EVALUATION OF THE EFFECT OF LOSS AND TRANSFORM METHODS ON THE PERFORMANCE OF HEC-HMS MODEL: A CASE STUDY IN KELANI RIVER BASIN, SRI LANKA

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August 2022

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

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August 2022

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ABSTRACT

Evaluation of the Effect of Loss and Transform Methods on the Performance of HEC-HMS Model: A Case Study in Kelani River Basin, Sri Lanka

Hydrological modelling plays a vital role in understanding the hydrological system of any watershed and providing reliable data to manage the water resources of the relevant watershed in a sustainable manner. Among the numerous types of hydrological models, HEC-HMS is very popular among hydrologic modellers due to its user-friendliness. Different methods are available in HEC-HMS to compute the hydrological process in a relevant watershed and the selection of appropriate methods among different available methods plays an important role in the performance of the model**.**

The objective of this study is to select the most suitable loss and transform methods for Kelani river basin, comparing different combinations of selected loss and transform methods available for event-based simulations. Seethawaka subbasin was selected as the study area. From the possible methods embedded in the HEC-HMS, two loss methods (SCS Curve Number method, Initial Constant method) and three transform methods (SCS Unit Hydrograph method, Clark Unit Hydrograph method, Snyder Unit Hydrograph method) were selected for this study. Six (06) different combinations using those loss and transform methods were tried out to evaluate the performance of the model. Percent Error in Peak (PEP) and Percent Error in Volume (PEV) objective functions were selected for this study to determine the performance of the model. Hourly rainfall and streamflow data for four (04) extreme flood events (May 2014, May 2016, May 2017, May 2018) which occurred in the recent past were used in this study as this is an event-based simulation. The 2018 flood event was used for the model calibration and other three events were used for the validation of the calibrated model.

Combination 01 (SCS-CN Loss Method and SCS-UH Transform Method) shows a better performance compared to other combinations w.r.t both PEP and PEV objective functions. N.S.E. and RMSE values were reported as 0.816 and 0.400 after calibrated w.r.t PEP objective function and as 0.830 and 0.400 after calibrated w.r.t. PEV objective function. Even considering the validation results, it was confirmed that Combination 01 shows the best results among all the 06 combinations.

It can be concluded that the SCS-CN loss method and SCS-UH transform method provides more reliable estimates w.r.t. both PEP and PEV objective functions in streamflow forecasting in Kelani river using HEC-HMS. Considering the ability of the model to predict the peak discharge and the time to peak, this developed model can be used to provide early flood warnings to the Deraniyagala area during extreme rainfall events as well.

Keywords: Event-based simulation, HEC-HMS, Hydrological modelling, Seethawaka river basin

ACKNOWLEDGEMENT

I would like to express my sincere gratitude to my research supervisor Prof. R.L.H. Lalith Rajapakse for the continuous guidance, support and encouragement given throughout my research work. His patient guidance and dedicated supervision were the key factors in the success of this study. I take this chance to declare my heartfelt thankfulness to my research supervisor for spending his valuable time for me to succeed in my research work.

Even though he is not in that position currently, I must thank Senior Professor N.T.S. Wijesekara, the former Centre Chairman of the UNESCO Madanjeet Singh Center for South Asia Water Management (UMCSAWM) for his valuable guidance given throughout my study period. I must thank my batchmates including N.L. Engiliyage, M.A.D.N. Ariyasena and S.P.S.P. Kulathunga for the immense support and motivation which was given by them through out the research work as well as the master degree program. The staff of UMCSAWM should also be heartfully remembered at this moment for providing all the necessary assistance and support during the study period. Besides, I would like to thank my office colleagues including G.H.R de Silva who motivated and helped me in many ways to successfully complete my research work.

Finally, my special thanks go to my family members including my mother and husband for their unconditional love, support and encouragement given throughout my study period. Without their support and motivation, this work would not have been possible.

