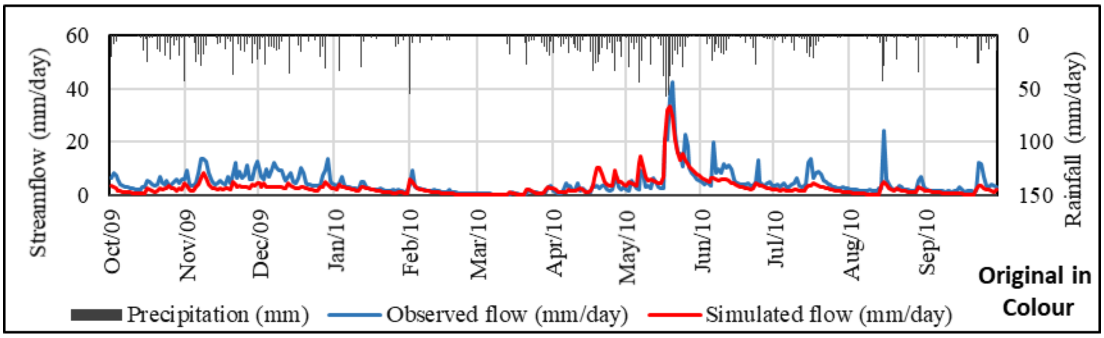
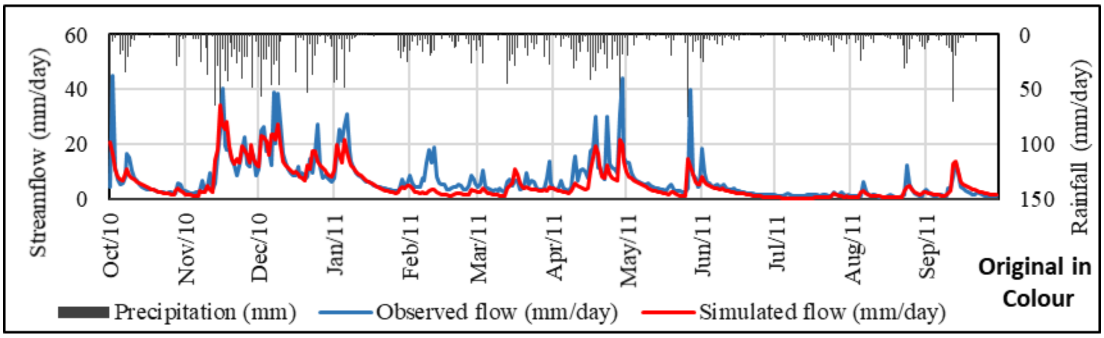
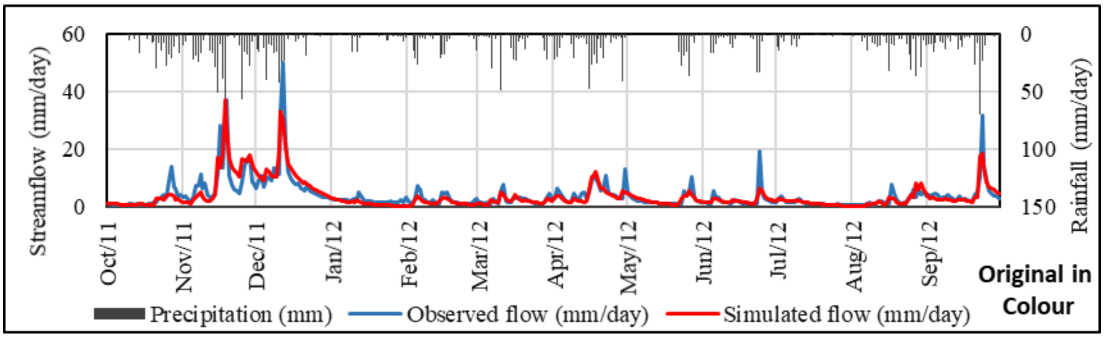

Streamflow (mm/day)
Rainfall (mm/day)
60
40
20
0
0
50
100
150
Oct/08
Nov/08
Dec/08
Jan/09
Feb/09
Mar/09
Apr/09
May/09
Jun/09
Jul/09
Aug/09
Sep/09
Precipitation (mm)
Observed flow (mm/day)
Simulated flow (mm/day)
Original in Colour


Streamflow (mm/day)
Rainfall (mm/day)
60
40
20
0
0
50
100
150
Oct/09
Nov/09
Dec/09
Jan/10
Feb/10
Mar/10
Apr/10
May/10
Jun/10
Jul/10
Aug/10
Sep/10
Precipitation (mm)
Observed flow (mm/day)
Simulated flow (mm/day)
Original in Colour


Streamflow (mm/day)
Rainfall (mm/day)
60
40
20
0
0
50
100
150
Oct/10
Nov/10
Dec/10
Jan/11
Feb/11
Mar/11
Apr/11
May/11
Jun/11
Jul/11
Aug/11
Sep/11
Precipitation (mm)
Observed flow (mm/day)
Simulated flow (mm/day)
Original in Colour


Streamflow (mm/day)
Rainfall (mm/day)
60
40
20
0
0
50
100
150
Oct/11
Nov/11
Dec/11
Jan/12
Feb/12
Mar/12
Apr/12
May/12
Jun/12
Jul/12
Aug/12
Sep/12
Precipitation (mm)
Observed flow (mm/day)
Simulated flow (mm/day)
Original in Colour

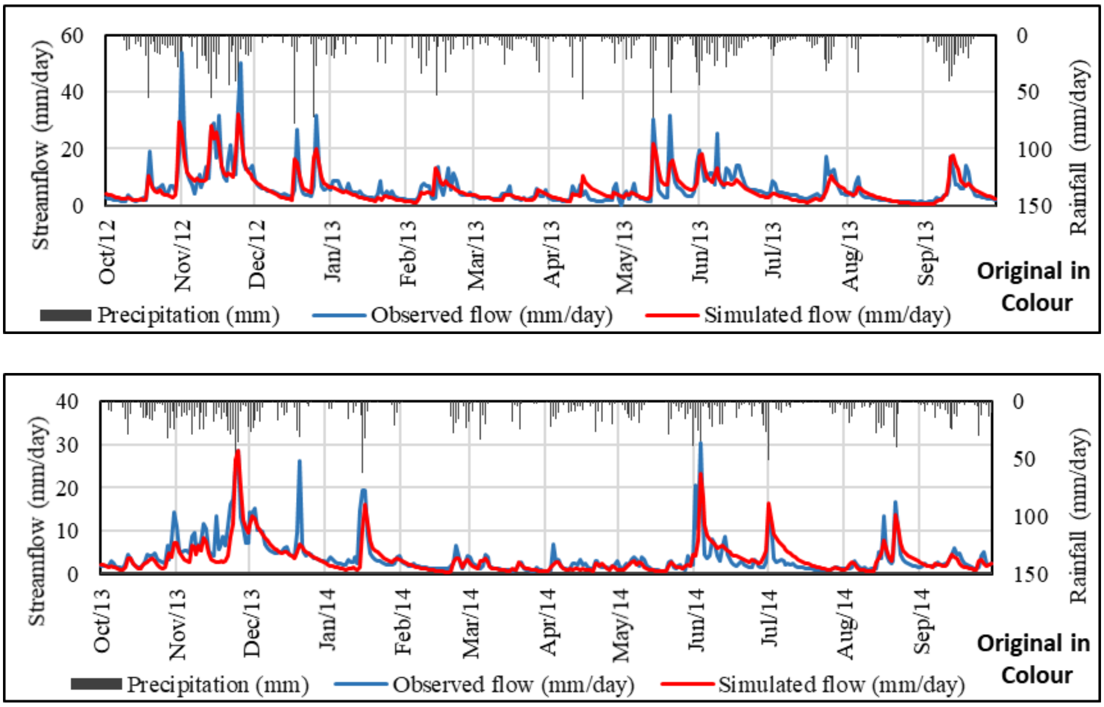
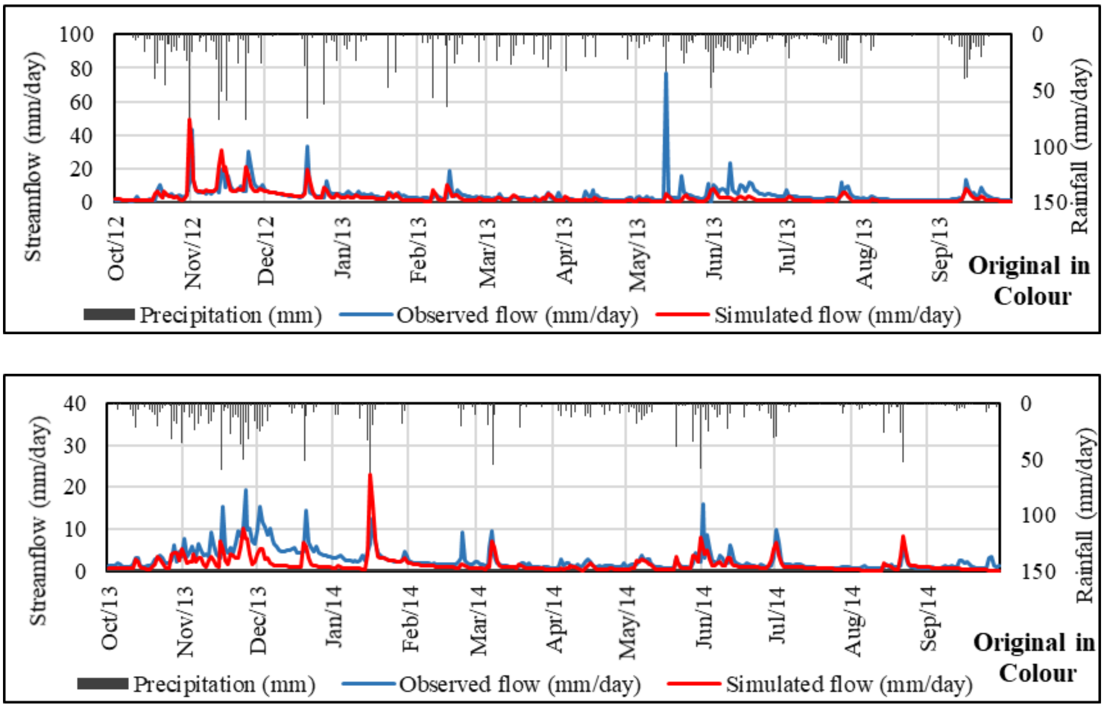


Figure D- 1: Fully Automatic Calibration result for Pitabaddara – Normal Plot



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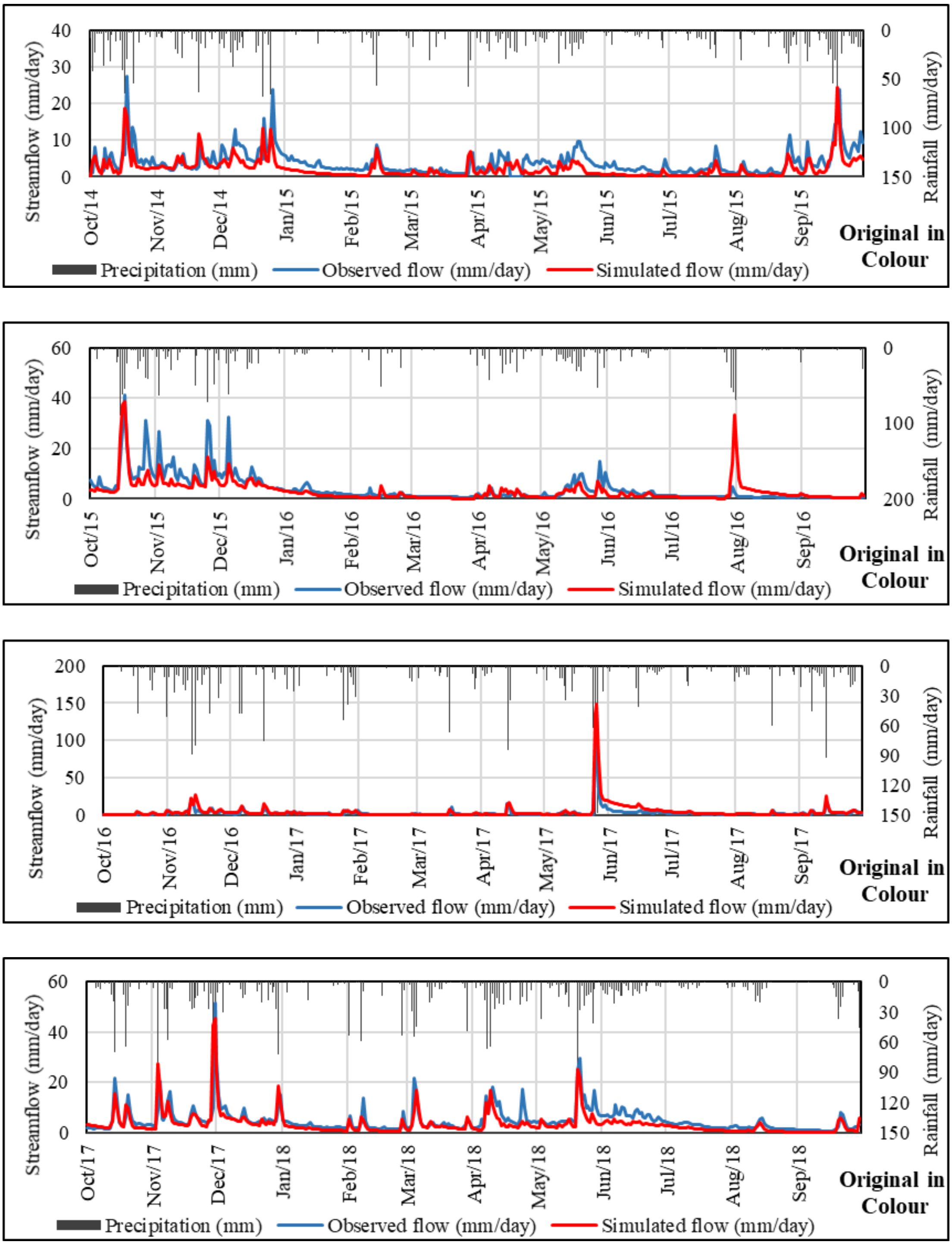

Figure D- 2: Fully Automatic Calibration result for Urawa Watershed – Normal Plot

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APPENDIX E : MODEL VERIFICATION RESULT

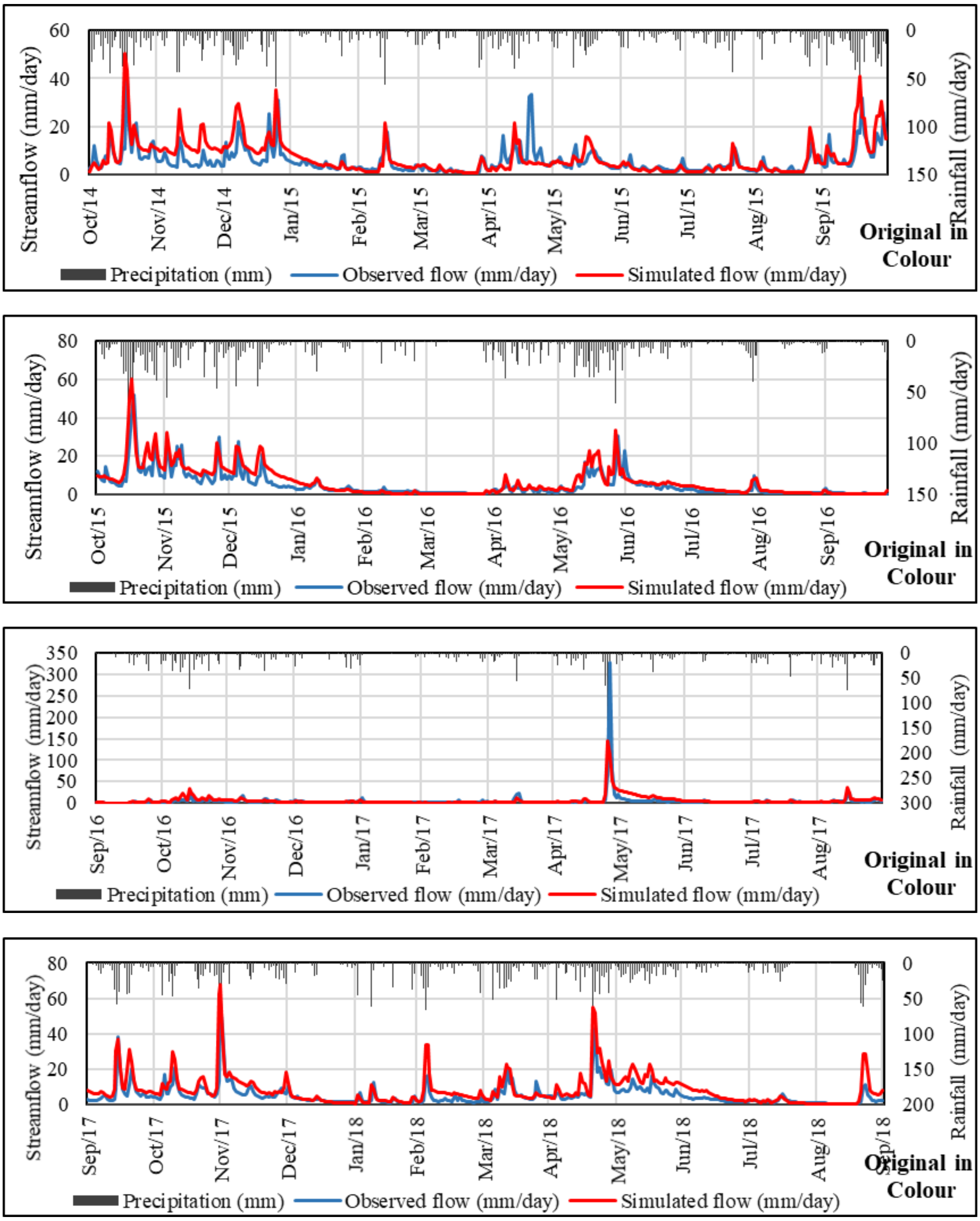

Figure E- 1: Verification Result for Pitabeddara Watershed – Normal Plot

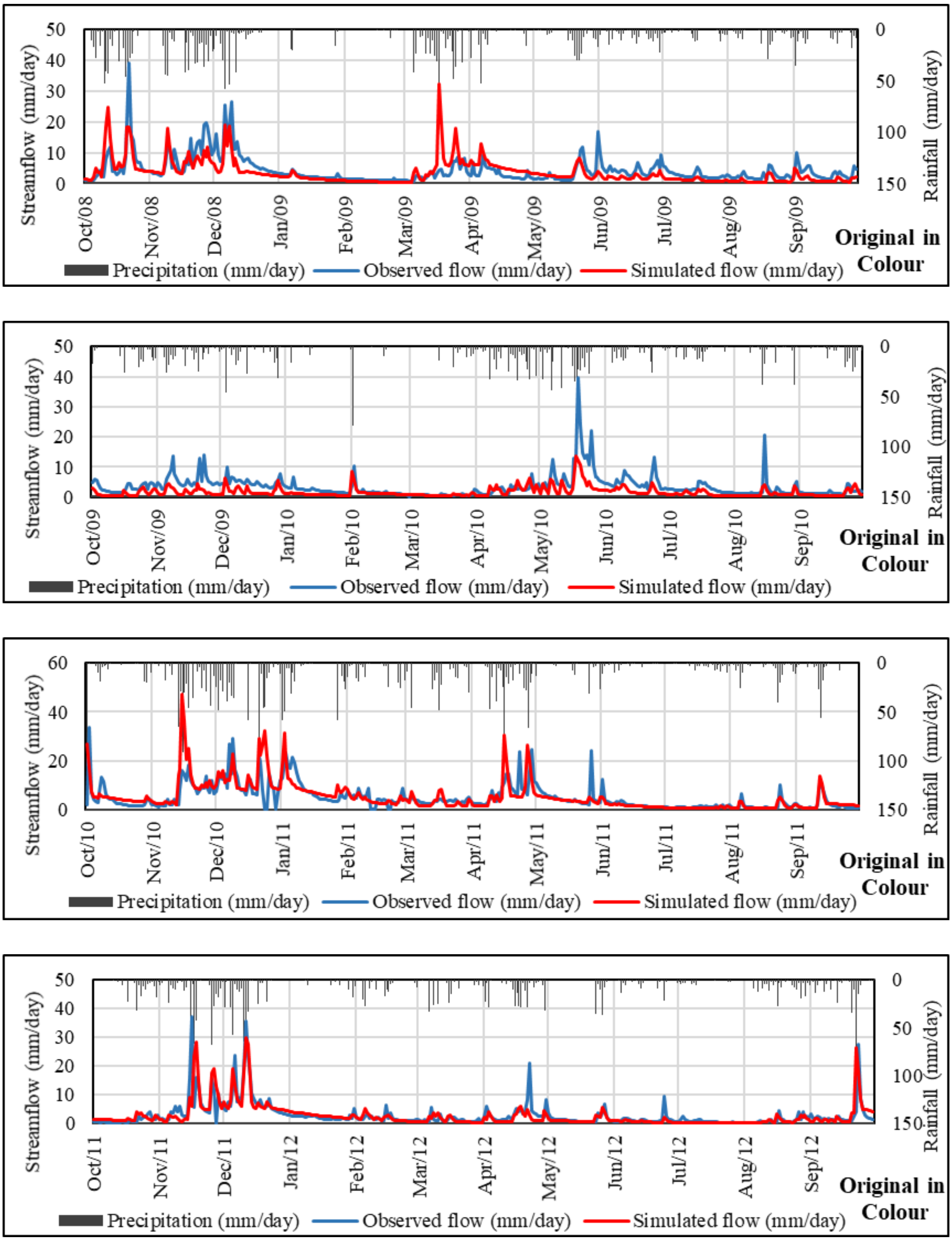

Figure E- 2: Verification Result for Urawa Watershed – Normal Plot

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APPENDIX F :SEASONAL STREAMFLOW ESTIMATION - CALIBRATION AND VALIDATION

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Table F- 1:Seasonal water balance for calibration period - Pitabaddara watershed

Water Year	Season	RF (mm /season)	Obs. SF (mm /season)	Sim. SF (mm /season)	SWB – Obs. SF (mm/season)	SWB – Sim. SF (mm/season)	SWBE	Percentage error	Sim. Runoff Coeff.	Obs. Runoff Coeff.
2008/09	Maha	146	966	945	494	515	-21	-4%	0.65	0.66
	Yala	129	853	679	437	611	-174	-40%	0.53	0.66
2009/10	Maha	113	748	530	389	607	-218	-56%	0.47	0.66
	Yala	160	962	104	643	561	81	13%	0.65	0.6
2010/11	Maha	211	165	155	460	556	-96	-21%	0.74	0.78
	Yala	125	883	738	371	516	-145	-39%	0.59	0.77
2011/12	Maha	145	898	962	558	495	64	11%	0.66	0.62
	Yala	123	564	599	673	637	36	5%	0.48	0.46
2012/13	Maha	182	128	132	543	505	38	7%	0.72	0.7
	Yala	152	979	107	543	451	92	17%	0.7	0.64
2013/14	Maha	141	870	916	545	499	46	8%	0.65	0.62
	Yala	136	552	688	810	674	136	17%	0.5	0.41
Average	Maha	156	107	103	498	530	-31	-6%	0.66	0.68
	Yala	137	799	803	579	575	4	1%	0.58	0.58

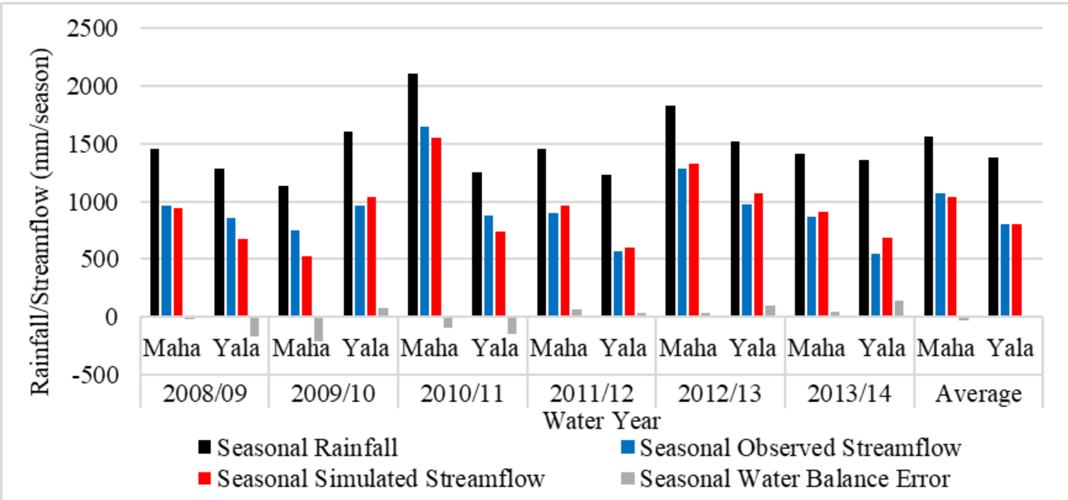

Figure F- 1: Seasonal water balance for calibration period - Pitabaddara watershed

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Table F- 2:Seasonal water balance for calibration period - Urawa watershed

Water Year	Season	RF (mm/season)	Obs. SF (mm/season)	Sim. SF (mm/season)	SWB – Obs. SF (mm/season)	SWB – Sim. SF (mm/season)	SWBE	Percentage error	Sim. Runoff Coeff.	Obs. Runoff Coeff.
2012/13	Maha	1647	945	117	701	474	228	33%	0.71	0.57
	Yala	1020	739	387	281	633	-352	-125%	0.38	0.72
2013/14	Maha	1207	684	519	523	688	-165	-32%	0.43	0.57
	Yala	831	296	268	535	563	-28	-5%	0.32	0.36
2014/15	Maha	1372	744	692	629	681	-52	-8%	0.5	0.54
	Yala	1187	661	406	526	781	-255	-48%	0.34	0.56
2015/16	Maha	1271	111	112	158	145	13	8%	0.89	0.88
	Yala	981	336	504	646	477	168	26%	0.51	0.34
2016/17	Maha	1290	387	680	903	609	293	33%	0.53	0.3
	Yala	1482	719	168	763	-205	969	127%	1.14	0.49
2017/18	Maha	1588	901	112	687	466	221	32%	0.71	0.57
	Yala	1260	870	763	390	497	-106	-27%	0.61	0.69
Average	Maha	1396	796	885	600	510	90	15%	0.63	0.57
	Yala	1127	603	669	524	458	66	13%	0.59	0.54

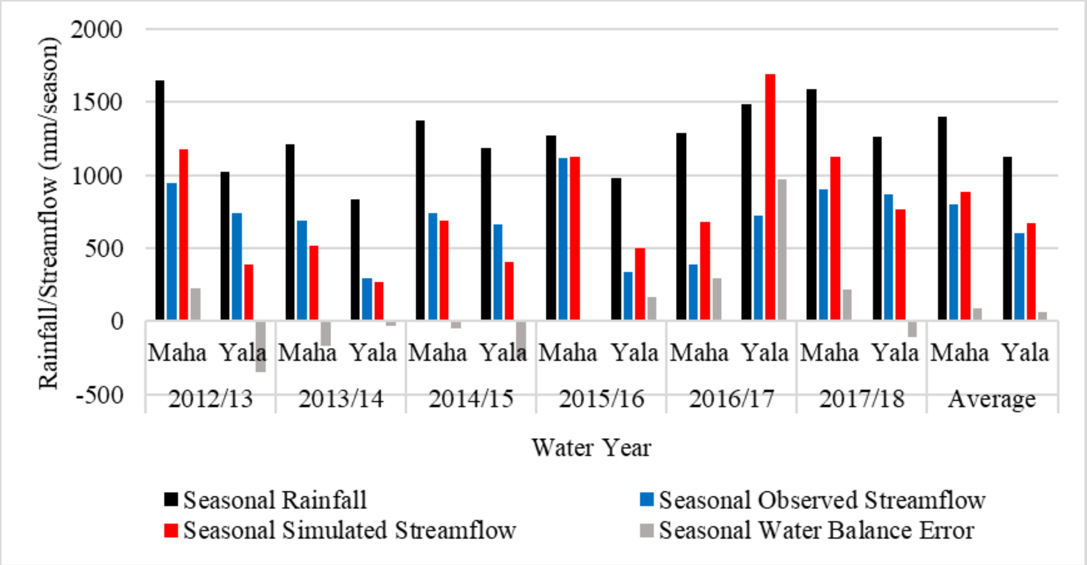

Figure F- 2 : Seasonal water balance for calibration period - Urawa watershed

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Table F- 3 : Seasonal water balance for verification period – Pitabaddara watershed

Water Year	Season	RF (mm /season)	Obs. SF (mm/ season)	Sim. SF (mm/ season)	SWB – Obs. SF (mm/season)	SWB – Sim. SF (mm/season)	SWBE	Percentage error	Sim. Runoff Coeff.	Obs. Runoff Coeff.
2014/ 15	Maha	1744	1077	1549	667	697	-30	-4%	0.89	0.62
	Yala	1703	1019	1047	684	656	27	4%	0.61	0.6
2015/ 16	Maha	1498	1228	1596	269	-99	368	137%	1.07	0.82
	Yala	1221	576	767	645	455	190	30%	0.63	0.47
2016/ 17	Maha	1190	512	667	678	523	155	23%	0.56	0.43
	Yala	1571	1135	1391	437	180	256	59%	0.89	0.72
2017/ 18	Maha	1716	1043	1555	673	161	512	76%	0.91	0.61
	Yala	1766	975	1472	791	294	497	63%	0.83	0.55
Average	Maha	1537	965	1342	572	195	377	66%	0.87	0.63
	Yala	1566	926	1169	639	396	243	38%	0.75	0.59

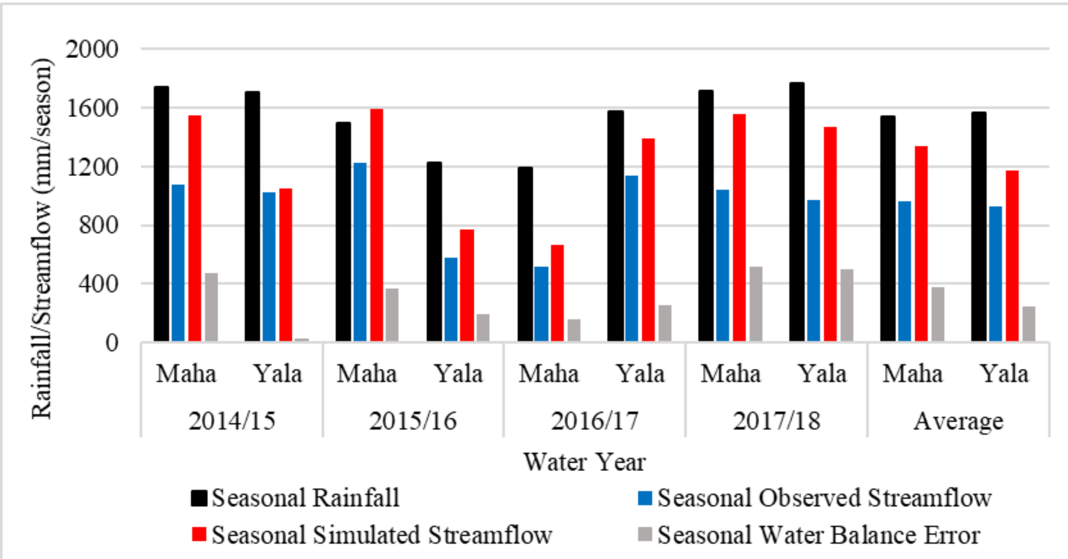

Figure F- 3: Seasonal water balance for verification period - Pitabaddara watershed

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Table F- 4: Seasonal water balance for verification period – Urawa watershed

Water Year	Season	RF (mm/season)	Obs. SF (mm/season)	Sim. SF (mm/season)	SWB – Obs. SF (mm/season)	SWB – Sim. SF (mm/season)	SWBE	Percentage error - %	Sim. Run off Coeff.	Obs. Run off Coeff.
2008/09	Maha	1666	956	859	710	808	-97	-14	0.5	0.5
	Yala	859	608	441	251	419	-168	-67	0.5	0.7
2009/10	Maha	771	567	243	203	528	-325	-160	0.3	0.7
	Yala	1289	714	383	575	906	-331	-58	0.3	0.5
2010/11	Maha	1782	1204	1302	578	480	98	17	0.7	0.6
	Yala	984	611	538	373	446	-73	-20	0.5	0.6
2011/12	Maha	1213	695	695	518	518	0	0	0.5	0.5
	Yala	884	368	284	516	600	-84	-16	0.3	0.4
Average	Maha	1358	856	775	502	583	-81	-16	0.5	0.6
	Yala	1004	575	411	429	593	-164	-38	0.4	0.5

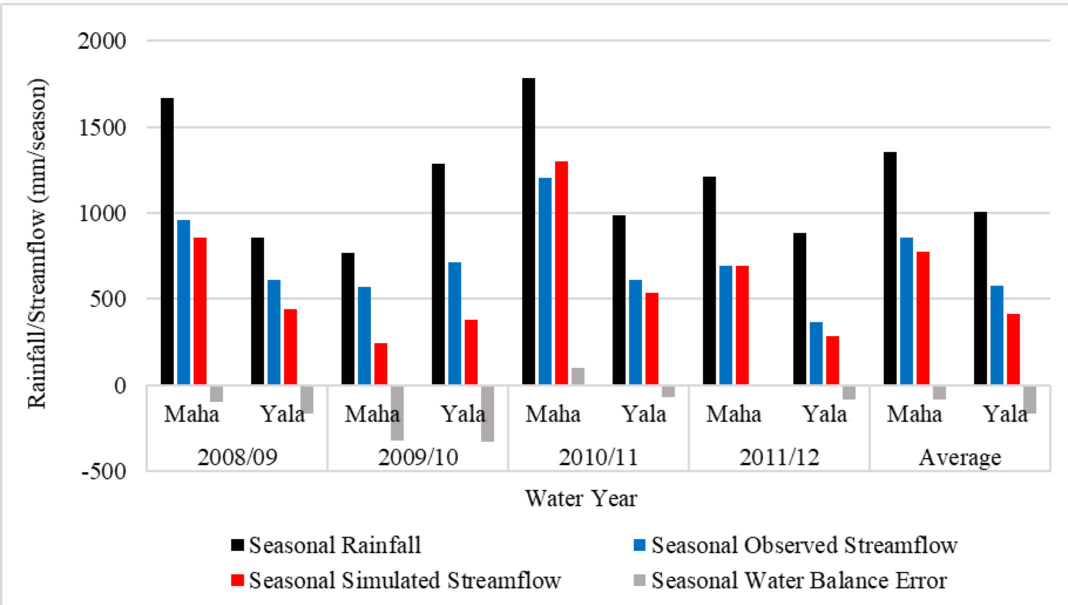

Figure F- 4: Seasonal water balance for verification period - Urawa watershed

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APPENDIX G : MODEL PARAMETER TRANSFORMATION (10 WATER YEARS STUDY PERIOD)

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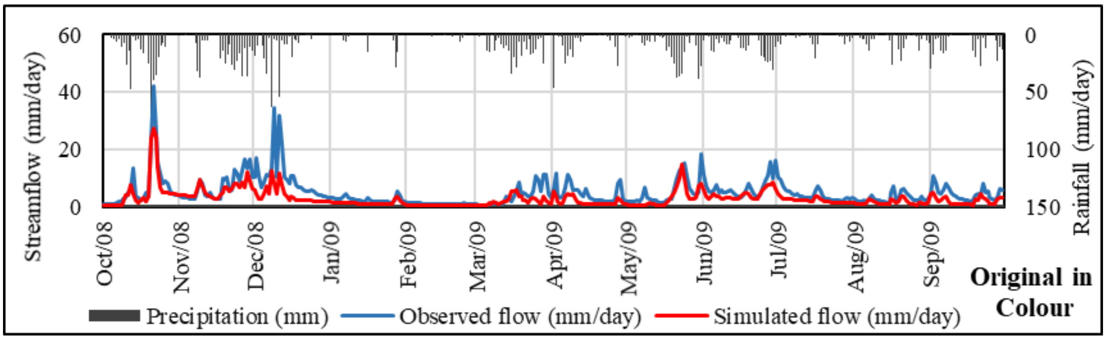
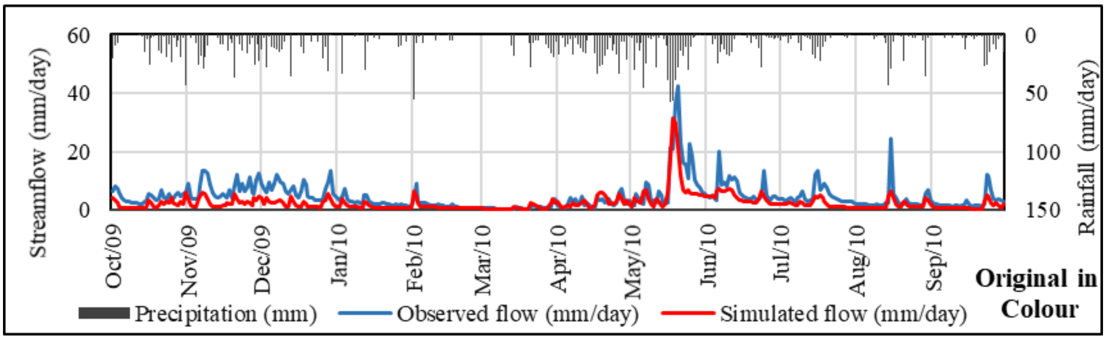
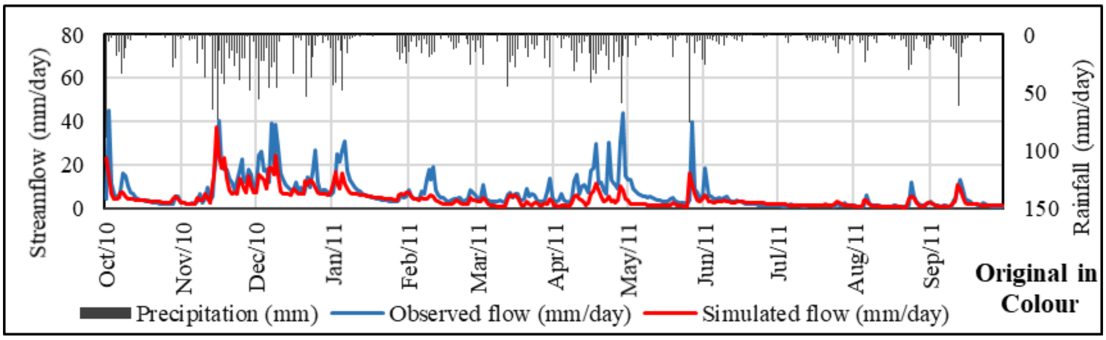


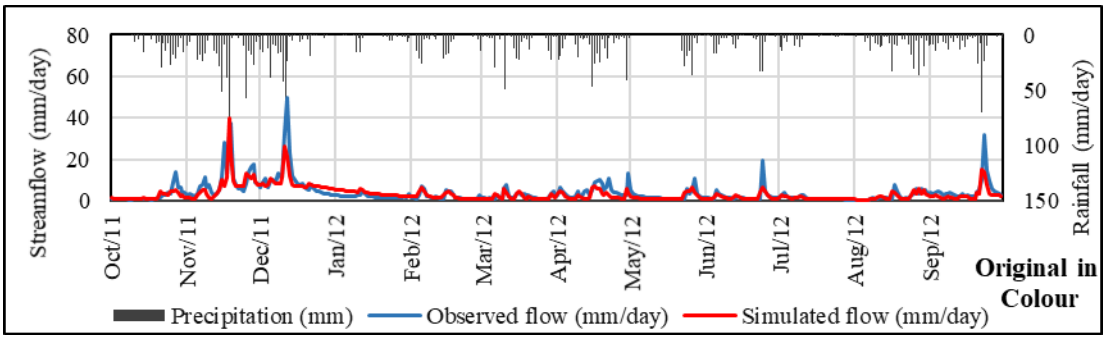
Streamflow (mm/day)
60
40
20
0
0
50
100
150
Rainfall (mm/day)
Oct/08
Nov/08
Dec/08
Jan/09
Feb/09
Mar/09
Apr/09
May/09
Jun/09
Jul/09
Aug/09
Sep/09
Precipitation (mm)
Observed flow (mm/day)
Simulated flow (mm/day)
Original in Colour



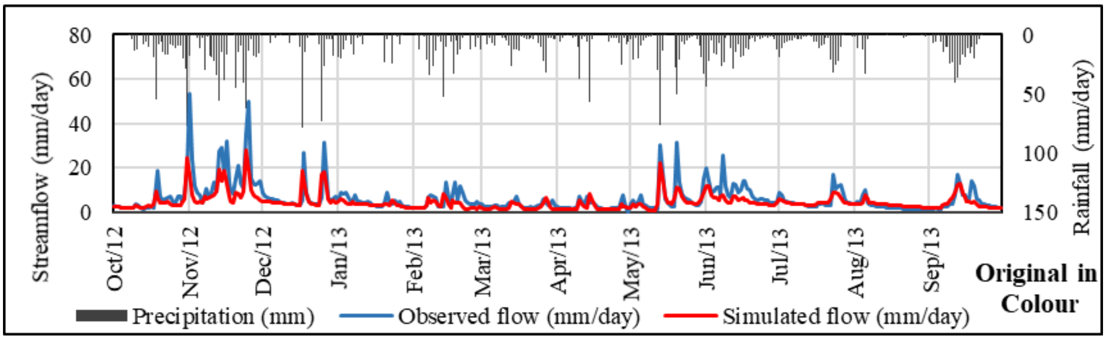
Streamflow (mm/day)
60
40
20
0
0
50
100
150
Rainfall (mm/day)
Oct/09
Nov/09
Dec/09
Jan/10
Feb/10
Mar/10
Apr/10
May/10
Jun/10
Jul/10
Aug/10
Sep/10
Precipitation (mm)
Observed flow (mm/day)
Simulated flow (mm/day)
Original in Colour

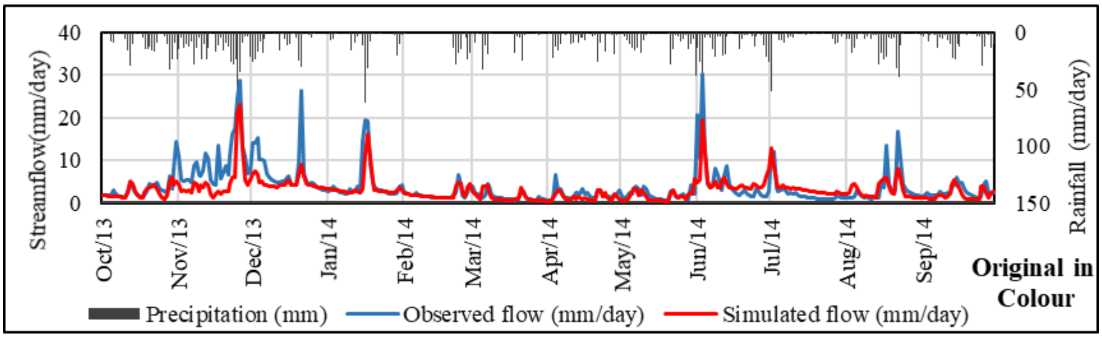


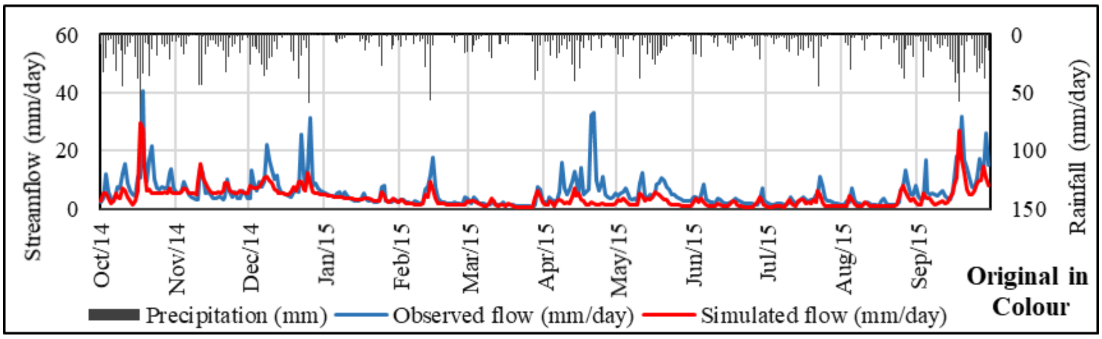
Streamflow (mm/day)
80
60
40
20
0
0
50
100
150
Rainfall (mm/day)
Oct/10
Nov/10
Dec/10
Jan/11
Feb/11
Mar/11
Apr/11
May/11
Jun/11
Jul/11
Aug/11
Sep/11
Precipitation (mm)
Observed flow (mm/day)
Simulated flow (mm/day)
Original in Colour

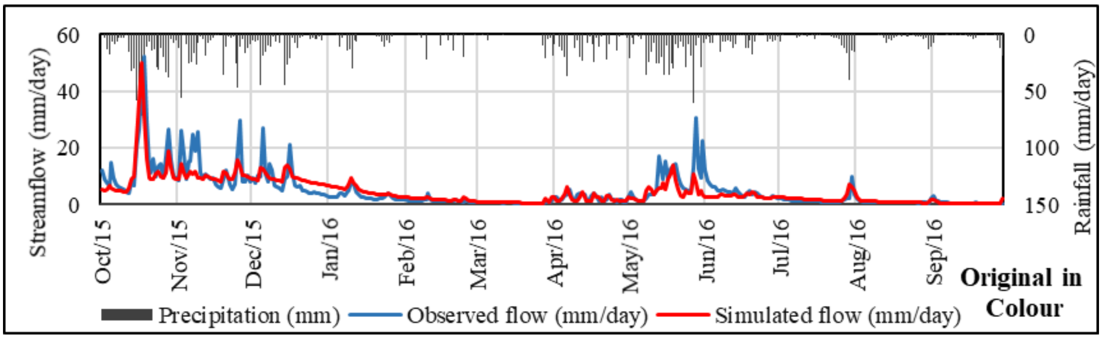


Streamflow (mm/day)
80
60
40
20
0
0
50
100
150
Rainfall (mm/day)
Oct/11
Nov/11
Dec/11
Jan/12
Feb/12
Mar/12
Apr/12
May/12
Jun/12
Jul/12
Aug/12
Sep/12
Precipitation (mm)
Observed flow (mm/day)
Simulated flow (mm/day)
Original in Colour


Streamflow (mm/day)
80
60
40
20
0
Rainfall (mm/day)
0
50
100
150
Oct/12
Nov/12
Dec/12
Jan/13
Feb/13
Mar/13
Apr/13
May/13
Jun/13
Jul/13
Aug/13
Sep/13
Precipitation (mm)
Observed flow (mm/day)
Simulated flow (mm/day)
Original in Colour


Streamflow(mm/day)
40
30
20
10
0
Rainfall (mm/day)
0
50
100
150
Oct/13
Nov/13
Dec/13
Jan/14
Feb/14
Mar/14
Apr/14
May/14
Jun/14
Jul/14
Aug/14
Sep/14
Precipitation (mm)
Observed flow (mm/day)
Simulated flow (mm/day)
Original in Colour


Streamflow (mm/day)
60
40
20
0
Rainfall (mm/day)
0
50
100
150
Oct/14
Nov/14
Dec/14
Jan/15
Feb/15
Mar/15
Apr/15
May/15
Jun/15
Jul/15
Aug/15
Sep/15
Precipitation (mm)
Observed flow (mm/day)
Simulated flow (mm/day)
Original in Colour


Streamflow (mm/day)
60
40
20
0
Rainfall (mm/day)
0
50
100
150
Oct/15
Nov/15
Dec/15
Jan/16
Feb/16
Mar/16
Apr/16
May/16
Jun/16
Jul/16
Aug/16
Sep/16
Precipitation (mm)
Observed flow (mm/day)
Simulated flow (mm/day)
Original in Colour

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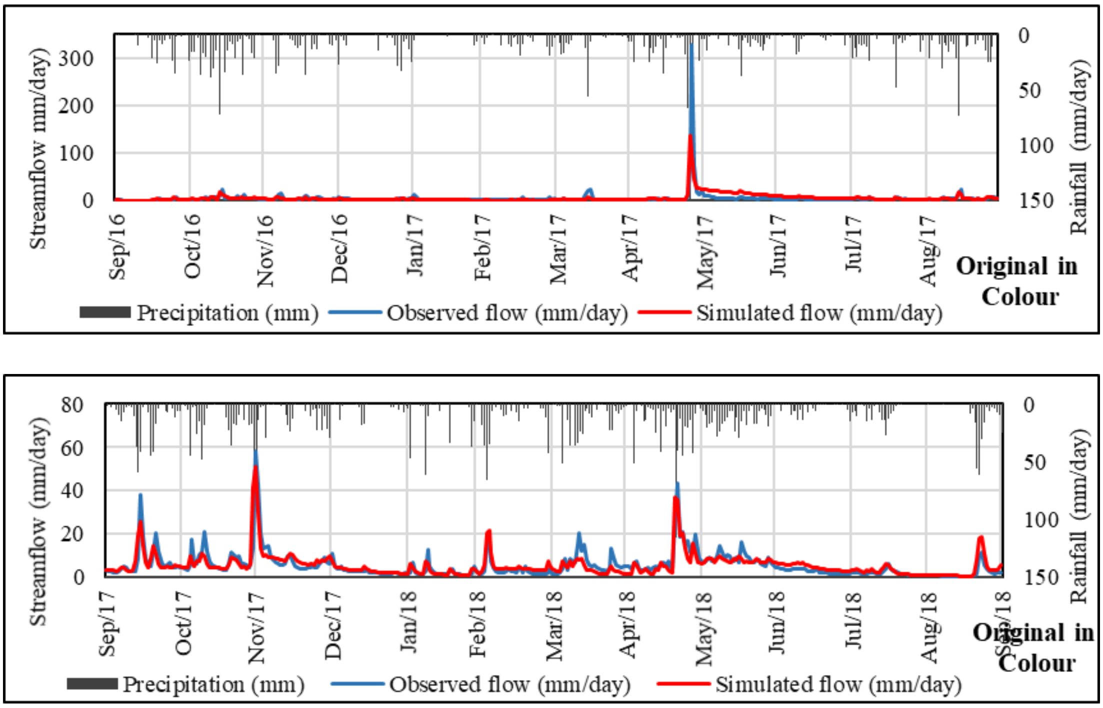
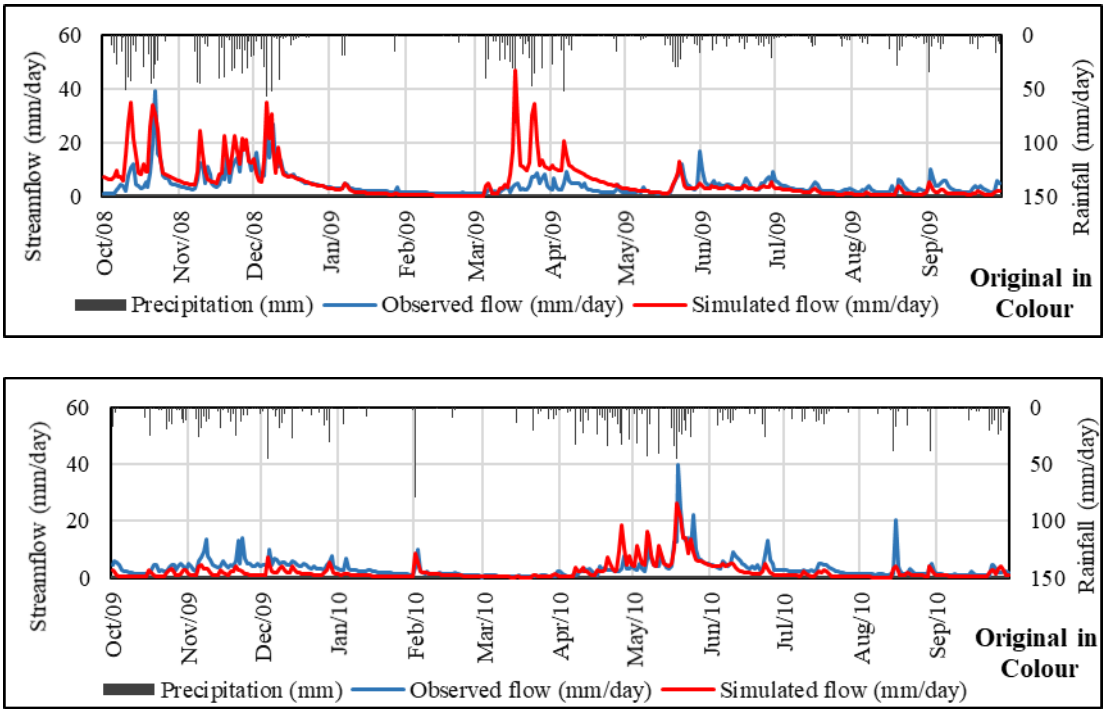


Figure G- 1: Parameter transformation to Pitabaddara – Hydrograph (Normal Plot)



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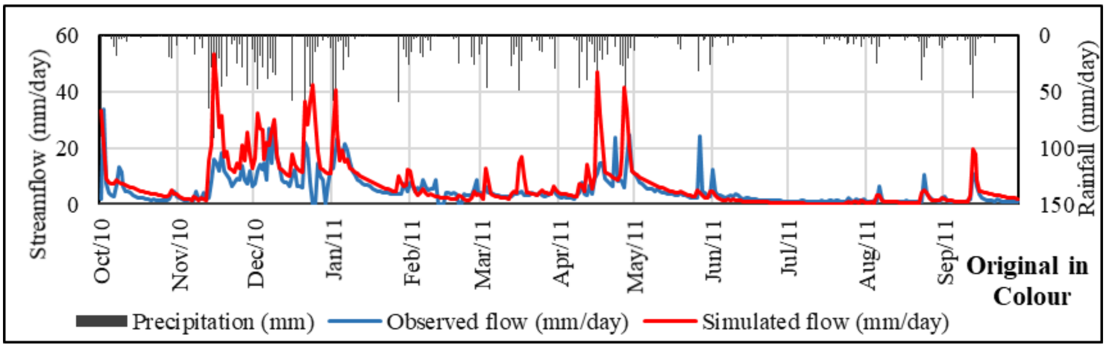
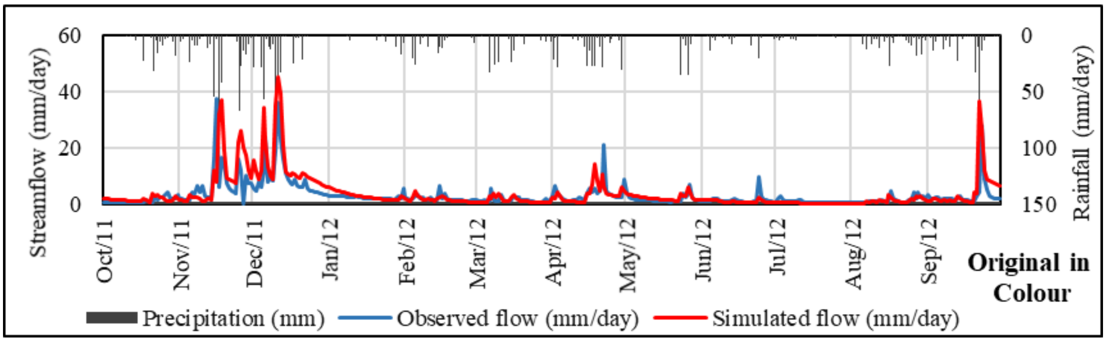
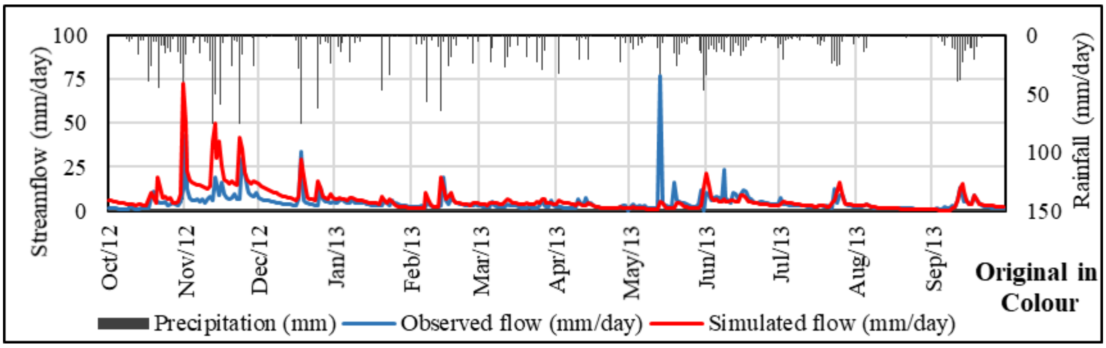
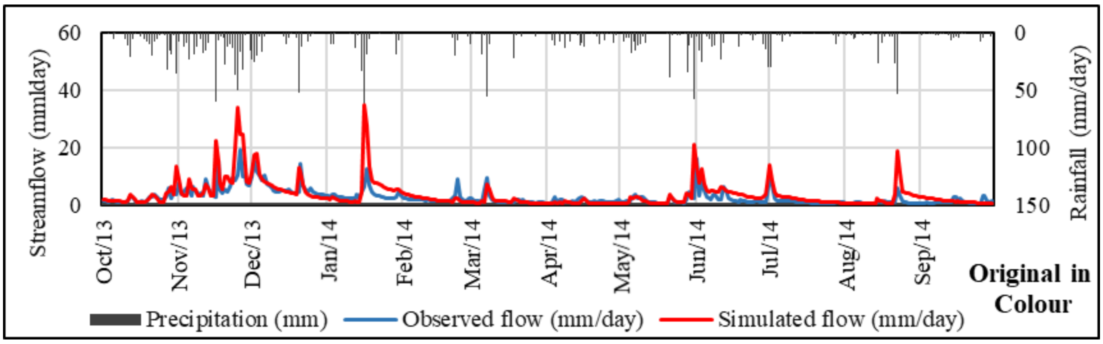

Streamflow (mm/day)
Rainfall (mm/day)
Oct/10 Nov/10 Dec/10 Jan/11 Feb/11 Mar/11 Apr/11 May/11 Jun/11 Jul/11 Aug/11 Sep/11
Original in Colour
Precipitation (mm)
Observed flow (mm/day)
Simulated flow (mm/day)


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


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


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

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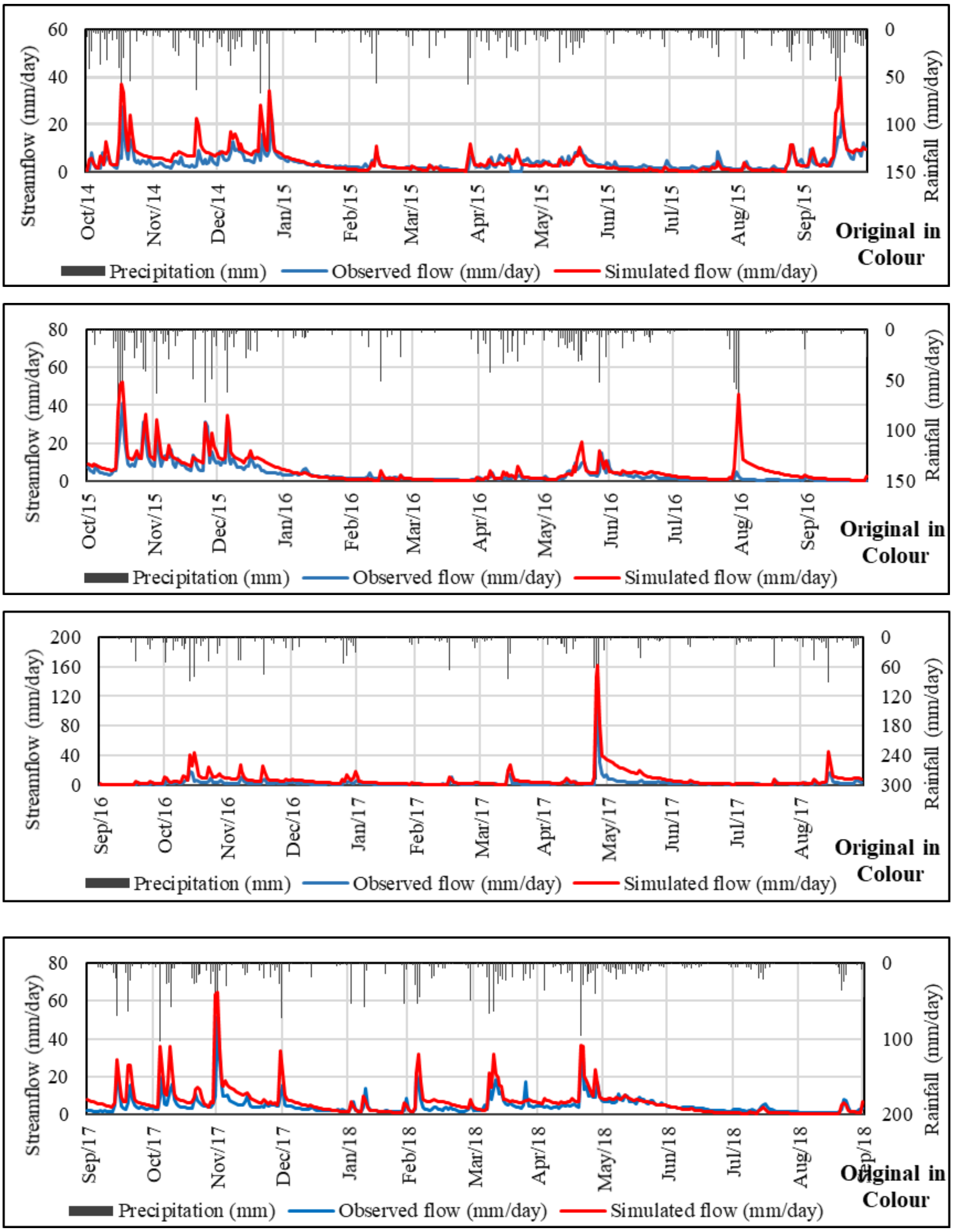

Figure G- 2:Parameter transformation to Urawa – Hydrograph (Normal Plot)

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APPENDIX H :PARAMETER TRANSFERABILITY SCHEMES FOR PITABADDARA CATCHMENT

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Temporal Parameter Transferability

Table H- 1: Numerical measures of unsorted FDC - Temporal Parameter Transferability for Urawa Catchment

Gauging Station	RMSE (mm/day)	MRAE	Annual Water Balance Error (%)	Flow Duration Curve - Unsorted					
				High		Medium		Low	
				RMSE (mm/day)	MRAE	RMSE (mm/day)	MRAE	RMSE (mm/day)	MRAE
Pitabeddara	7.79	0.604	32	23.92	0.445	4.33	0.624	0.63	0.58

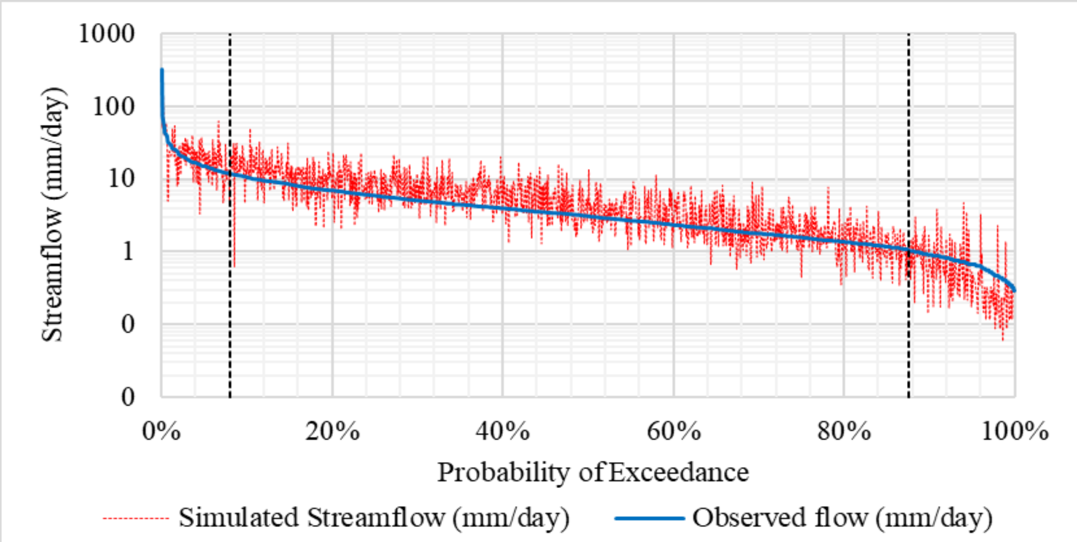

Figure H- 1: Unsorted FDC - Temporal Parameter Transferability for Pitabaddara catchment

Table H- 2 : Numerical measures of sorted FDC - Temporal Parameter Transferability for Pitabaddara Catchment

Gauging Station	RMSE (mm/day)	MRAE	Flow Duration Curve - Sorted					
			High		Medium		Low	
			RMSE (mm/day)	MRAE	RMSE (mm/day)	MRAE	RMSE (mm/day)	MRAE
Pitabeddara	5.6	0.332	18.53	0.404	2.206	0.311	0.274	0.42

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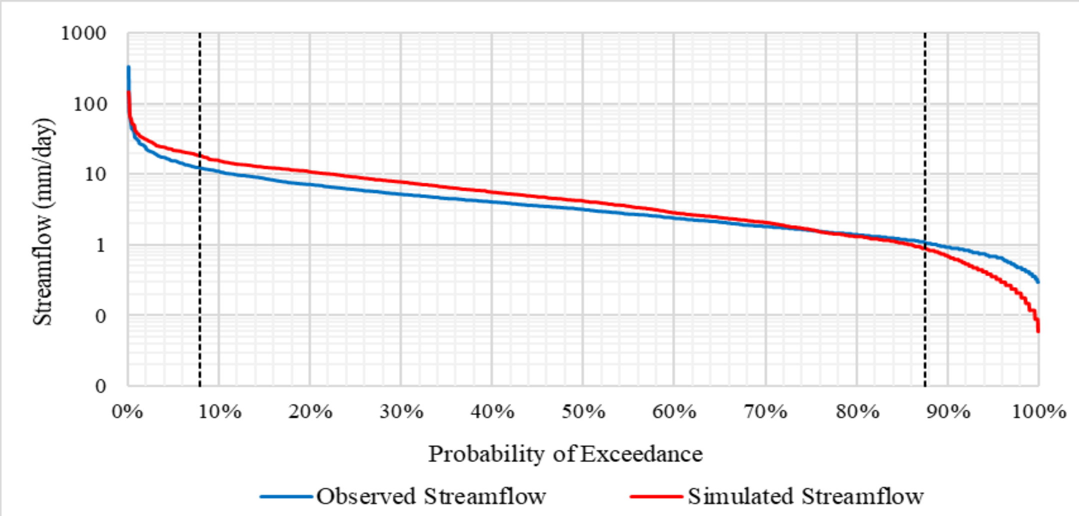
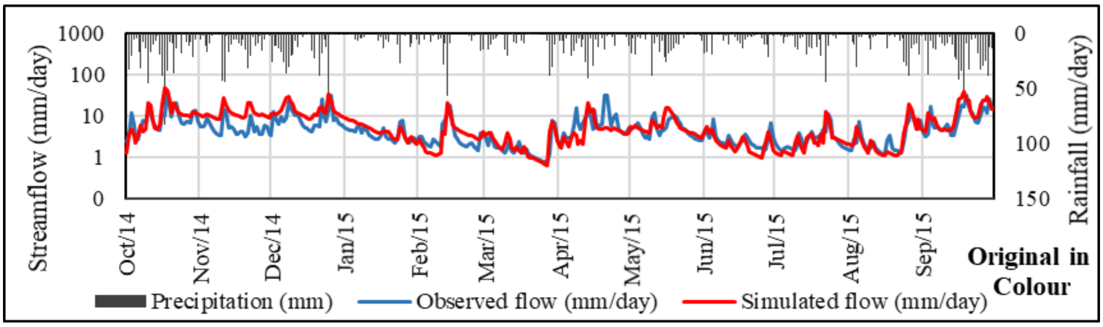


Figure H- 2: Sorted FDC - Temporal Parameter Transferability for Pitabaddara catchment

Table H- 3: Annual RMSE and MRAE value for Temporal parameter transferability - Pitabaddara Catchment

Water Year	2014/15	2015/16	2016/17	2017/18
RMSE (mm/day)	5.23	4.10	12.99	5.52
MRAE	0.49	0.58	0.69	0.65



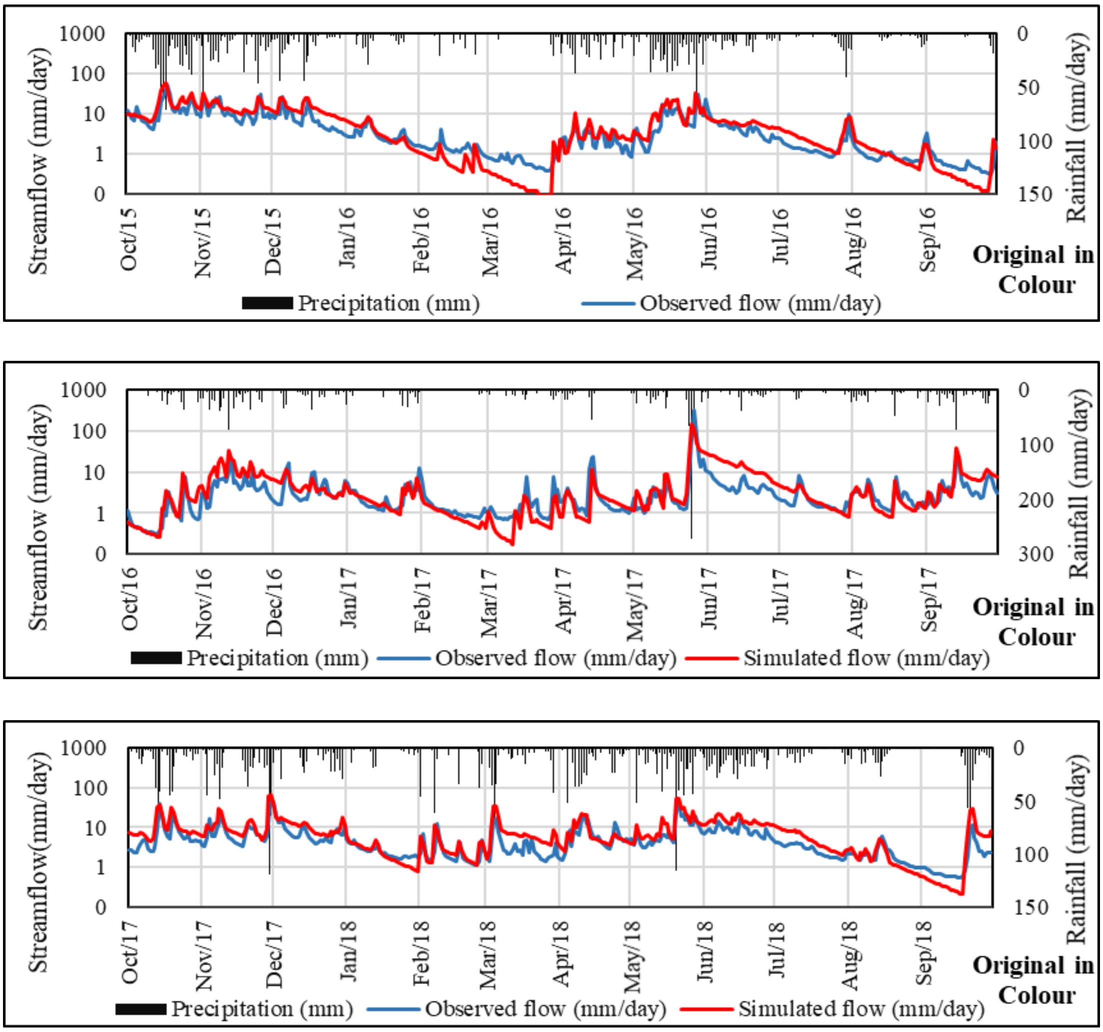


Figure H- 3:Flow Hydrograph Temporal parameter transferability - Pitabaddara Catchment

Table H- 4: Annual Water Balance for Temporal parameter transferability - Pitabaddara Catchment

Water Year	RF (mm/ year)	Sim. SF (mm/ year)	Obs. SF (mm/ year)	WB Sim. SF (mm/year)	WB Obs. SF (mm/year)	AW BE (mm/ year)	Percentage error	Sim. Runoff Coeff.	Obs. Runoff Coeff.
2014/15	3447	2596	2096	851	1351	500	24%	0.75	0.61
2015/16	2719	2361	1803	358	915	558	31%	0.87	0.66
2016/17	2762	2059	1647	703	1115	412	25%	0.75	0.60
2017/18	3483	3027	2018	456	1465	1009	50%	0.87	0.58
Average	3103	2511	1891	592	1211	620	33%	0.81	0.61

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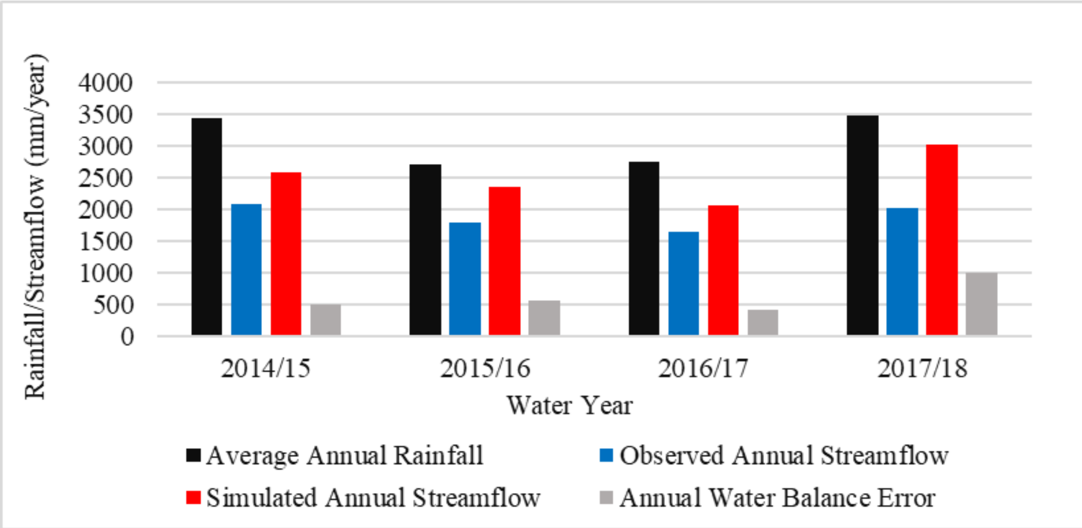

Figure H- 4: Annual Water Balance for Temporal parameter transferability - Pitabaddara Catchment

Spatial Parameter Transferability

Table H- 5: Numerical measures of unsorted FDC - Spatial Parameter Transferability for Pitabaddara Catchment

Gauging Station	RMSE (mm/day)	MRAE	Annual Water Balance Error (%)	Flow Duration Curve - Unsorted					
				High		Medium		Low	
				RMSE (mm/day)	MRAE	RMSE (mm/day)	MRAE	RMSE (mm/day)	MRAE
Pitabeddara	3.973	0.419	-13	11.65	0.468	2.452	0.412	0.63	0.42

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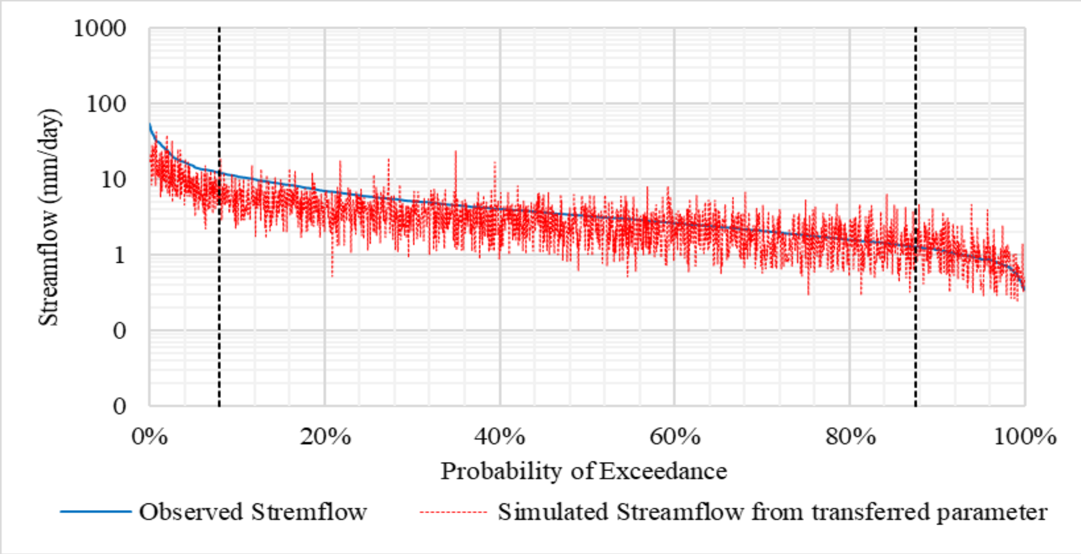

Figure H- 5: Unsorted FDC - Spatial Parameter Transferability for Pitabaddara catchment

Table H- 6: Numerical measures of sorted FDC - Spatial Parameter Transferability for Pitabaddara Catchment

Gauging Station	RMSE (mm/day)	MRAE	Flow Duration Curve - Sorted					
			High		Medium		Low	
			RMSE (mm/day)	MRAE	RMSE (mm/day)	MRAE	RMSE (mm/day)	MRAE
Pitabeddara	2.732	0.291	8.155	0.385	1.623	0.280	0.293	0.303

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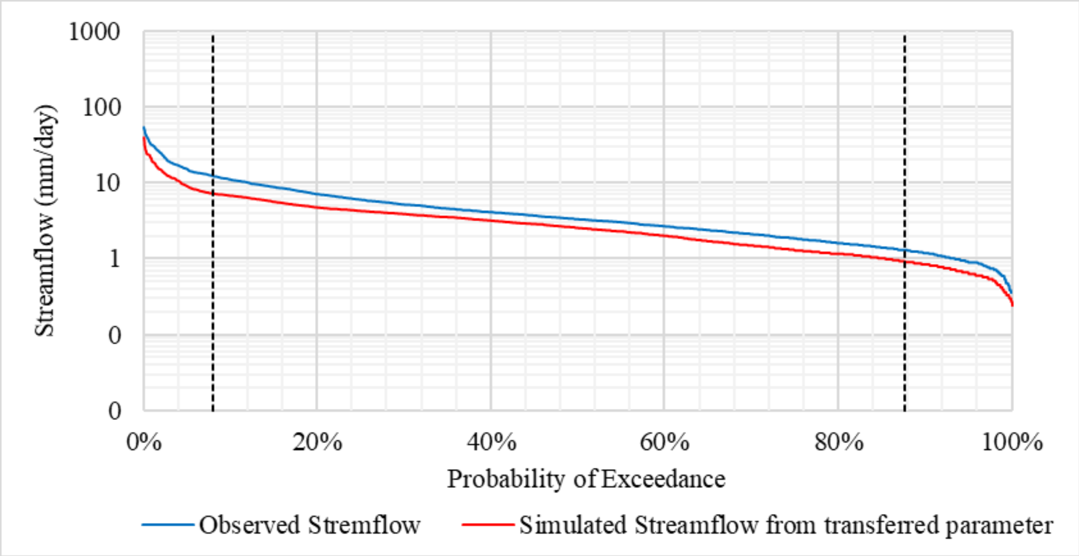
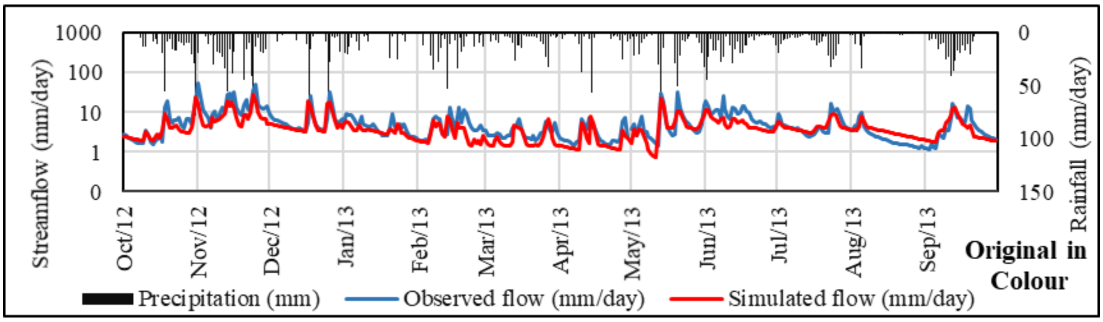


Figure H- 6: Sorted FDC - Spatial Parameter Transferability for Pitabaddara catchment

Table H- 7: Annual RMSE and MRAE value for Spatial parameter transferability - Pitabaddara Catchment

Water Year	2012/13	2013/14	2014/15	2015/16	2016/17	2017/18
RMSE	4.503	2.695	4.476	3.548	13.114	3.261
MRAE	0.337	0.398	0.396	0.375	0.779	0.391



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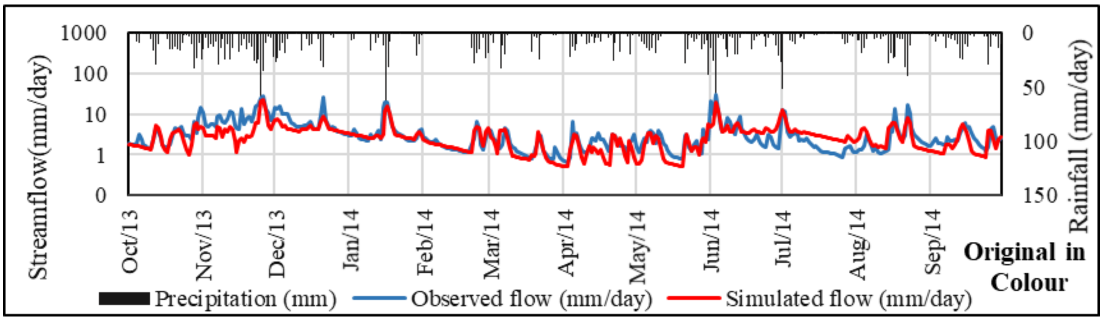
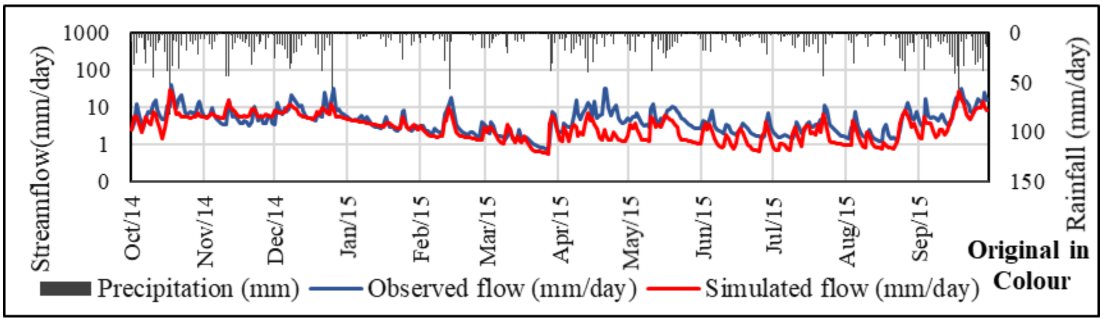
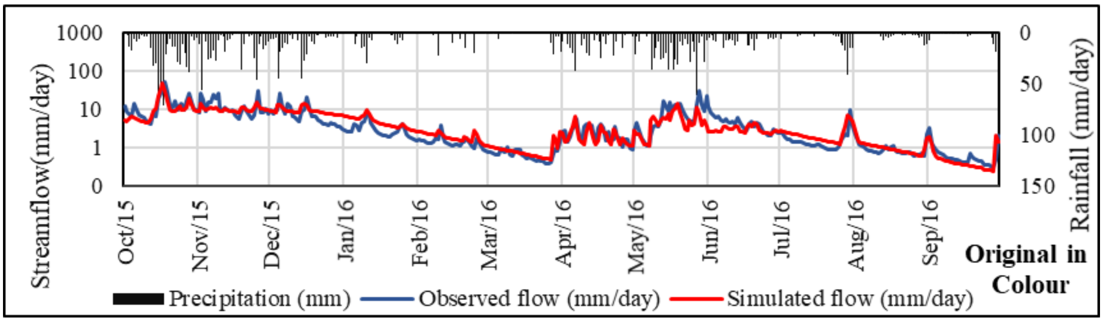


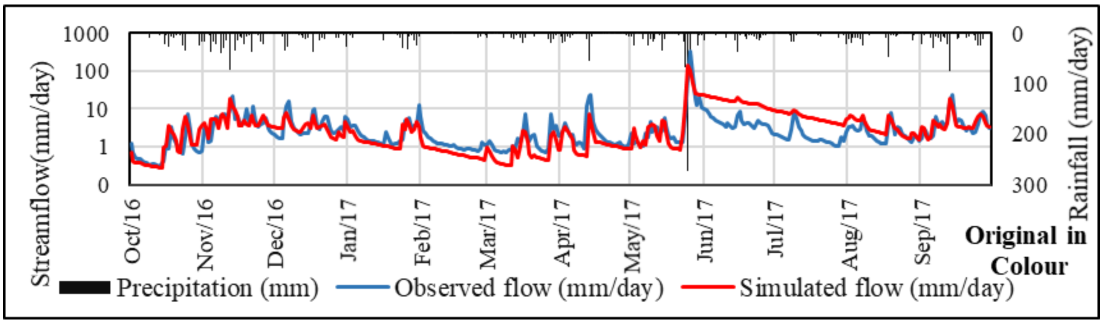
Streamflow(mm/day)
1000
100
10
1
0
Rainfall (mm/day)
0
50
100
150
Oct/13
Nov/13
Dec/13
Jan/14
Feb/14
Mar/14
Apr/14
May/14
Jun/14
Jul/14
Aug/14
Sep/14
Precipitation (mm)
Observed flow (mm/day)
Simulated flow (mm/day)
Original in Colour



Streamflow(mm/day)
1000
100
10
1
0
Rainfall (mm/day)
0
50
100
150
Oct/14
Nov/14
Dec/14
Jan/15
Feb/15
Mar/15
Apr/15
May/15
Jun/15
Jul/15
Aug/15
Sep/15
Precipitation (mm)
Observed flow (mm/day)
Simulated flow (mm/day)
Original in Colour



Streamflow(mm/day)
1000
100
10
1
0
Rainfall (mm/day)
0
50
100
150
Oct/15
Nov/15
Dec/15
Jan/16
Feb/16
Mar/16
Apr/16
May/16
Jun/16
Jul/16
Aug/16
Sep/16
Precipitation (mm)
Observed flow (mm/day)
Simulated flow (mm/day)
Original in Colour



Streamflow(mm/day)
1000
100
10
1
0
Rainfall (mm/day)
0
100
200
300
Oct/16
Nov/16
Dec/16
Jan/17
Feb/17
Mar/17
Apr/17
May/17
Jun/17
Jul/17
Aug/17
Sep/17
Precipitation (mm)
Observed flow (mm/day)
Simulated flow (mm/day)
Original in Colour

`

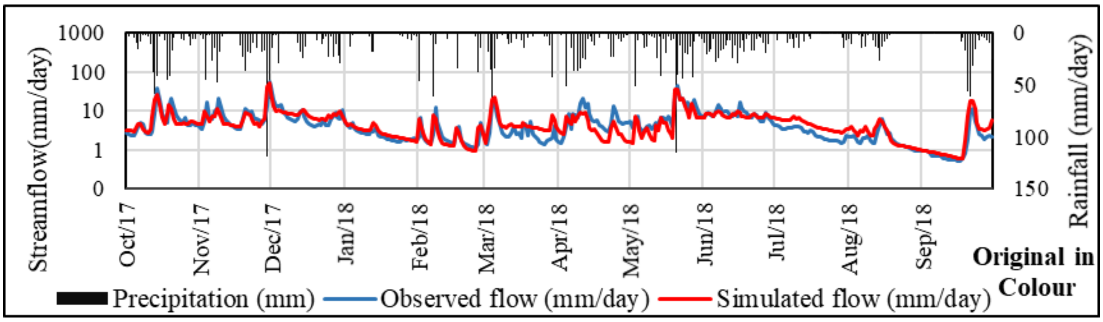


Figure H- 7:Flow Hydrograph Spatial parameter transferability - Pitabaddara Catchment

Table H- 8: Annual Water Balance for Spatial parameter transferability - Pitabaddara Catchment

Water Year	RF (mm/ year)	Sim. SF (mm/ year)	Obs. SF (mm/ year)	WB Sim. SF (mm/year)	WB Obs. SF (mm/year)	AW BE (mm/ year)	Percent age error	Sim. Runo ff Coeff	Obs. Runo ff Coeff
2012/13	3352	1634	2266	1718	1086	-632	-28%	0.49	0.68
2013/14	2777	1130	1422	1647	1355	-292	-21%	0.41	0.51
2014/15	3447	1402	2096	2054	1359	-694	-33%	0.41	0.61
2015/16	2719	1645	1803	1074	915	-159	-9%	0.60	0.66
2016/17	2762	1829	1647	933	1115	182	11%	0.66	0.60
2017/18	3483	2012	2018	1470	1465	-6	0%	0.58	0.58
Average	3090	1609	1875	1483	1216	-267	-13%	0.52	0.61

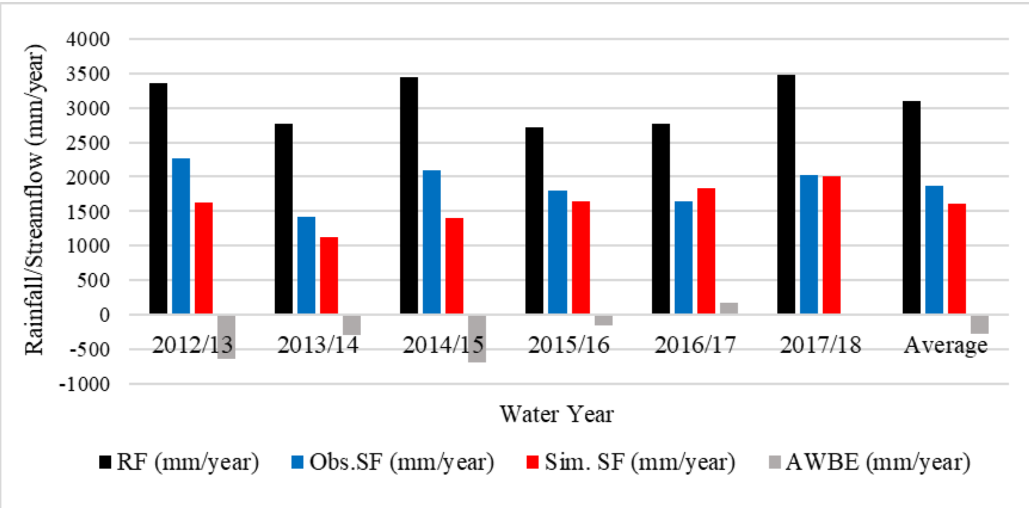


Figure H- 8: Annual Water Balance for Spatial parameter transferability - Pitabaddara Catchment

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<u>Spatiotemporal Parameter Transferability</u>

Table H- 9: Numerical measures of unsorted FDC - Spatiotemporal Parameter Transferability for Pitabaddara Catchment

Gauging Station	RMSE (mm/day)	MRAE	Annual Water Balance Error (%)	Flow Duration Curve - Unsorted					
				High		Medium		Low	
				RMSE (mm/day)	MRAE	RMSE (mm/day)	MRAE	RMSE (mm/day)	MRAE
Pitabeddara	4.097	0.444	-35	11.89	0.477	2.599	0.488	0.57	0.39

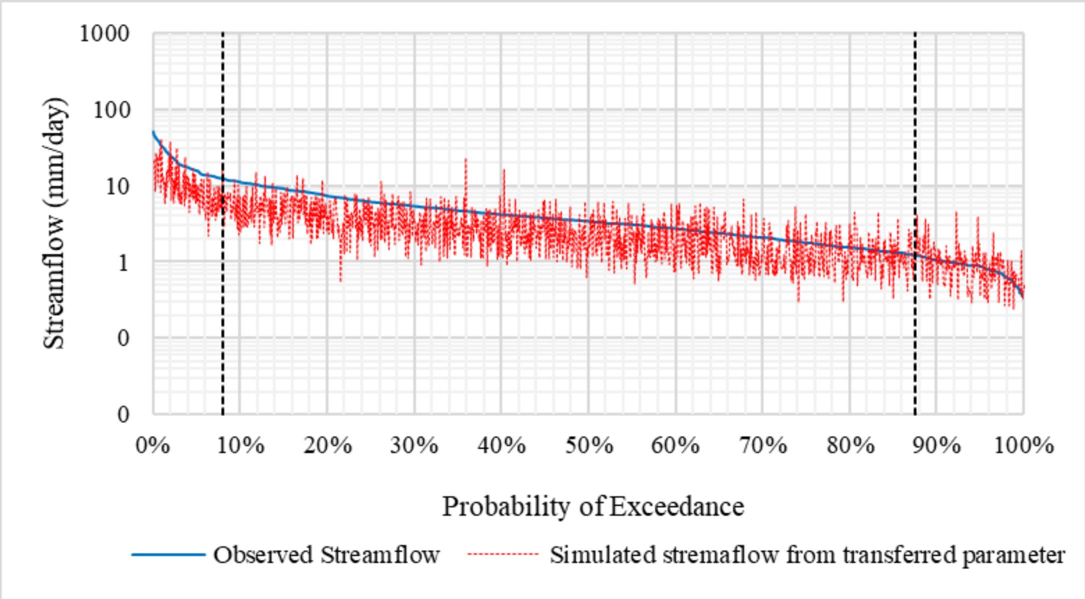

Figure H- 9: Unsorted FDC – Spatiotemporal Parameter Transferability for Pitabaddara catchment

Table H- 10: Numerical measures of sorted FDC - Spatiotemporal Parameter Transferability for Pitabaddara Catchment

Gauging Station	RMSE (mm/day)	MRAE	Flow Duration Curve - Sorted					
			High		Medium		Low	
			RMSE (mm/day)	MRAE	RMSE (mm/day)	MRAE	RMSE (mm/day)	MRAE
Pitabeddara	2.807	0.349	8.150	0.386	1.783	0.352	0.262	0.300

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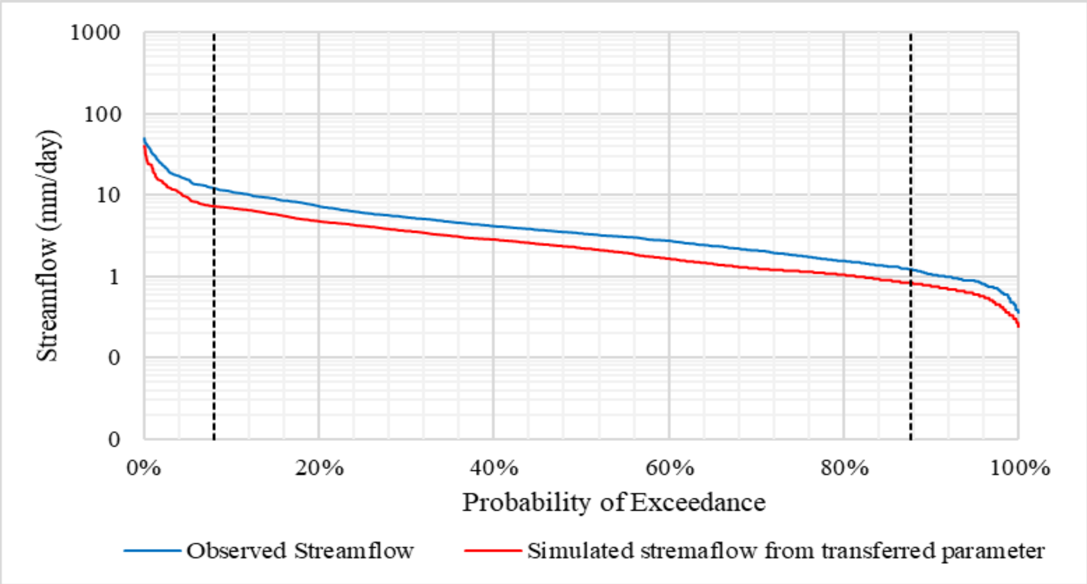
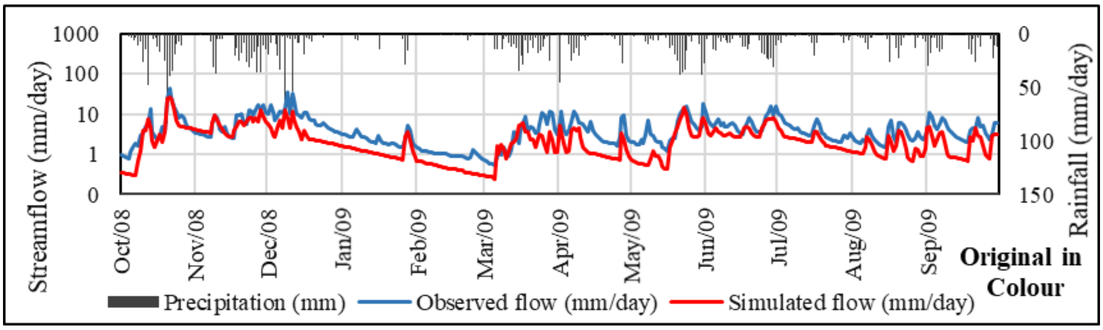
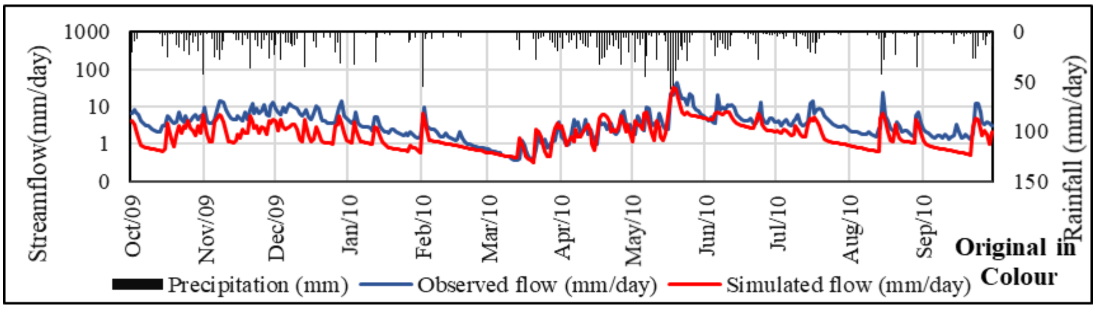


Figure H- 10: Sorted FDC – Spatiotemporal Parameter Transferability for Pitabaddara catchment

Table H- 11: Annual RMSE and MRAE value for Spatiotemporal parameter transferability - Pitabaddara Catchment

Water Year	2008/09	2009/10	2010/11	2011/12
RMSE	3.566	3.664	5.614	3.075
MRAE	0.480	0.508	0.389	0.397





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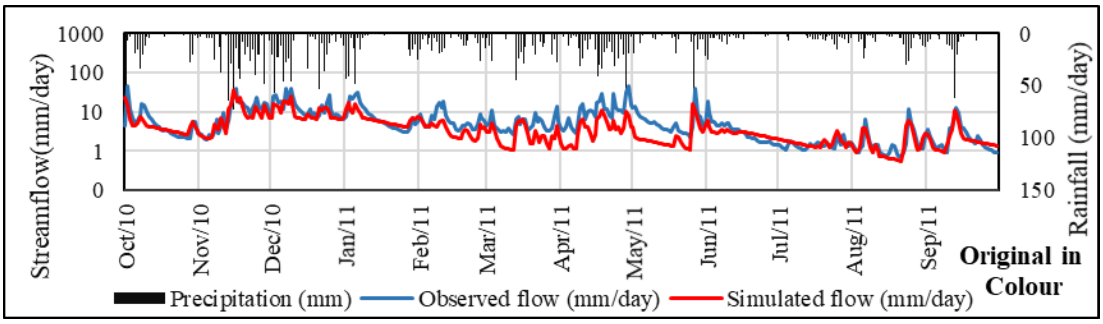

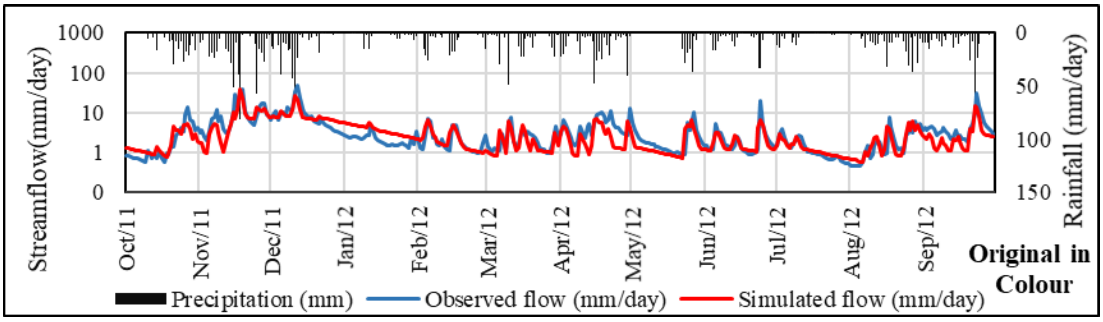

Figure H- 11: Flow Hydrograph Spatiotemporal parameter transferability - Pitabaddara Catchment

Table H- 12: Annual Water Balance for Spatiotemporal parameter transferability - Pitabaddara Catchment

Water Year	RF (mm/ year)	Sim. SF (mm/ year)	Obs. SF (mm/ year)	WB Sim. SF (mm/year)	WB Obs. SF(mm /year)	AWBE (mm/ year)	Percentage error	Sim. Runoff Coef.	Obs. Runoff Coef.
2008/09	2750	1028	1819	1722	931	-791	-43%	0.37	0.66
2009/10	2654	917	1706	1737	948	-789	-46%	0.35	0.64
2010/11	3367	1671	2536	1696	831	-865	-34%	0.50	0.75
2011/12	2692	1212	1461	1480	1231	-249	-17%	0.45	0.54
Average	2866	1207	1880	1659	985	-673	-35%	0.42	0.65

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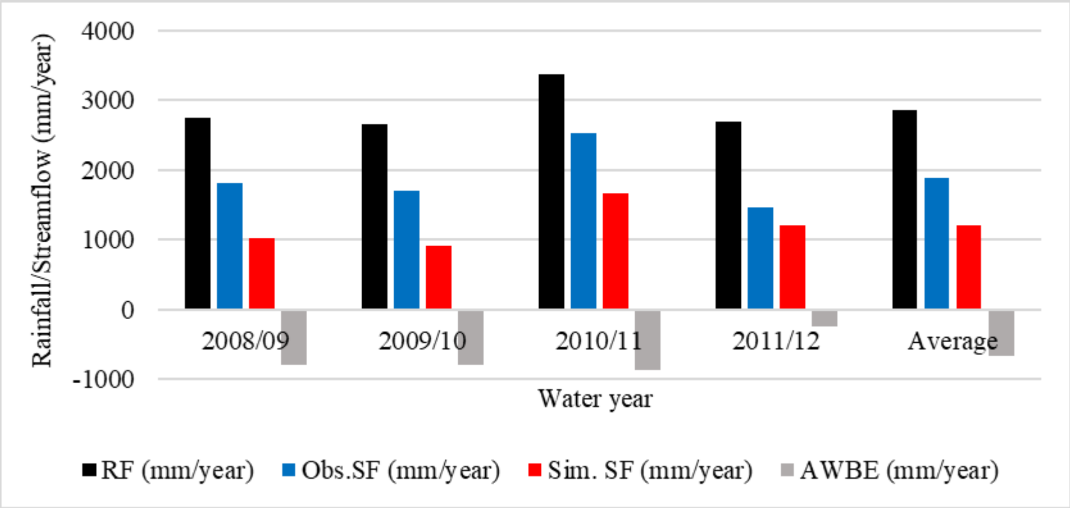

Figure H- 12: Annual Water Balance for Spatiotemporal parameter transferability - Pitabaddara Catchment

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APPENDIX I :PARAMETER TRANSFERABILITY SCHEMES FOR URAWA CATCHMENT

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Temporal Parameter Transferability

Table I- 1: Numerical measures of unsorted FDC - Temporal Parameter Transferability for Urawa Catchment

Gauging Station	RMSE (mm/day)	MRAE	Annual Water Balance Error (%)	Flow Duration Curve - Unsorted					
				High		Medium		Low	
				RMSE (mm/day)	MRAE	RMSE (mm/day)	MRAE	RMSE (mm/day)	MRAE
Urawa	3.25	0.523	-17	9.3	0.449	2.62	0.522	0.70	0.562

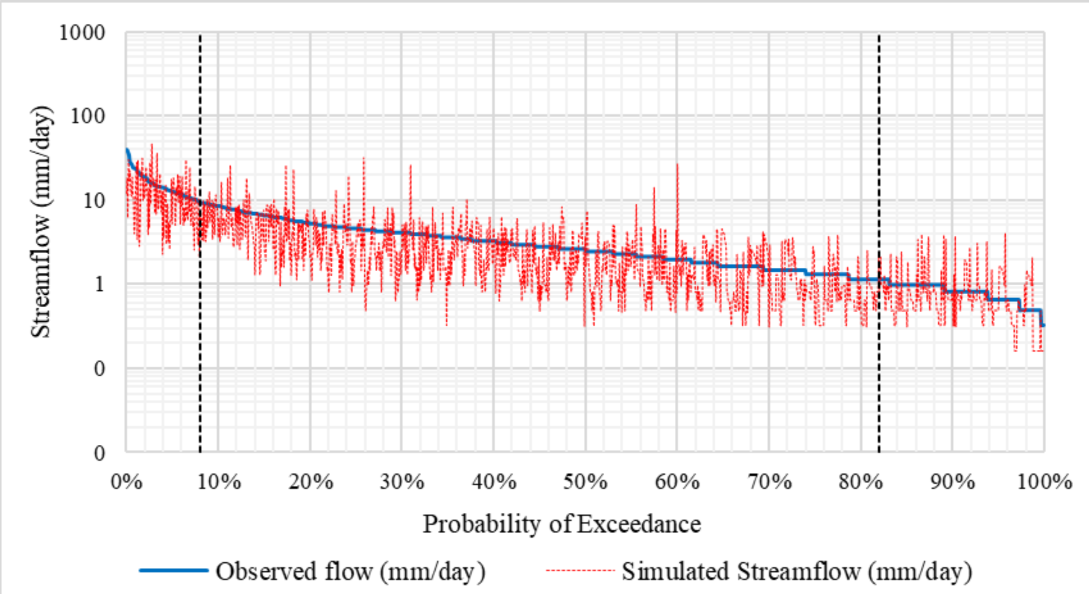

Figure I- 1: Unsorted FDC - Temporal Parameter Transferability for Pitabaddara catchment

Table I- 2: Numerical measures of sorted FDC - Temporal Parameter Transferability for Urawa Catchment

Gauging Station	RMSE (mm/day)	MRAE	Flow Duration Curve - Sorted					
			High		Medium		Low	
			RMSE (mm/day)	MRAE	RMSE (mm/day)	MRAE	RMSE (mm/day)	MRAE
Urawa	0.782	0.278	1.758	0.107	0.741	0.264	0.333	0.412

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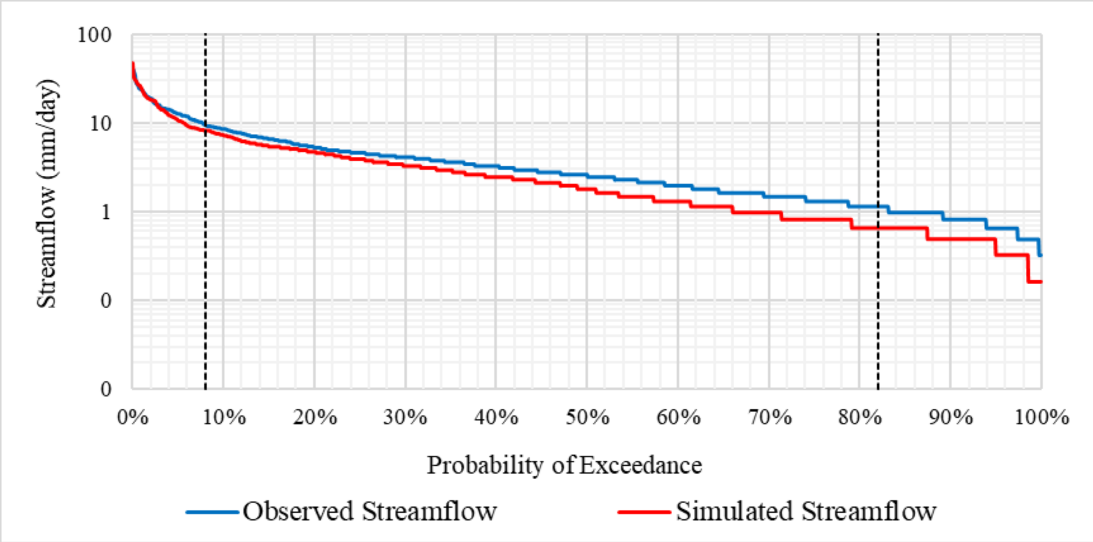
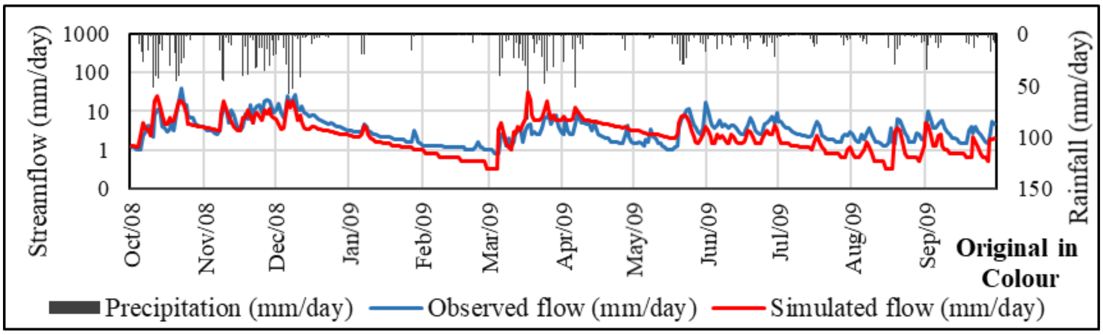
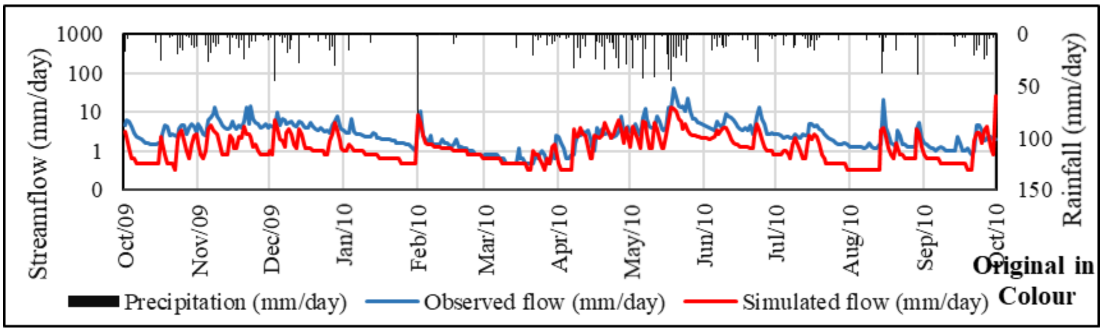


Figure I- 2: Sorted FDC - Temporal Parameter Transferability for Urawa catchment

Table I- 3: Annual RMSE and MRAE value for Temporal parameter transferability – Urawa Catchment

Water Year	2008/09	2009/10	2010/11	2011/12
RMSE	3.55	3.30	4.25	2.99
MRAE	0.58	0.55	0.44	0.50





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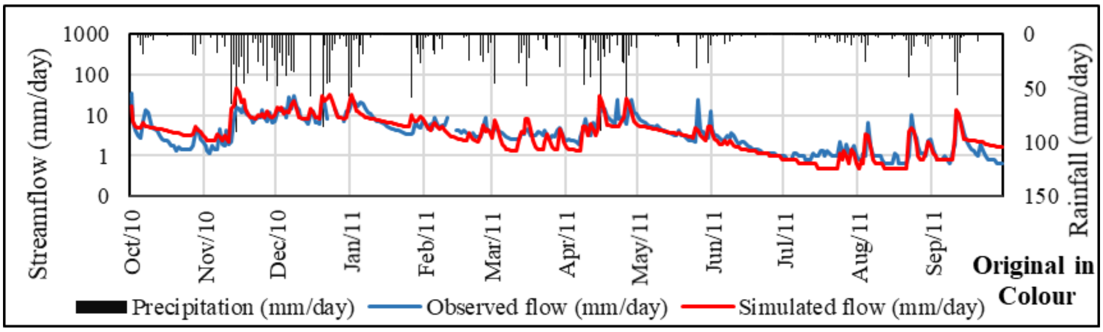

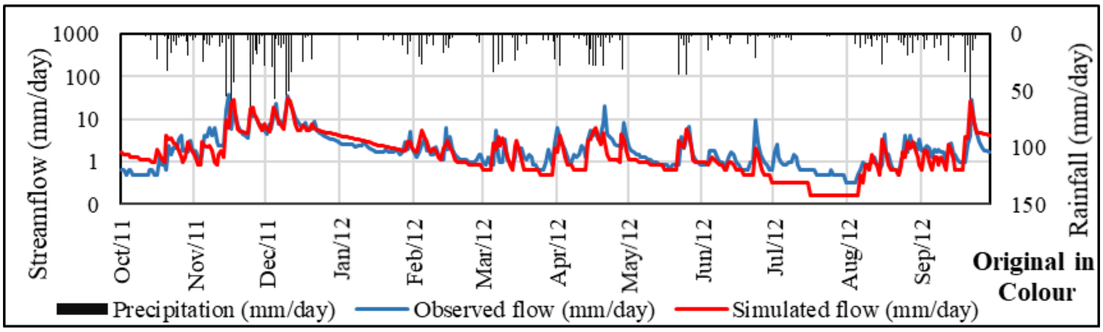

Figure I- 3: Flow Hydrograph Temporal parameter transferability - Urawa Catchment

Table I- 4: Annual Water Balance for Temporal parameter transferability – Urawa Catchment

Water Year	RF (mm/ year)	Sim. SF (mm/ year)	Obs. SF (mm/ year)	WB Sim. SF (mm/year)	WB Obs. SF(mm /year)	AWBE (mm/year)	Percentage error	Sim. Runoff Coef.	Obs. Runoff Coef.
2008/09	2525.	1299.	1564.	1226.2	961.5	-264.8	-17	0.51	0.62
2009/10	2059.	624.8	1279	1434.3	780.1	-654.2	-51	0.30	0.62
2010/11	2766.	1840.	1815.	925.9	951	25.1	1	0.67	0.66
2011/12	2097.	979.3	1063.	1117.8	1033.3	-84.5	-8	0.47	0.51
Average	2362	1185.	1430.	1176	931.5	-244.6	-17	0.50	0.61

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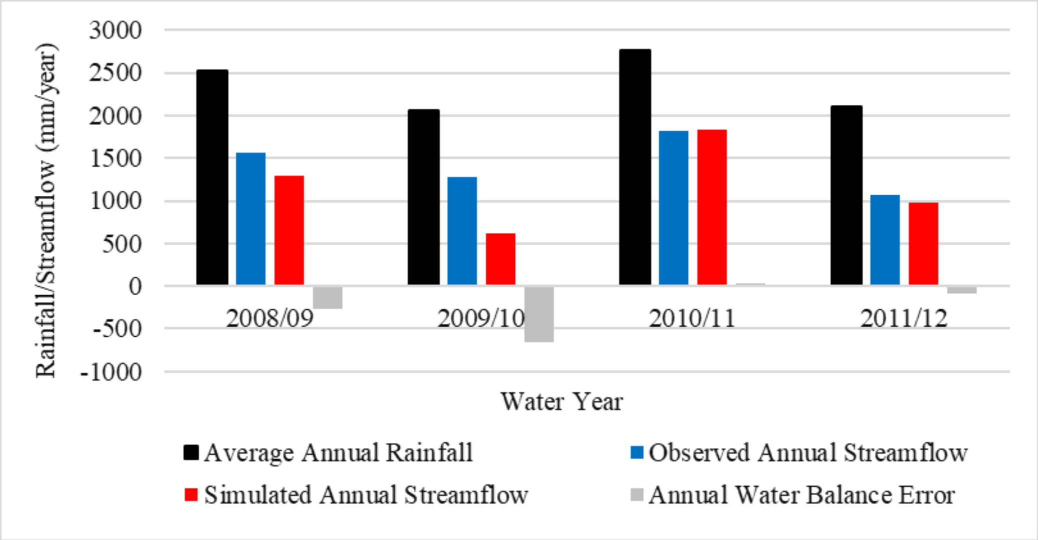

Figure I- 4: Annual Water Balance for Temporal parameter transferability – Urawa Catchment

Spatial Parameter Transferability

Table I- 5: Numerical measures of unsorted FDC - Spatial Parameter Transferability for Urawa Catchment

Gauging Station	RMSE (mm/day)	MRAE	Annual Water Balance Error (%)	Flow Duration Curve - Unsorted					
				High		Medium		Low	
				RMSE (mm/day)	MRAE	RMSE (mm/day)	MRAE	RMSE (mm/day)	MRAE
Urawa	5.003	0.682	53	12.42	0.55	4.09	0.65	1.07	0.83

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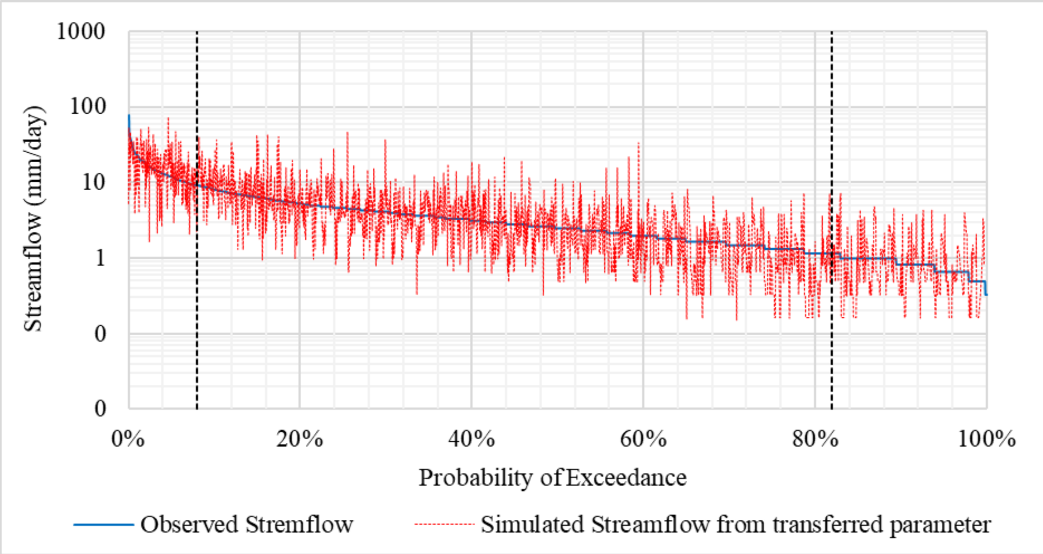

Figure I- 5: Unsorted FDC - Spatial Parameter Transferability for Urawa catchment

Table I- 6: Numerical measures of sorted FDC - Spatial Parameter Transferability for Urawa Catchment

Gauging Station	RMSE (mm/day)	MRAE	Flow Duration Curve - Sorted					
			High		Medium		Low	
			RMSE (mm/day)	MRAE	RMSE (mm/day)	MRAE	RMSE (mm/day)	MRAE
Urawa	1.797	0.073	6.203	0.252	0.433	0.051	0.077	0.086

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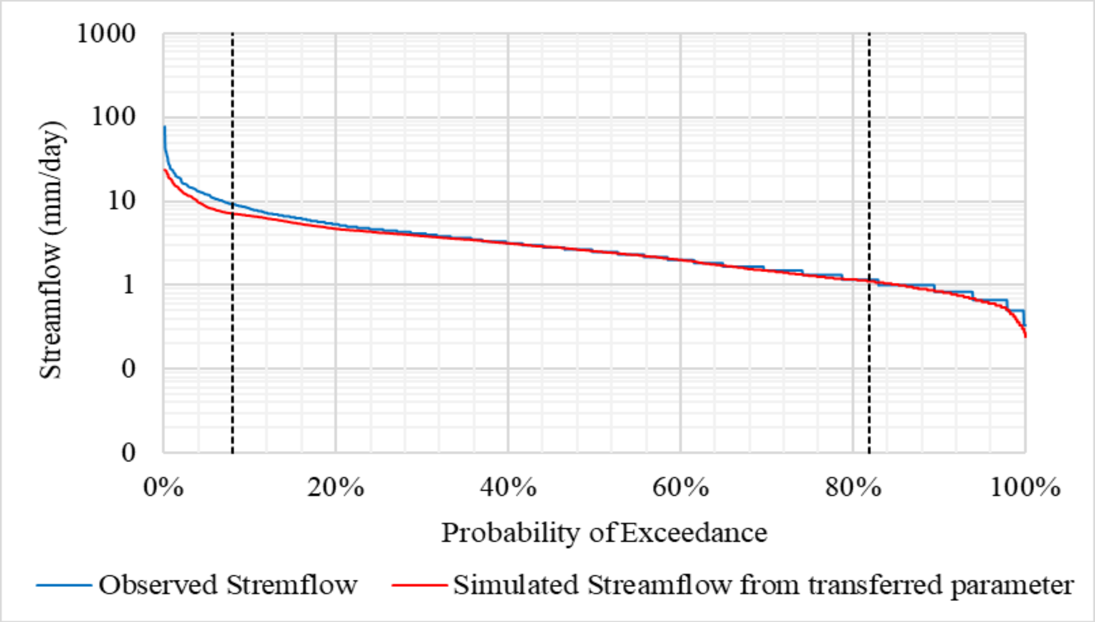
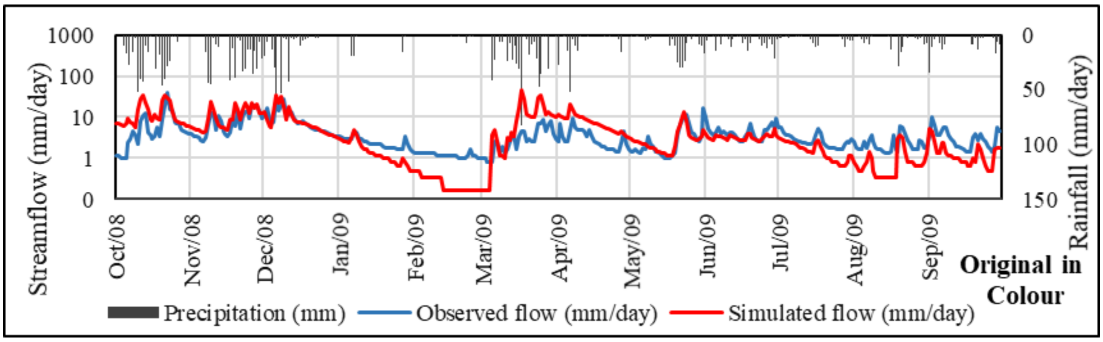


Figure I- 6: Sorted FDC - Spatial Parameter Transferability for Urawa catchment

Table I- 7: Annual RMSE and MRAE value for Spatial parameter transferability - Urawa Catchment

Water Year	2008/09	2009/10	2010/11	2011/12	2012/13	2013/14
RMSE	5.14	2.95	6.09	4.02	7.07	3.31
MRAE	0.81	0.57	0..66	0.63	0.70	0.70



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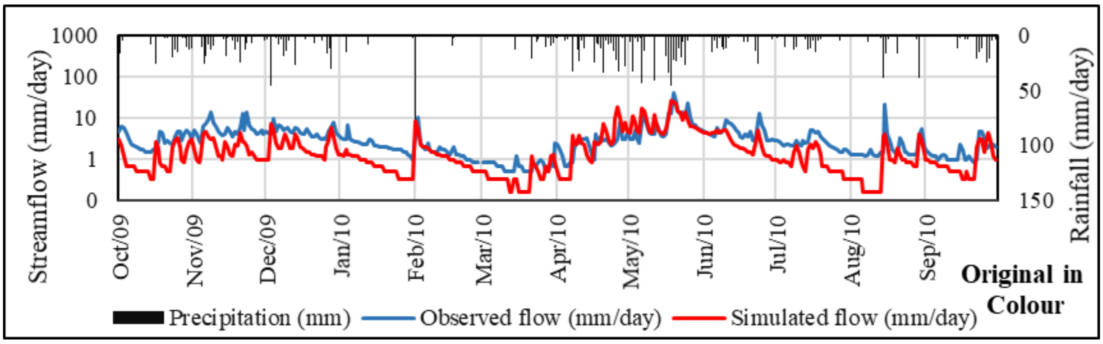
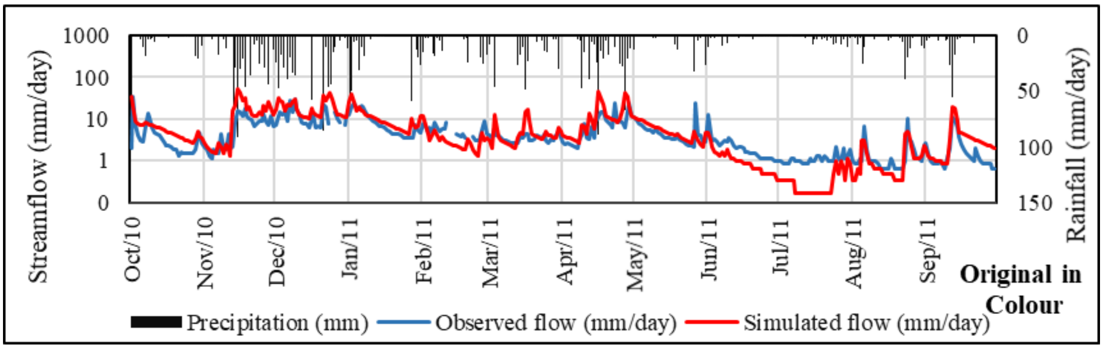
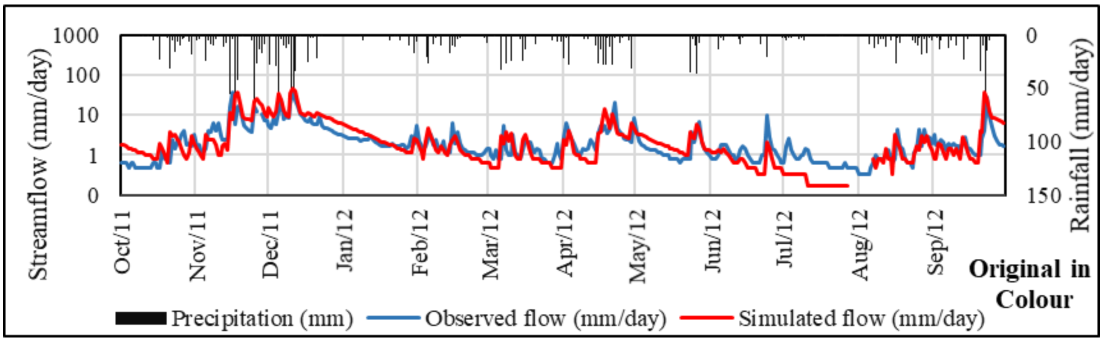


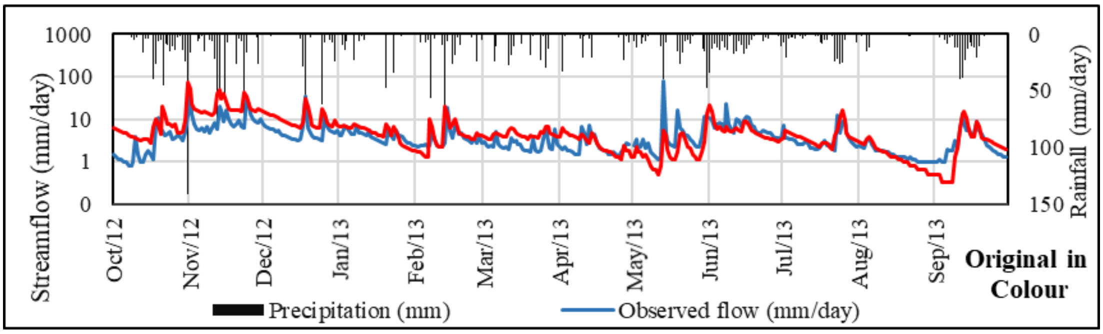
Streamflow (mm/day)
1000
100
10
1
0
Rainfall (mm/day)
0
50
100
150
Oct/09
Nov/09
Dec/09
Jan/10
Feb/10
Mar/10
Apr/10
May/10
Jun/10
Jul/10
Aug/10
Sep/10
Original in Colour
Precipitation (mm)
Observed flow (mm/day)
Simulated flow (mm/day)



Streamflow (mm/day)
1000
100
10
1
0
Rainfall (mm/day)
0
50
100
150
Oct/10
Nov/10
Dec/10
Jan/11
Feb/11
Mar/11
Apr/11
May/11
Jun/11
Jul/11
Aug/11
Sep/11
Original in Colour
Precipitation (mm)
Observed flow (mm/day)
Simulated flow (mm/day)



Streamflow (mm/day)
1000
100
10
1
0
Rainfall (mm/day)
0
50
100
150
Oct/11
Nov/11
Dec/11
Jan/12
Feb/12
Mar/12
Apr/12
May/12
Jun/12
Jul/12
Aug/12
Sep/12
Original in Colour
Precipitation (mm)
Observed flow (mm/day)
Simulated flow (mm/day)



Streamflow (mm/day)
1000
100
10
1
0
Rainfall (mm/day)
0
50
100
150
Oct/12
Nov/12
Dec/12
Jan/13
Feb/13
Mar/13
Apr/13
May/13
Jun/13
Jul/13
Aug/13
Sep/13
Original in Colour
Precipitation (mm)
Observed flow (mm/day)

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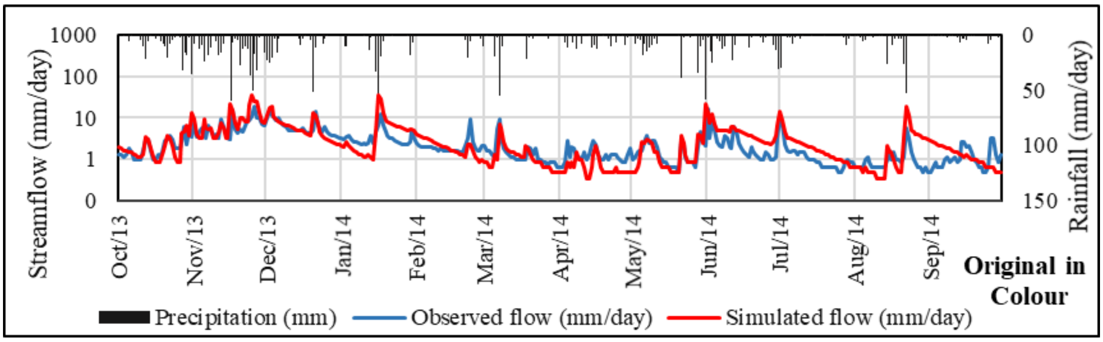

Figure I- 7:Flow Hydrograph Spatial parameter transferability - Urawa Catchment

Table I- 8: Annual Water Balance for Spatial parameter transferability - Urawa Catchment

Water Year	RF (mm/ year)	Sim. SF (mm/ year)	Obs.SF (mm/ year)	WB Sim. SF (mm/year)	WB Obs. SF (mm/year)	AWBE (mm/ year)	Percentage error	Sim. Runoff Coeff.	Obs. Runoff Coeff.
2008/09	2526	1969	1564	557	962	405	26%	0.78	0.62
2009/10	1968	838	1277	1130	691	-439	-34%	0.43	0.65
2010/11	2857	2473	1816	383	1040	657	36%	0.87	0.64
2011/12	2097	1304	1065	794	1033	239	22%	0.62	0.51
2012/13	2667	2303	1684	363	983	620	37%	0.86	0.63
2013/14	2029	1289	979	741	1051	310	32%	0.64	0.48
Average	2357	1696	1397	661	960	299	20%	0.70	0.59

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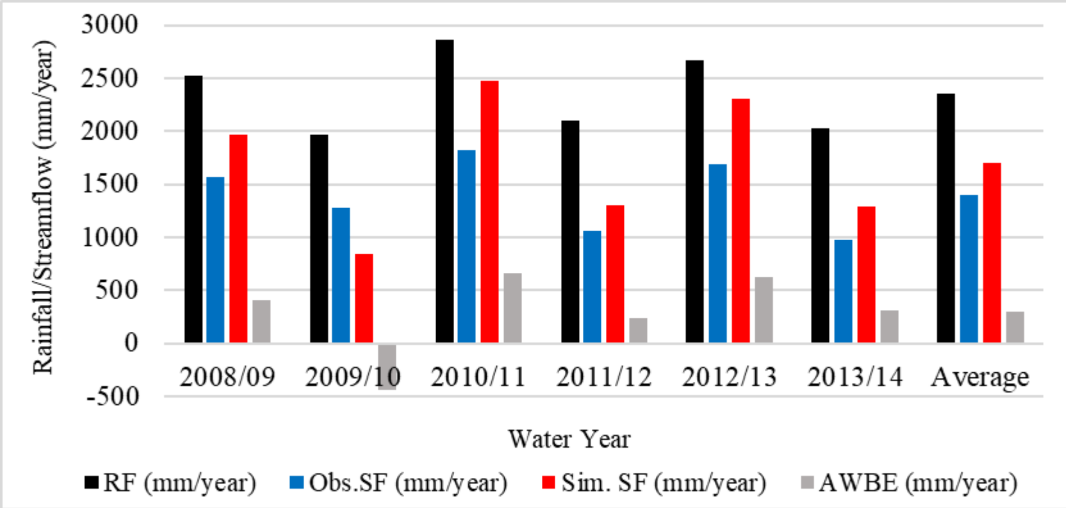

Figure I- 8: Annual Water Balance for Spatial parameter transferability – Urawa Catchment

Spatiotemporal Parameter Transferability

Table I- 9: Numerical measures of unsorted FDC - Spatiotemporal Parameter Transferability for Urawa Catchment

Gauging Station	RMSE (mm/day)	MRAE	Annual Water Balance Error (%)	Flow Duration Curve - Unsorted					
				High		Medium		Low	
				RMSE (mm/day)	MRAE	RMSE (mm/day)	MRAE	RMSE (mm/day)	MRAE
Urawa	5.69	1.03	62	13.4	0.517	4.76	0.85	2.50	1.98

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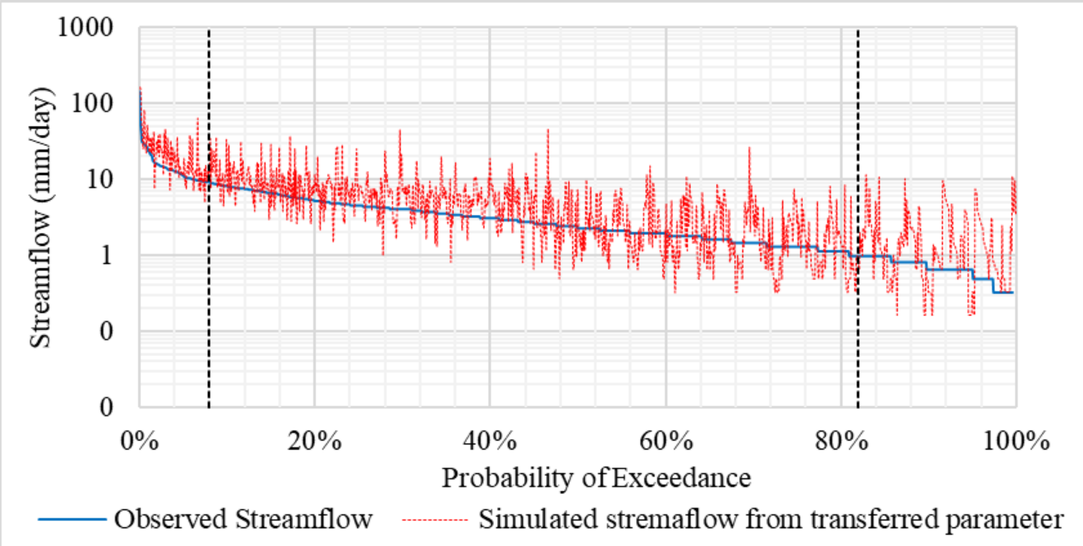

Figure I- 9: Unsorted FDC – Spatiotemporal Parameter Transferability for Urawa catchment

Table I- 10: Numerical measures of sorted FDC - Spatiotemporal Parameter Transferability for Urawa Catchment

Gauging Station	RMSE (mm/day)	MRAE	Flow Duration Curve - Sorted					
			High		Medium		Low	
			RMSE (mm/day)	MRAE	RMSE (mm/day)	MRAE	RMSE (mm/day)	MRAE
Urawa	4.334	0.416	13.750	0.753	2.219	0.458	0.102	0.096

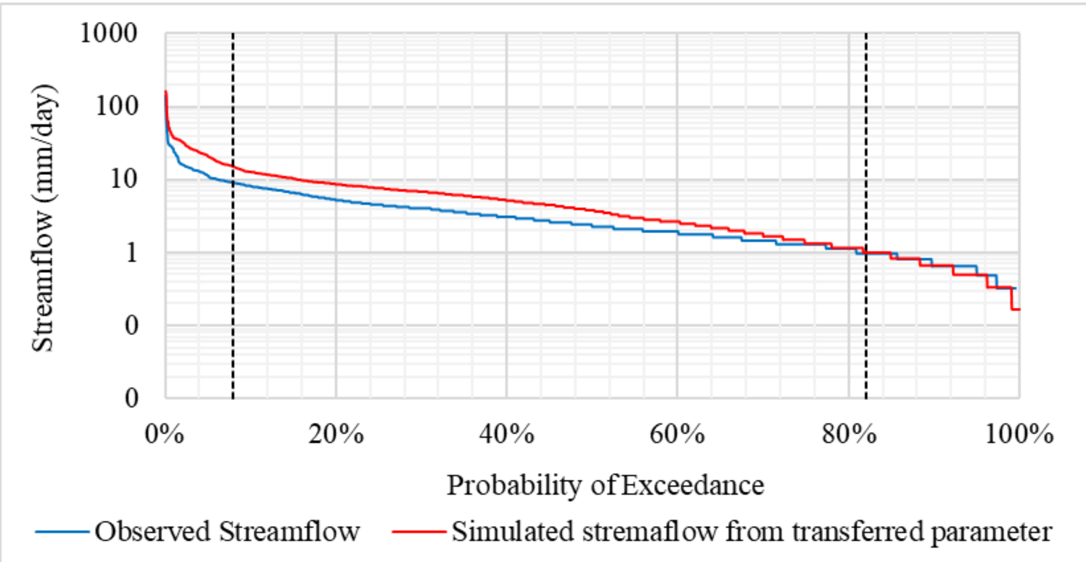

Figure I- 10: Sorted FDC – Spatiotemporal Parameter Transferability for Urawa catchment

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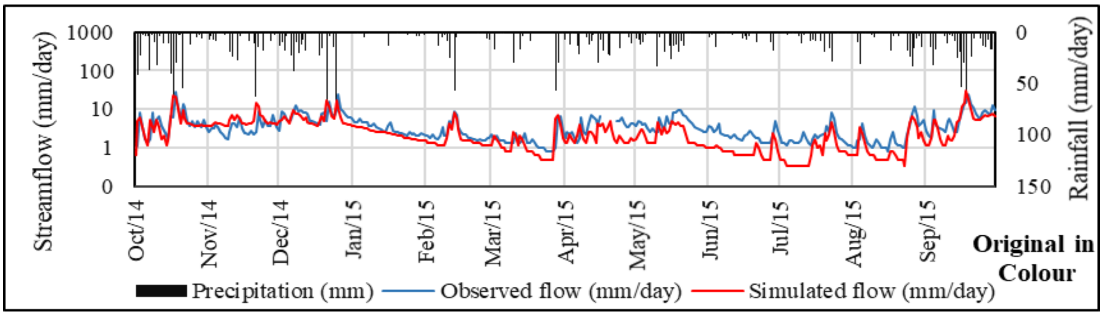
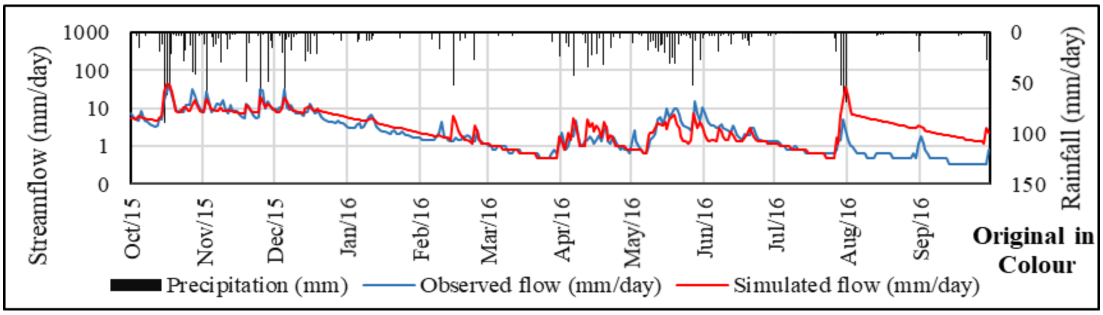
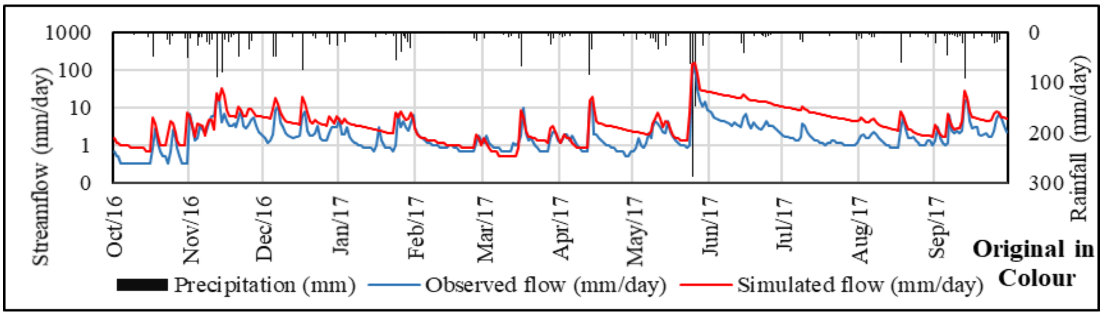
Table I- 11: Annual RMSE and MRAE value for Spatiotemporal parameter transferability - Urawa Catchment

Water Year	2014/15	2015/16	2016/17	2017/18
RMSE	3.930	4.570	8.280	4.990
MRAE	0.550	1.290	1.680	0.610







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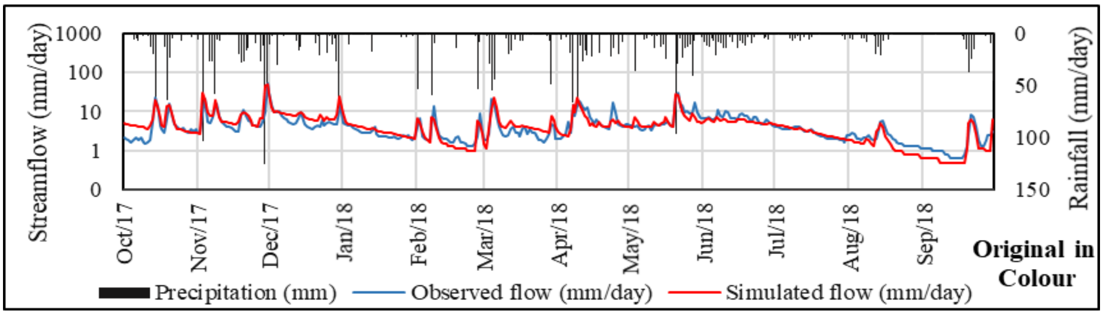

Figure I- 11: Flow Hydrograph Spatiotemporal parameter transferability – Urawa Catchment

Table I- 12: Annual Water Balance for Spatiotemporal parameter transferability - Urawa Catchment

Water Year	RF (mm/ year)	Sim. SF (mm/ year)	Obs. SF (mm/ year)	WB Sim. SF (mm/ year)	WB Obs. SF(mm /year)	AW BE (mm/ year)	Percent age error	Sim. Runoff Coef.	Obs. Runoff Coef.
2014/15	2559	1705	1405	854	1155	301	21%	0.67	0.55
2015/16	2253	2167	1449	86	803	718	50%	0.96	0.64
2016/17	2772	2614	1106	158	1666	1508	136%	0.94	0.40
2017/18	2848	2481	1771	367	1077	710	40%	0.87	0.62
Averag	2608	2242	1432	366	1175	809	62%	0.86	0.55

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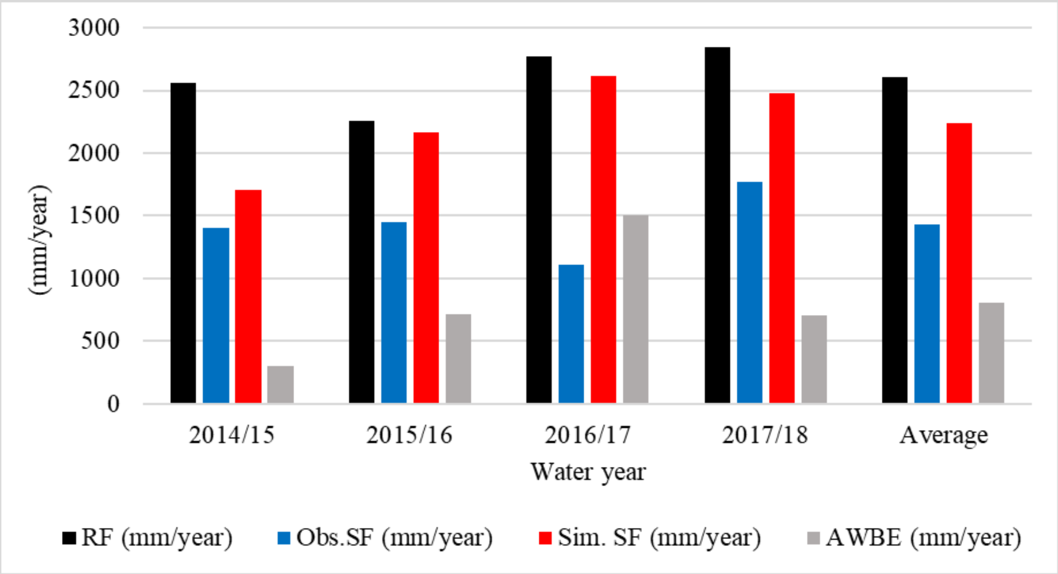

Figure I- 12: Annual Water Balance for Spatiotemporal parameter transferability – Urawa Catchment

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APPENDIX J : SIMULATED STREAMFLOW FROM TRANSFERRED PARAMETERS FOR ANNUAL, SEASONAL AND MONTHLY SCALE – PITABADDARA CATCHMENT

Model Performance for Temporal Parameter Transferability

Table J- 1: Numerical measures for Annual sorted FDC for Temporal Parameter Transferability - Pitabaddara Catchment

Flow Regime	2014/15		2015/16		2016/17		2017/18	
	MRAE	RMSE (mm/day)	MRAE	RMSE (mm/day)	MRAE	RMSE (mm/day)	MRAE	RMSE (mm/day)
Overall	0.206	2.430	0.381	2.410	0.338	10.241	0.486	3.989
High	0.330	6.291	0.250	5.405	0.798	35.742	0.529	10.585
Medium	0.203	1.857	0.356	2.083	0.291	1.967	0.511	2.959
Low	0.145	0.228	0.620	0.326	0.340	0.254	0.300	0.289

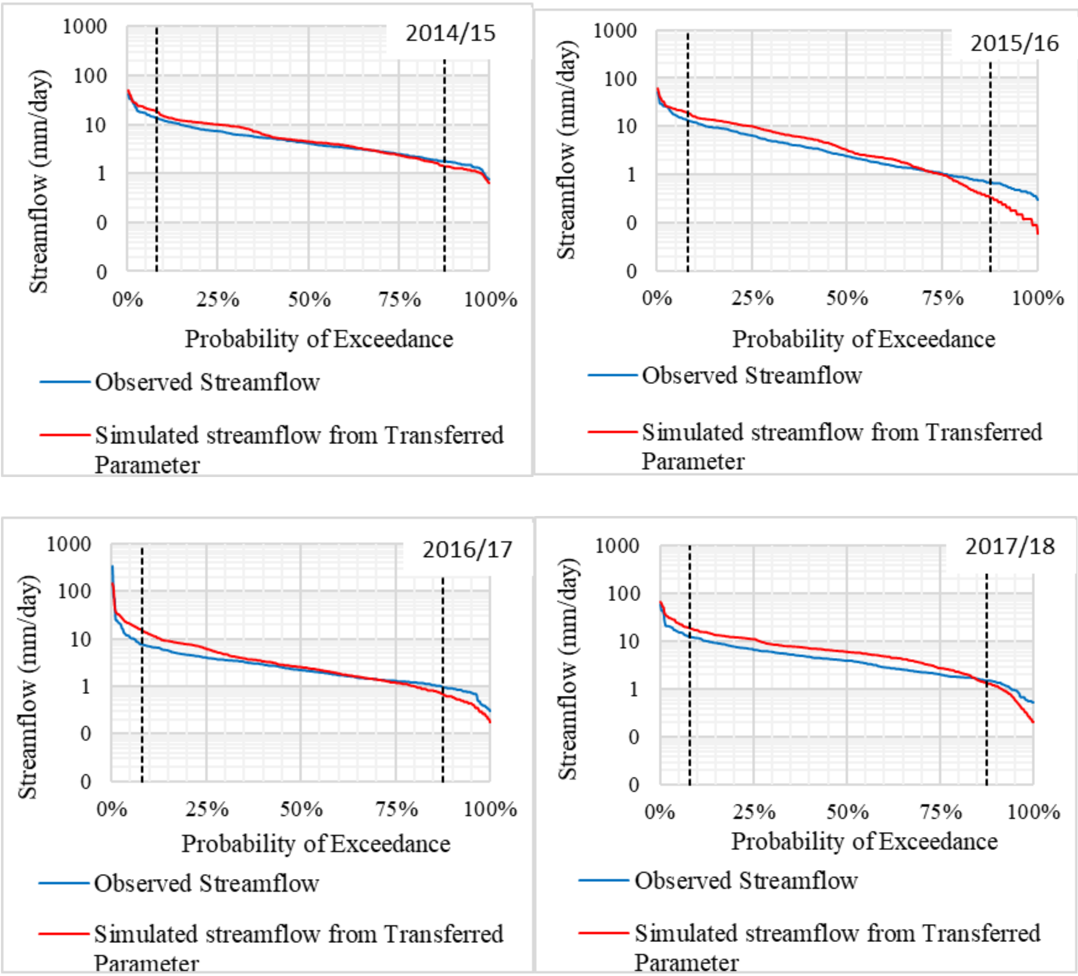

Figure J- 1: Annual FDC for Temporal Parameter Transferability - Pitabaddara Catchment

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Table J- 2: Seasonal streamflow prediction for Temporal Parameter Transferability - Pitabaddara Catchment

Water Year	Season	Obs. SF (mm/season)	Sim. SF (mm/season)	Error (mm/season)	Error Percentage (%)
2014/15	Maha	1077	1549	-473	-44%
	Yala	1019	1047	-27	-3%
2015/16	Maha	1228	1596	-368	-30%
	Yala	576	767	-190	-33%
2016/17	Maha	512	667	-155	-30%
	Yala	1135	1391	-256	-23%
2017/18	Maha	1043	1555	-512	-49%
	Yala	975	1472	-497	-51%
Average	Maha	965	1342	-377	-39%
	Yala	926	1169	-243	-26%

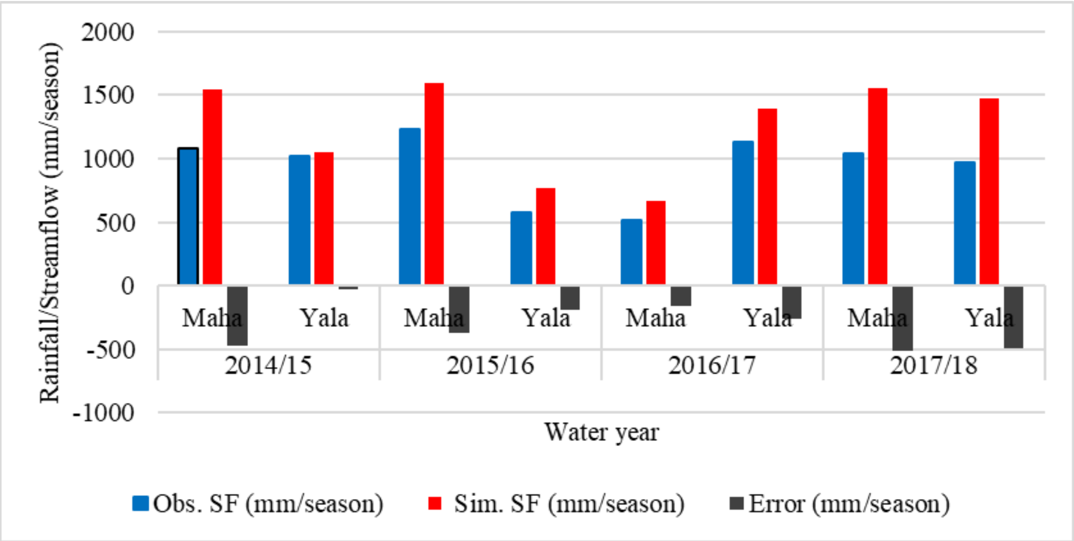

Figure J- 2: Seasonal streamflow prediction for Temporal Parameter Transferability - Pitabaddara Catchment

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Table J- 3: Average monthly streamflow prediction for Temporal Parameter Transferability - Pitabaddara Catchment

Month	Obs. SF (mm/month)	Sim. SF (mm/month)	Error (mm/month)	Error (%)
October	253	348	-96	-38%
November	248	398	-150	-61%
December	242	349	-107	-44%
January	96	105	-9	-9%
February	65	63	3	4%
March	62	88	-26	-42%
April	158	138	20	12%
May	332	379	-47	-14%
June	156	278	-122	-78%
July	75	105	-31	-41%
August	69	69	1	1%
September	136	199	-63	-46%

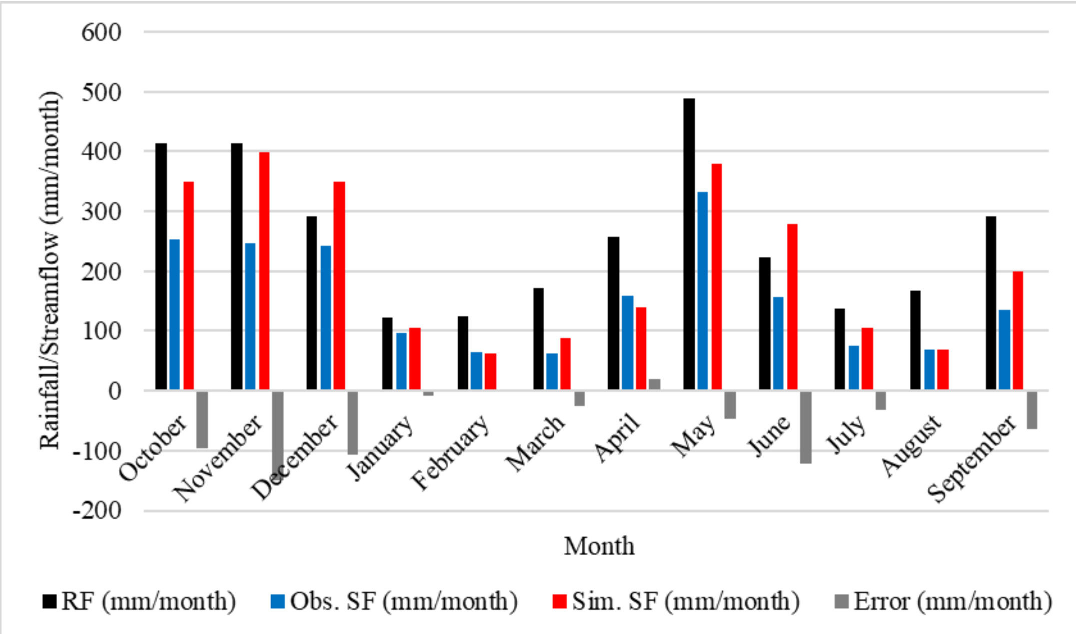
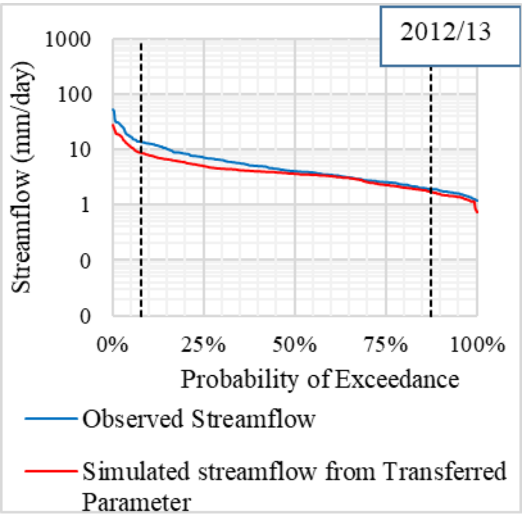


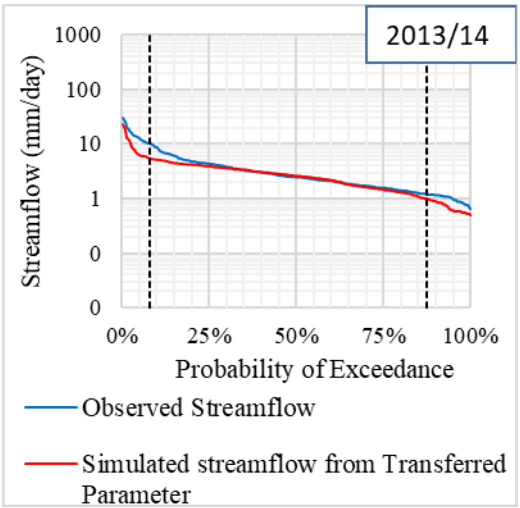
Figure J- 3 : Average monthly streamflow prediction for Temporal Parameter Transferability - Pitabaddara Catchment

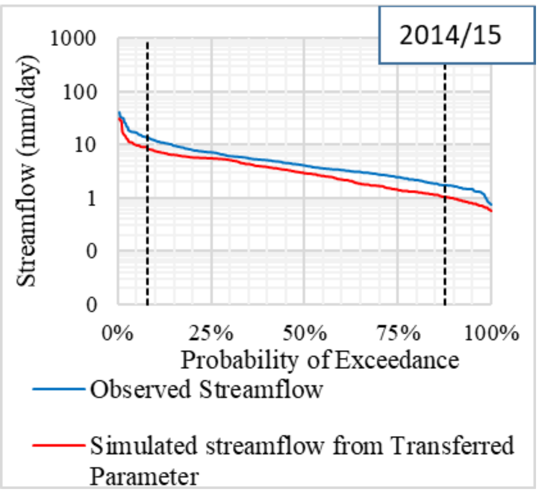
Model Performance for Spatial Parameter Transferability

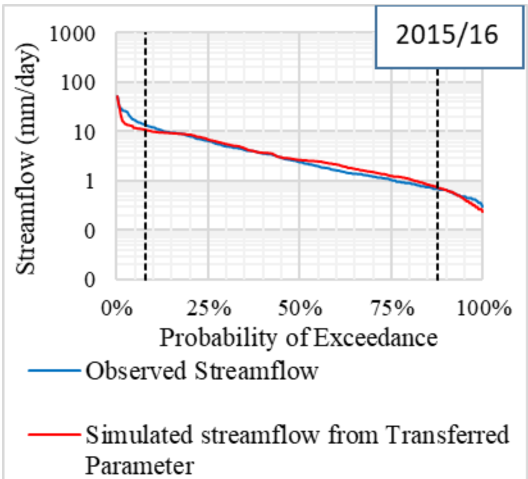
Table J- 4: Numerical measures for Annual sorted FDC for Spatial Parameter Transferability - Pitabaddara Catchment

Flow Regime	2012/13		2013/14		2014/15		2015/16		2016/17		2017/18	
	MRAE	RMSE (mm/day)	MRAE	RMSE (mm/day)	MRAE	RMSE	MRAE	RMSE	MRAE	RMSE (mm/day)	MRAE	RMSE
Overall	0.19	3.40	0.14	1.97	0.34	2.80	0.15	2.11	0.30	10.38	0.14	1.11
High	0.37	10.48	0.43	6.35	0.39	8.05	0.30	7.23	0.56	36.50	0.15	3.11
Medium	0.18	1.87	0.09	0.91	0.32	1.82	0.14	0.62	0.26	1.42	0.15	0.76
Low	0.13	0.23	0.28	0.30	0.40	0.60	0.09	0.06	0.34	0.27	0.07	0.07









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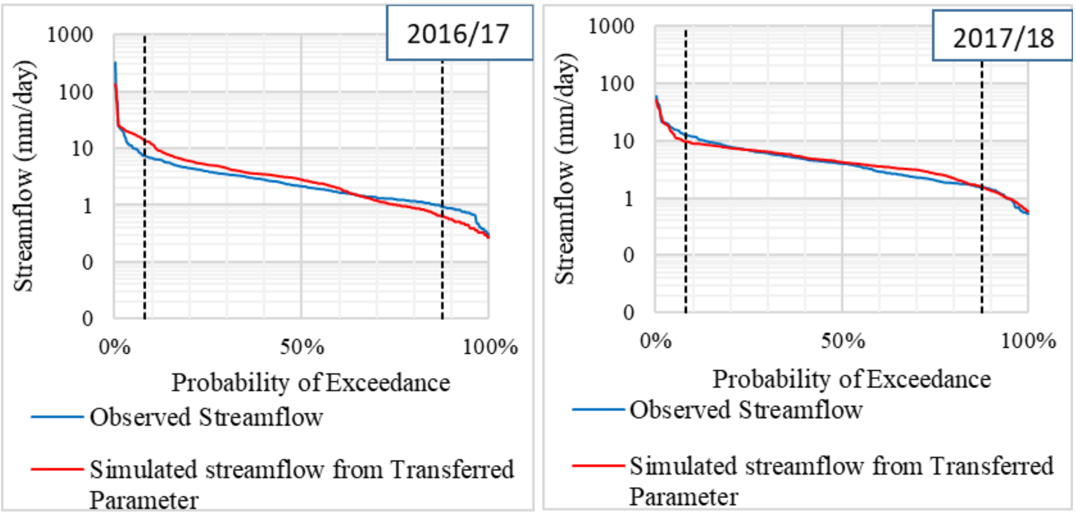

Figure J- 4: Annual sorted FDC for Spatial Parameter Transferability - Pitabaddara Catchment

Table J- 5: Seasonal streamflow prediction for Spatial Parameter Transferability - Pitabaddara Catchment

Water Year	Season	Obs. SF (mm/season)	Sim. SF (mm/season)	Error (mm/season)	Error (%)
2012/13	Maha	1286	872	415	32%
	Yala	979	762	217	22%
2013/14	Maha	870	615	255	29%
	Yala	552	514	38	7%
2014/15	Maha	1077	871	205	19%
	Yala	1019	531	489	48%
2015/16	Maha	1228	1205	23	2%
	Yala	575	439	136	24%
2016/17	Maha	512	420	92	18%
	Yala	1135	1409	-274	-24%
2017/18	Maha	1043	1080	-37	-4%
	Yala	975	932	43	4%
Average	Maha	1003	844	159	16%
	Yala	873	765	108	12%

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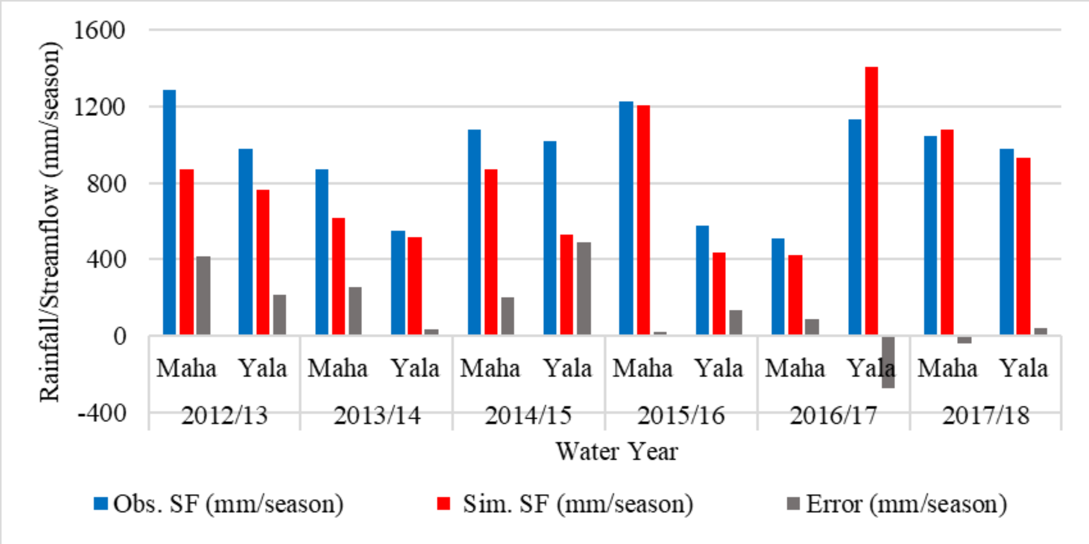

Figure J- 5: Seasonal streamflow prediction for Spatial Parameter Transferability - Pitabaddara Catchment

Table J- 6: Average monthly streamflow prediction for Spatial Parameter Transferability - Pitabaddara Catchment

Month	Obs. SF (mm/month)	Sim. SF (mm/month)	Error (mm/month)	Error (%)
October	212	283	-72	-34%
November	300	396	-96	-32%
December	235	307	-72	-31%
January	112	116	-4	-3%
February	78	82	-4	-5%
March	67	90	-24	-36%
April	130	124	7	5%
May	267	297	-30	-11%
June	179	266	-86	-48%
July	90	119	-29	-32%
August	77	86	-9	-11%
September	129	181	-52	-40%

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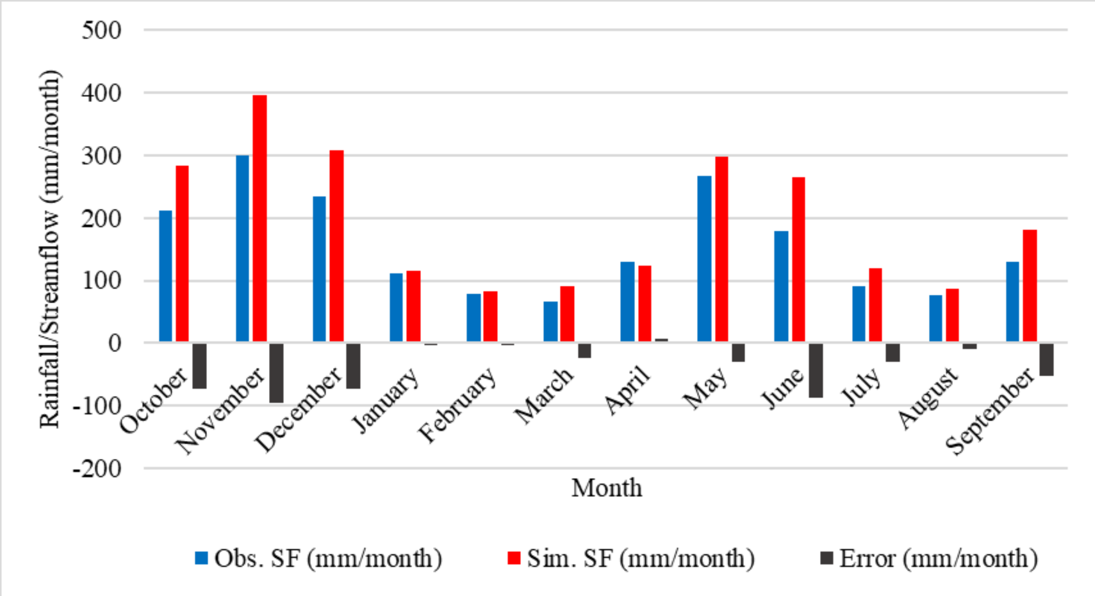

Figure J- 6: Average monthly streamflow prediction for Spatial Parameter Transferability - Pitabaddara Catchment

<u>Model Performance Spatiotemporal Parameter Transferability</u>

Table J- 7: Numerical measures for Annual sorted FDC for Spatiotemporal Parameter Transferability - Pitabaddara Catchment

Flow Regime	2008/09		2009/10		2010/11		2011/12	
	MRAE	RMSE (mm/day)	MRAE	RMSE (mm/day)	MRAE	RMSE (mm/day)	MRAE	RMSE (mm/day)
Overall	0.479	2.800	0.463	2.949	0.267	3.880	0.125	1.924
High	0.388	6.927	0.475	7.919	0.377	11.098	0.278	6.648
Medium	0.473	2.237	0.492	2.155	0.285	2.570	0.108	0.487
Low	0.579	0.579	0.273	0.354	0.079	0.105	0.136	0.109

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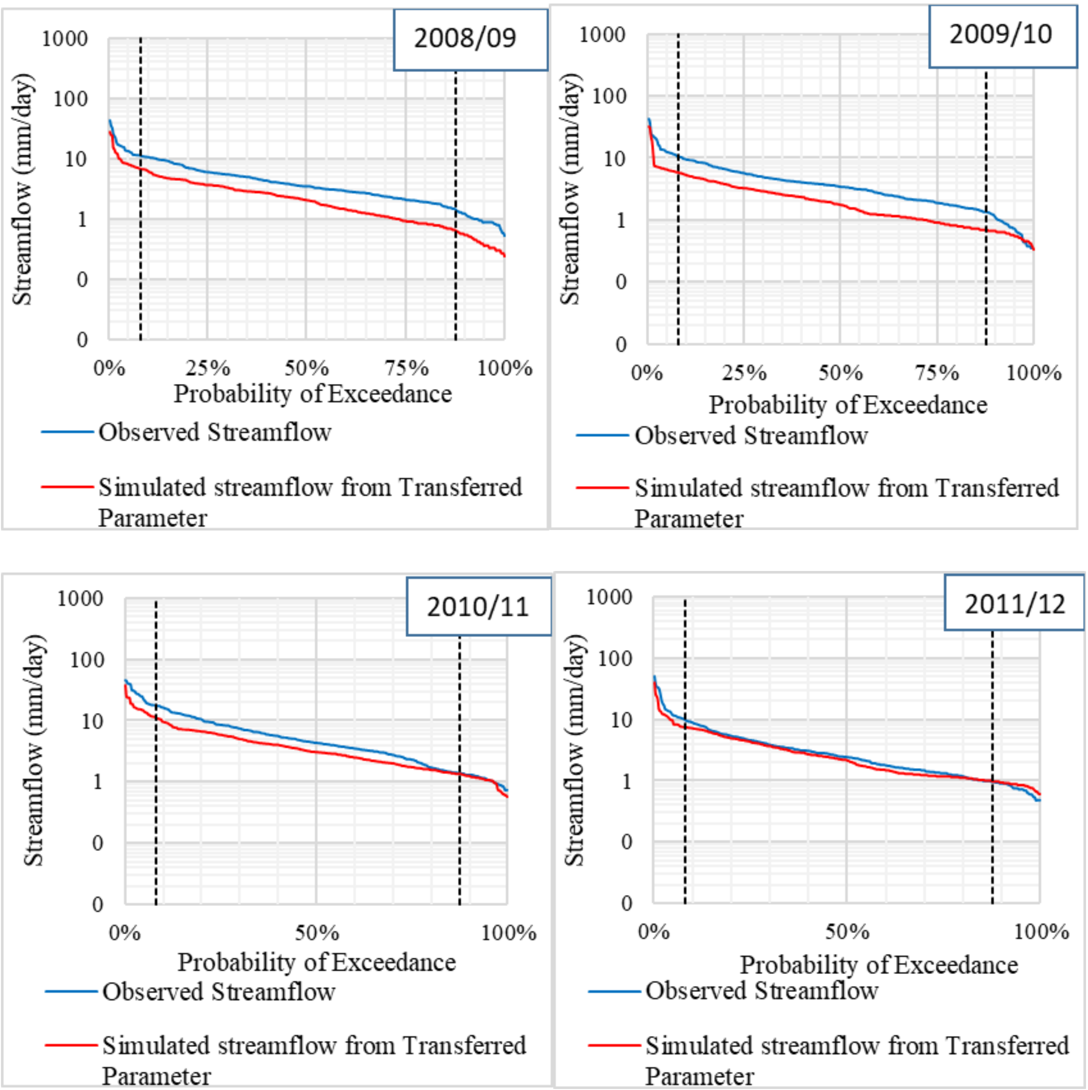

Figure J- 7: Annual sorted FDC for Spatiotemporal Parameter Transferability - Pitabaddara Catchment

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Table J- 8: Seasonal streamflow prediction for Spatiotemporal Parameter Transferability - Pitabaddara Catchment

Water Year	Season	Obs. SF (mm/season)	Sim. SF (mm/season)	Error (mm/season)	Error (%)
2008/09	Maha	966	574	392	41%
	Yala	853	454	399	47%
2009/10	Maha	748	326	422	56%
	Yala	962	614	348	36%
2010/11	Maha	1652	1187	466	28%
	Yala	883	484	399	45%
2011/12	Maha	898	813	85	9%
	Yala	564	399	164	29%
Average	Maha	1066	725	341	32%
	Yala	816	488	328	40%

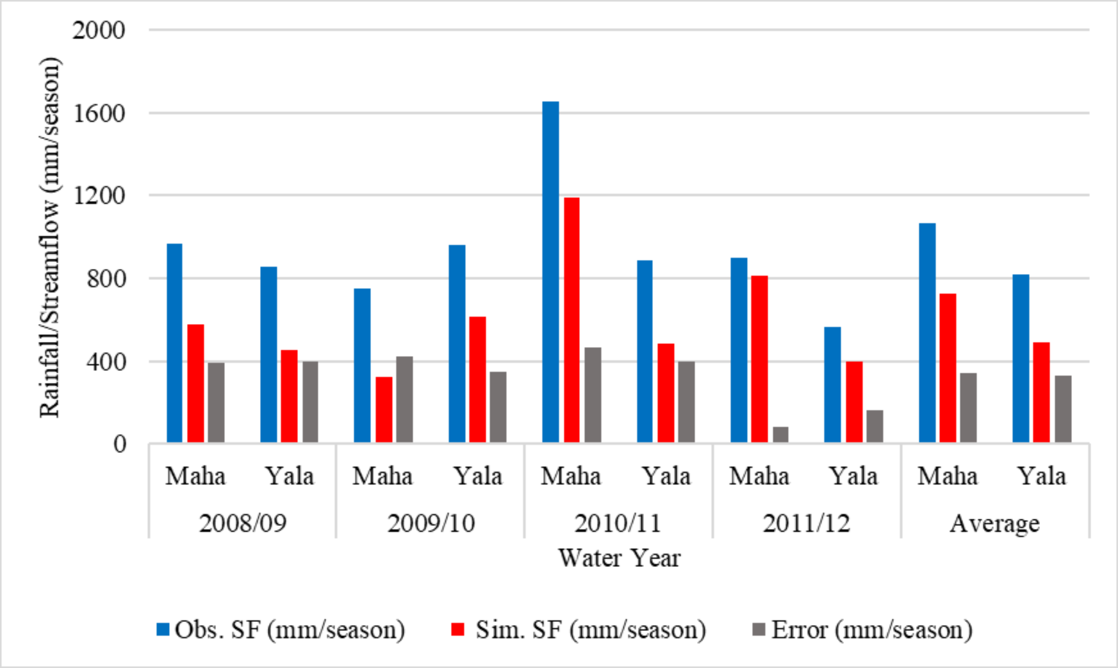

Figure J- 8: Seasonal streamflow prediction for Spatiotemporal Parameter Transferability - Pitabaddara Catchment

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Table J- 9: Average monthly streamflow prediction for Spatiotemporal Parameter Transferability - Pitabaddara Catchment

Month	Obs. SF (mm/month)	Sim. SF (mm/month)	Error (mm/season)	Error (%)
October	160	160	0	0%
November	269	300	-31	-12%
December	326	288	38	12%
January	129	112	17	13%
February	85	51	33	39%
March	96	86	9	10%
April	188	175	13	7%
May	191	195	-4	-2%
June	146	138	7	5%
July	92	84	8	8%
August	82	68	14	17%
September	116	98	19	16%

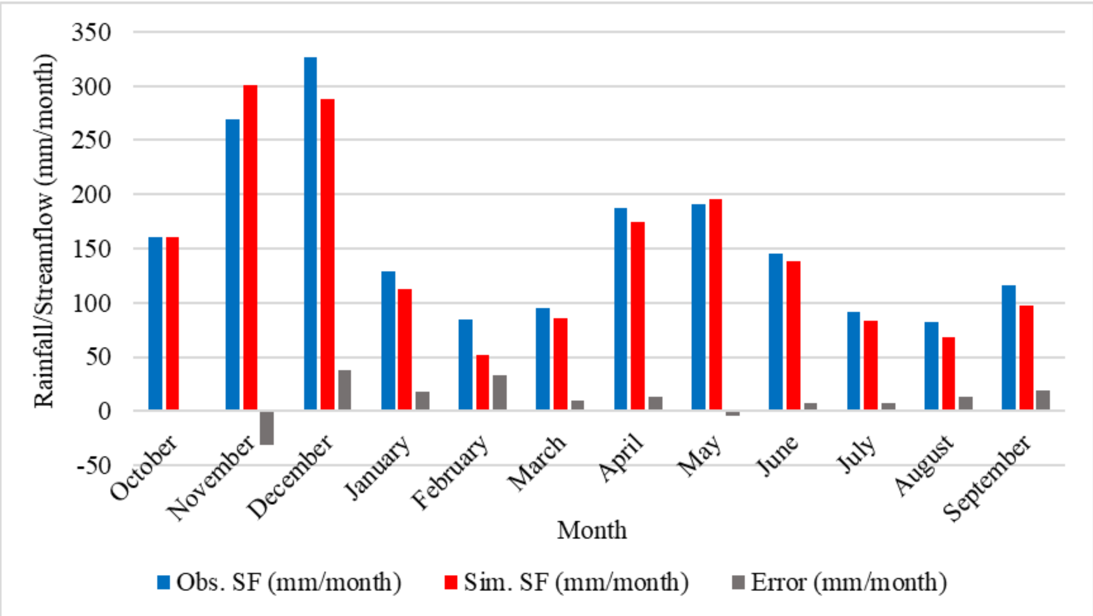

Figure J- 9: Average monthly streamflow prediction for Spatiotemporal Parameter Transferability - Pitabaddara Catchment

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APPENDIX K : SIMULATED STREAMFLOW FROM TRANSFERRED PARAMETERS FOR ANNUAL, SEASONAL AND MONTHLY SCALE – URAWA CATCHMENT

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<u>Model Performance for Temporal Parameter Transferability</u>

Table K- 1: Numerical measures for Annual sorted FDC for Temporal Parameter Transferability - Urawa Catchment

Flow Regime	2008/09		2009/10		2010/11		2011/12	
	MRAE	RMSE (mm/day)	MRAE	RMSE (mm/day)	MRAE	RMSE (mm/day)	MRAE	RMSE (mm/day)
Overall	0.263	0.926	0.535	2.773	0.078	1.135	0.167	0.734
High	0.125	2.342	0.523	8.258	0.124	3.927	0.131	2.432
Medium	0.211	0.685	0.550	1.811	0.039	0.308	0.118	0.282
Low	0.516	0.645	0.486	0.487	0.218	0.212	0.387	0.241

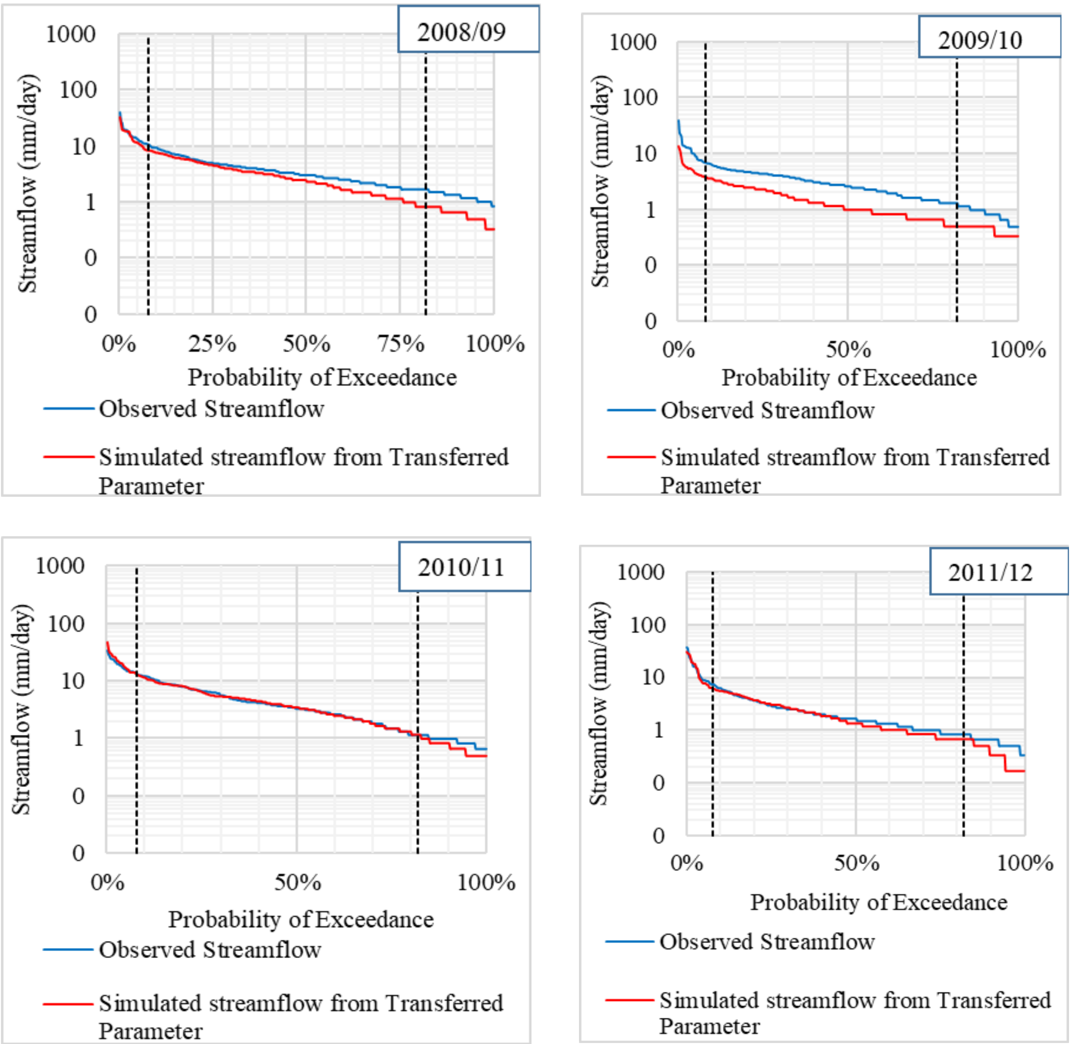

Figure K- 1: Annual FDC for Temporal Parameter Transferability - Urawa Catchment

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Table K- 2: Seasonal streamflow prediction for Temporal Parameter Transferability - Urawa Catchment

Water Year	Season	Obs. SF (mm/season)	Sim. SF (mm/season)	Error (mm/season)	Error(%)
2008/09	Maha	956	859	97	10%
	Yala	608	441	167	27%
2009/10	Maha	567	243	324	57%
	Yala	714	383	331	46%
2010/11	Maha	1204	1302	-98	-8%
	Yala	611	538	73	12%
2011/12	Maha	695	695	0	0%
	Yala	368	284	84	23%
Average	Maha	856	775	81	9%
	Yala	575	411	164	29%

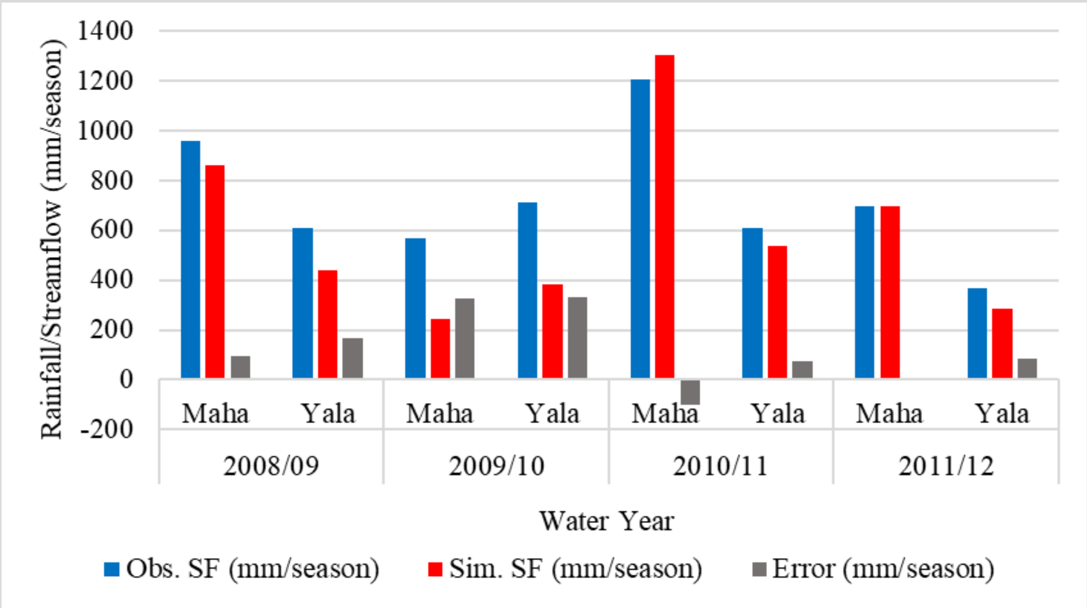

Figure K- 2: Seasonal streamflow prediction for Temporal Parameter Transferability - Urawa Catchment

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Table K- 3: Average monthly streamflow prediction for Temporal Parameter Transferability - Urawa Catchment

Month	Obs. SF (mm/month)	Sim. SF (mm/month)	Error (mm/month)	Error (%)
October	122	120	2	1%
November	212	174	39	18%
December	264	236	28	10%
January	124	122	2	1%
February	64	60	4	7%
March	70	90	-21	-30%
April	131	108	24	18%
May	151	114	36	24%
June	100	61	39	39%
July	57	27	30	53%
August	60	27	33	55%
September	76	50	27	35%

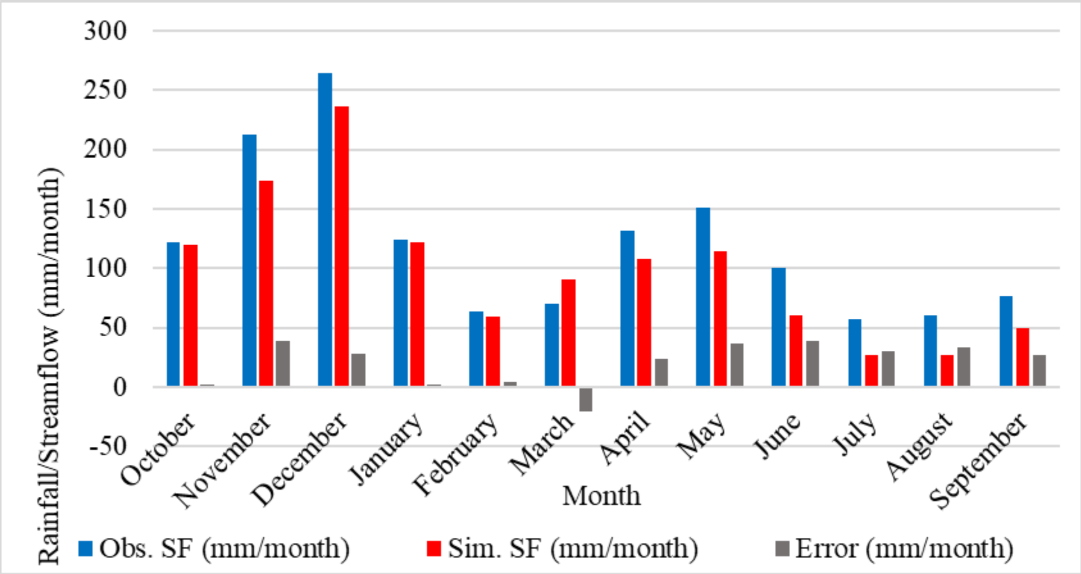
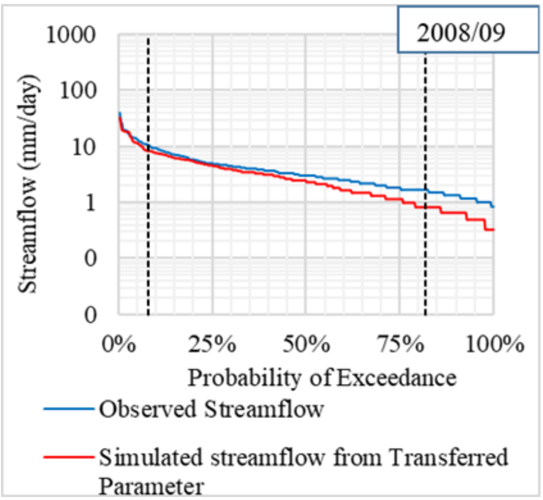


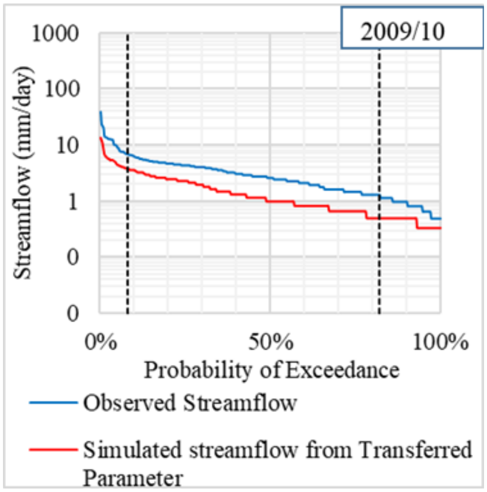
Figure K- 3: Average monthly streamflow prediction for Temporal Parameter Transferability - Urawa Catchment

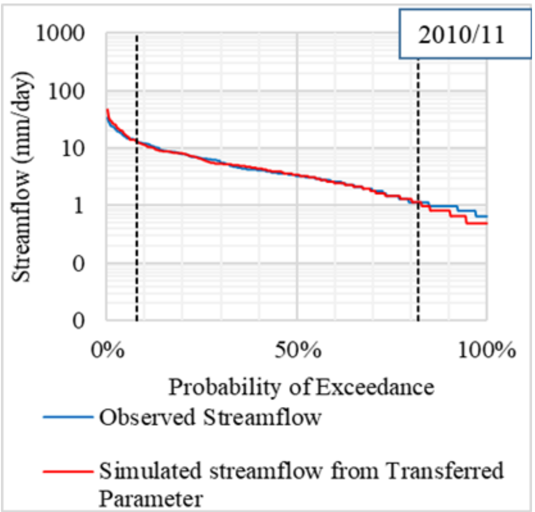
Model Performance for Spatial Parameter Transferability

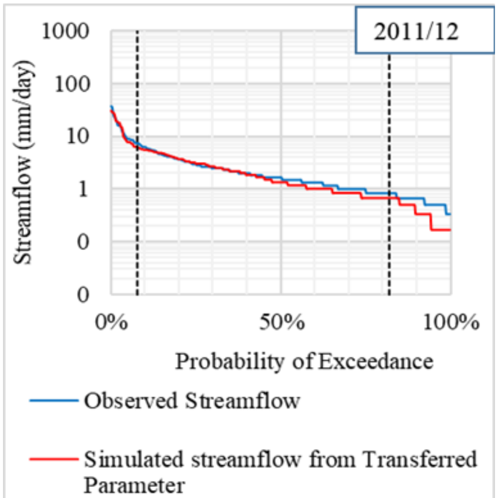
Table K- 4: Numerical measures for Annual sorted FDC for Spatial Parameter Transferability - Urawa Catchment

Flow Regime	2008/09		2009/10		2010/11		2011/12		2012/13		2013/14	
	MRAE	RMSE (mm/day)	MRAE	RMSE (mm/day)	MRAE	RMSE (mm/day)	MRAE	RMSE (mm/day)	MRAE	RMSE (mm/day)	MRAE	RMSE (mm/day)
Overall	0.37	2.95	0.48	1.46	0.31	3.82	0.23	2.10	0.31	3.17	0.22	2.18
High	0.57	8.99	0.13	2.90	0.60	11.96	0.41	6.87	0.57	9.32	0.54	7.13
Medium	0.27	1.72	0.48	1.40	0.22	2.12	0.15	0.92	0.31	2.04	0.19	0.75
Low	0.69	0.84	0.62	0.57	0.52	0.47	0.50	0.30	0.18	0.28	0.20	0.15









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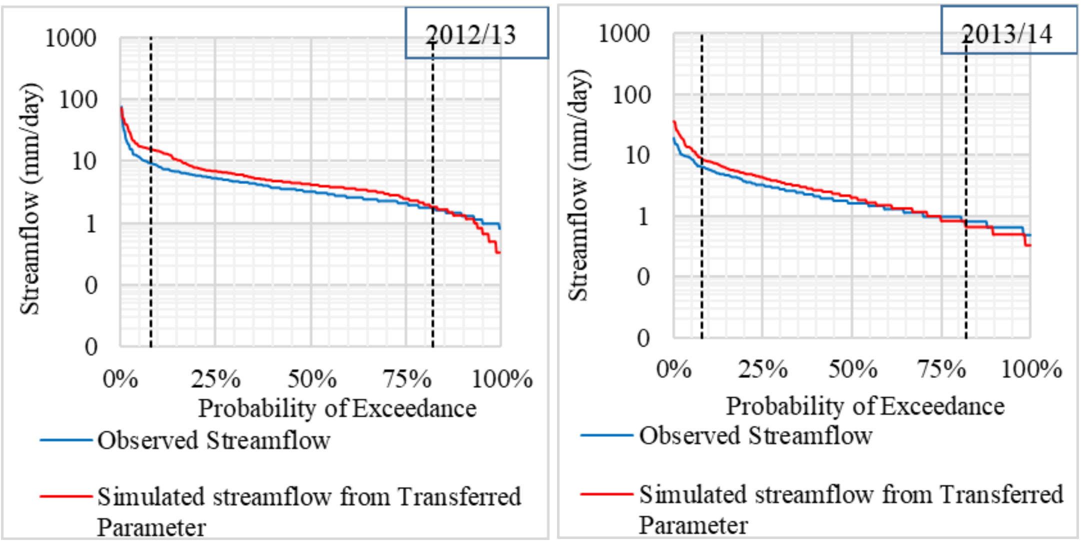

Figure K- 4: Annual sorted FDC for Spatial Parameter Transferability - Urawa Catchment

Table K- 5: Seasonal streamflow prediction for Spatial Parameter Transferability - Urawa Catchment

Water Year	Season	Obs. SF (mm/season)	Sim. SF (mm/season)	Error (mm/season)	Error (%)
2008/09	Maha	956	1410	-454	-48%
	Yala	608	559	50	8%
2009/10	Maha	565	251	314	56%
	Yala	714	621	93	13%
2010/11	Maha	1204	1729	-526	-44%
	Yala	613	744	-131	-21%
2011/12	Maha	696	914	-218	-31%
	Yala	368	390	-22	-6%
2012/13	Maha	945	1685	-740	-78%
	Yala	739	618	120	16%
2013/14	Maha	684	861	-177	-26%
	Yala	295	428	-133	-45%
Average	Maha	842	1142	-300	-36%
	Yala	556	560	-4	-1%

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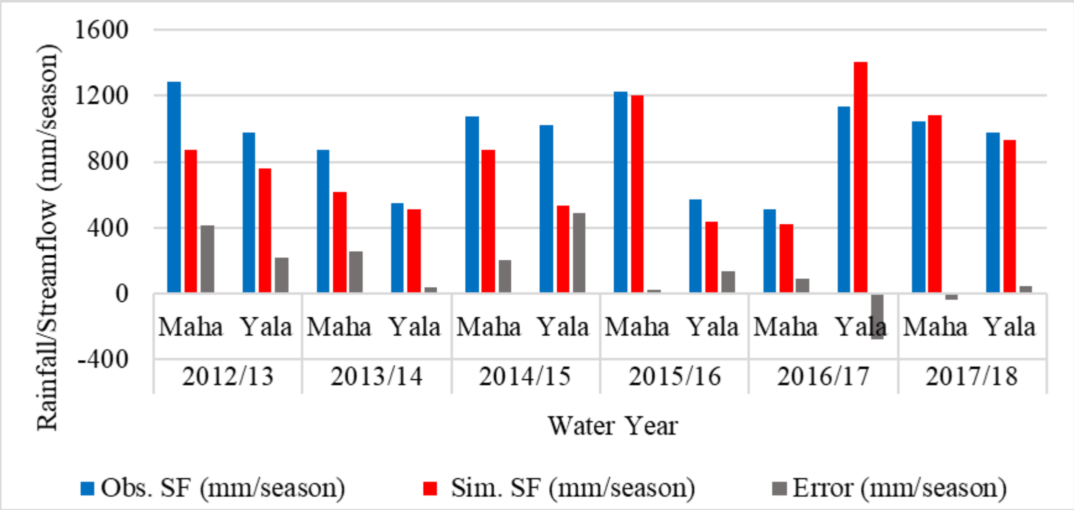

Figure K- 5: Seasonal streamflow prediction for Spatial Parameter Transferability - Urawa Catchment

Table K- 6: Average monthly streamflow prediction for Spatial Parameter Transferability - Urawa Catchment

Month	Obs. SF (mm/month)	Sim. SF (mm/month)	Error (mm/month)	Error (%)
October	109	168	-59	-54%
November	231	285	-54	-24%
December	240	368	-128	-54%
January	122	162	-40	-33%
February	71	75	-4	-5%
March	69	117	-48	-69%
April	106	134	-28	-26%
May	139	144	-5	-3%
June	118	103	14	12%
July	65	53	12	18%
August	54	39	15	28%
September	74	68	5	7%

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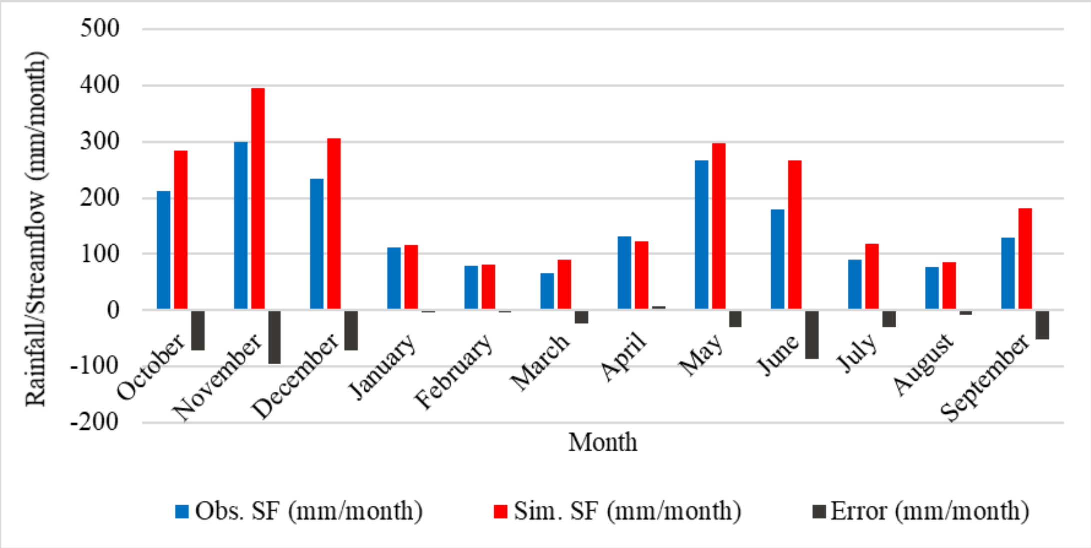

Figure K- 6:Average monthly streamflow prediction for Spatial Parameter Transferability - Urawa Catchment

Model Performance Spatiotemporal Parameter Transferability

Table K- 7: Numerical measures for Annual sorted FDC for Spatiotemporal Parameter Transferability - Urawa Catchment

Flow Regime	2014/15		2015/16		2016/17		2017/18	
	MRAE	RMSE (mm/day)	MRAE	RMSE (mm/day)	MRAE	RMSE (mm/day)	MRAE	RMSE (mm/day)
Overall	0.282	2.596	0.519	3.004	1.197	7.854	0.429	3.742
High	0.594	8.524	0.434	8.368	1.881	24.734	0.602	11.644
Medium	0.204	1.108	0.612	2.169	1.343	4.203	0.389	2.059
Low	0.465	0.567	0.182	0.139	0.298	0.253	0.516	0.713

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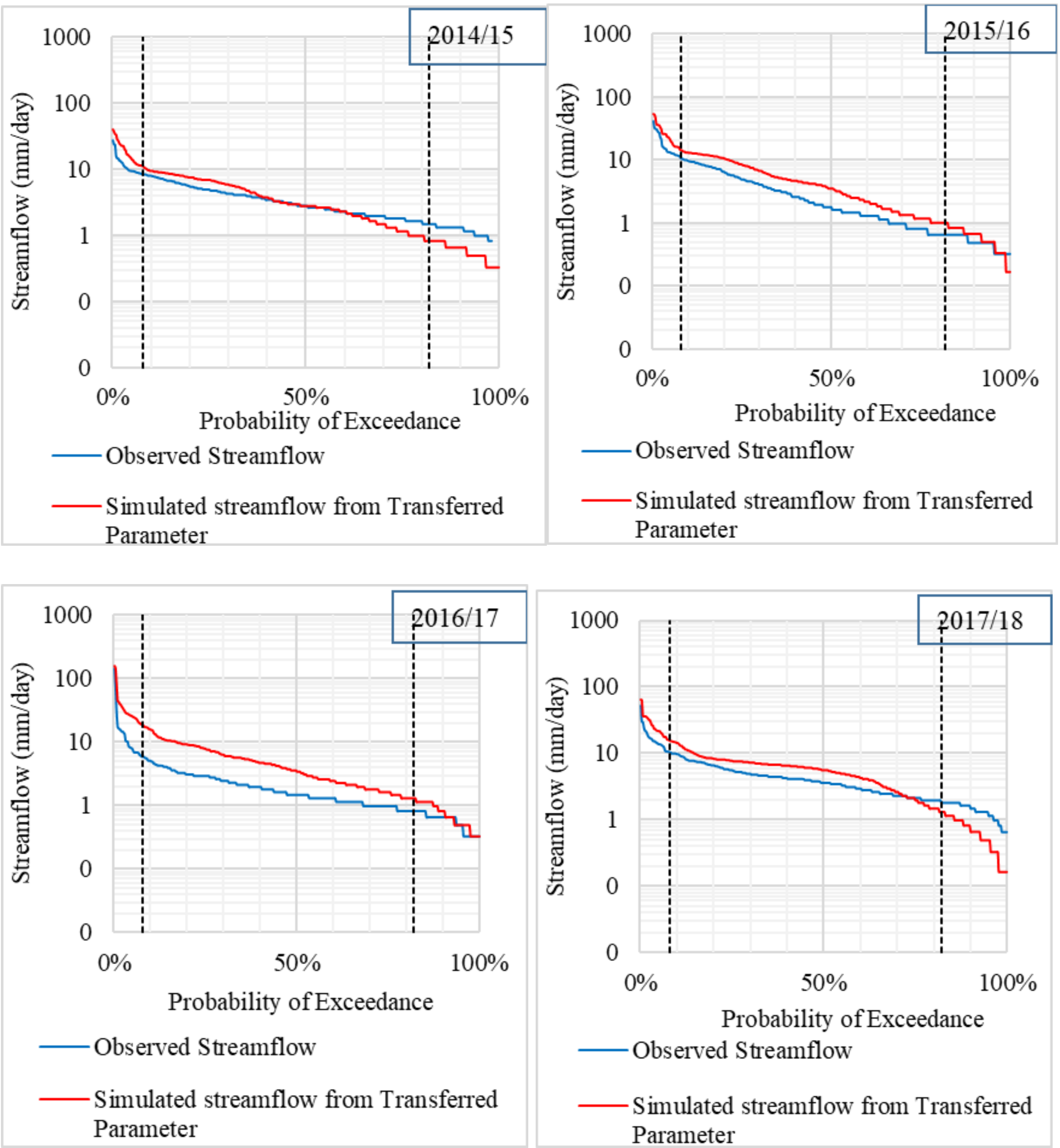

Figure K- 7: Annual sorted FDC for Spatiotemporal Parameter Transferability - Urawa Catchment

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Table K- 8: Seasonal streamflow prediction for Spatiotemporal Parameter Transferability - Urawa Catchment

Water Year	Season	Obs. SF (mm/season)	Sim. SF (mm/season)	Error (mm/season)	Error (%)
2014/15	Maha	744	1102	-358	-48%
	Yala	661	603	58	9%
2015/16	Maha	1114	1447	-334	-30%
	Yala	336	719	-384	-114%
2016/17	Maha	387	1001	-614	-159%
	Yala	719	1613	-894	-124%
2017/18	Maha	901	1513	-612	-68%
	Yala	870	968	-98	-11%
Average	Maha	786	1266	-480	-61%
	Yala	646	976	-330	-51%

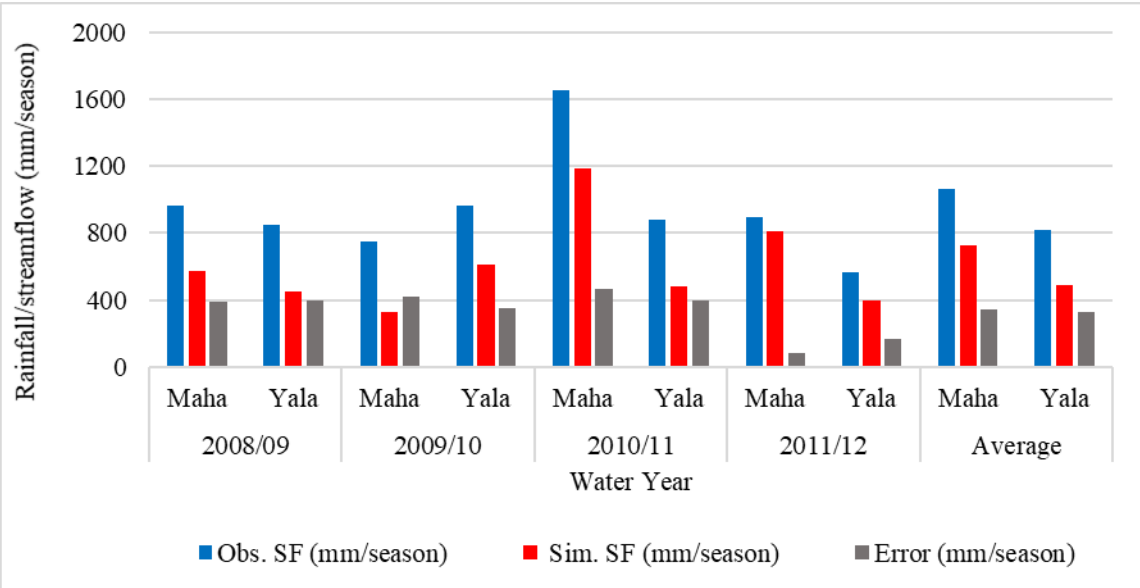

Figure K- 8:Seasonal streamflow prediction for Spatiotemporal Parameter Transferability - Urawa Catchment

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Table K- 9: Average monthly streamflow prediction for Spatiotemporal Parameter Transferability - Urawa Catchment

Month	Obs. SF (mm/month)	Sim. SF (mm/month)	Error (mm/month)	Error (%)
October	169	223	-55	-32%
November	211	317	-106	-50%
December	201	395	-194	-96%
January	86	204	-118	-138%
February	58	77	-19	-32%
March	61	80	-19	-31%
April	101	129	-28	-27%
May	218	141	77	35%
June	118	379	-260	-221%
July	58	98	-40	-68%
August	54	90	-37	-69%
September	98	111	-13	-13%

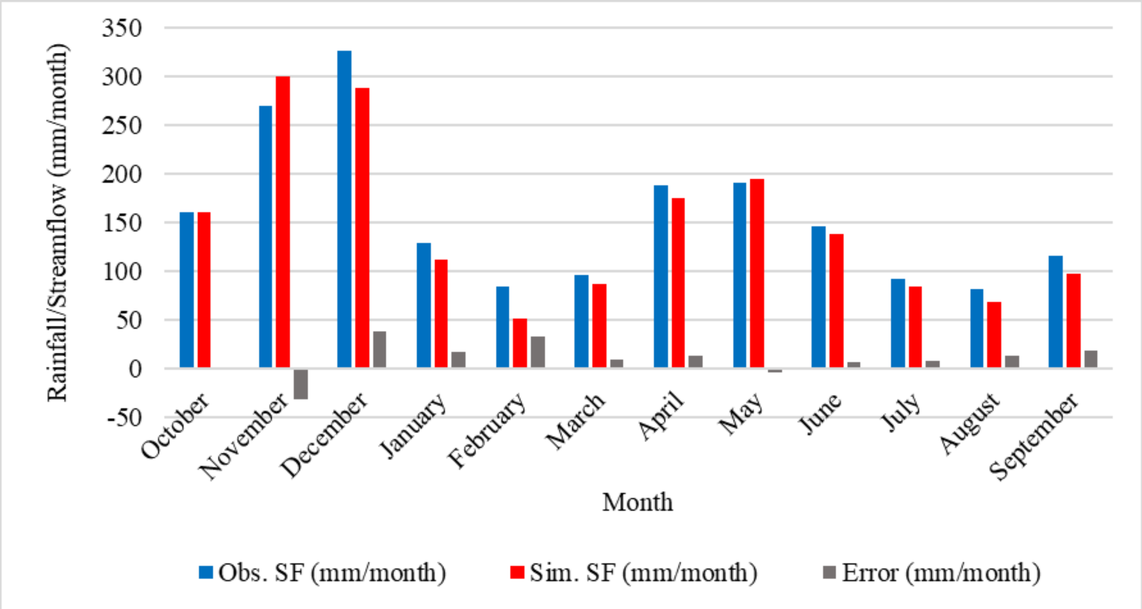

Figure K- 9: Average monthly streamflow prediction for Spatiotemporal Parameter Transferability - Urawa Catchment

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The findings, interpretations and conclusions expressed in this thesis/dissertation are entirely based on the results of the individual research study and should not be attributed in any manner to or do neither necessarily reflect the views of UNESCO Madanjeet Singh Centre for South Asia Water Management (UMCSAWM), nor of the individual members of the MSc panel, nor of their respective organizations.