TABLE OF CONTENT

DECLARATION OF THE CANDIDATE AND SUPERVISOR .... **III**

ABSTRACT .... **V**

ACKNOWLEDGEMENT .... **VII**

TABLE OF CONTENT .... **IX**

LIST OF FIGURES .... **XIII**

LIST OF TABLES .... **XV**

1 INTRODUCTION **1**

1.1 General 1

1.1.1 Hydrological Modelling in Sri Lanka 2

1.1.2 Why HEC-HMS? 3

1.1.3 Kelani River Basin 5

1.2 Problem Statement 5

1.3 Overall Objective 6

1.4 Specific Objectives 6

2 LITERATURE REVIEW **7**

2.1 Hydrological Modelling 7

2.2 Classifications of Hydrological Modelling 8

2.3 HEC-HMS Model 11

2.3.1 HEC-HMS Model Structure 12

2.3.2 Precipitation Loss Model 13

2.3.3 Transform Model 14

2.3.4 Baseflow Model 15

2.4 Model Optimization, Calibration and Validation 17

2.4.1 Selection of Events 17

2.4.2 Objective Function 18

2.4.3 Selection of objective function based on the study purpose 21

2.4.4 Calibration and Validation Process 24

2.5 Sensitivity Analysis 26

2.6 Selection of Most Suitable Modelling Methods in HEC-HMS 27

2.7 Summary of the Literature Survey 35

3 METHODOLOGY 37

3.1 Methodology Outline 37

3.2 Methodology Flowchart 39

4 DATA CHECKING AND ANALYSIS 40

4.1 Study Area 40

4.2 Data Collection 44

4.2.1 Storm Events 44

4.3 Data Checking 45

4.3.1 Visual Data Checking 45

4.3.2 Thiessen Average Rainfall 46

4.4 Selection of Computing Methods 50

5 MODEL DEVELOPMENT AND APPLICATIONS 53

5.1 HEC-HMS Model Development 53

5.1.1 Development of Basin Model 53

5.1.2 Development of Loss Model 53

5.1.3 Development of Transform Model 56

5.1.4 Development of Baseflow Model 59

5.1.5 Development of Routing Model 60

5.1.6 Development of Precipitation Model 61

5.1.7 Control Specifications 61

5.1.8 Simulation Time Interval 61

5.2 Selection of Objective Function 61

5.3 Sensitivity Analysis 62

5.4 Model Calibration 62

5.5 Model Validation 63

5.6 Selection of the Best Option 63

6 RESULTS 65

6.1 General 65

6.2 Results of Sensitivity Analysis 65

6.2.1 Combination 01 (SCS-CN Loss method and SCS-UH Transform method) 65

6.2.2 Combination 02 (SCS-CN loss method and Clark-UH Transform method) 68

6.2.3 Combination 03 (SCS-CN Loss method and Snyder-UH Transform method) 69

6.2.4 Combination 04 (Initial Constant Loss method and SCS-UH Transform method) 70

6.2.5 Combination 05 (Initial Constant Loss method and Clark-UH Transform method) 71

6.2.6 Combination 06 (Initial Constant Loss method and Snyder-UH Transform method) 72

6.3 Model Calibration Results 73

6.3.1 Outflow Hydrographs in Calibration Period 74

6.3.2 Flow Duration Curve for Calibration Period 76

6.4 Model Validation Results 77

6.4.1 Outflow Hydrographs in Validation Period 79

6.4.2 Flow Duration Curves for Validation Period 83

7 DISCUSSION 87

7.1 Event Selection 87

7.2 Data Resolution 87

7.3 Sensitivity Analysis 88

7.4 Model Calibration 88

7.5 Model Validation 89

7.6 Selection of the Best Combination 90

7.7 Summary of the Discussion..90

8 CONCLUSIONS...93

9 RECOMMENDATIONS 95

BIBLIOGRAPHY 97

ANNEXURE 01 : ISOHYETAL MAP OF SRI LANKA...105

ANNEXURE 02 : VISUAL DATA CHECKING 107

ANNEXURE 03 : CALIBRATION AND VALIDATION RESULTS..........................110

LIST OF FIGURES

Figure 3-1: Methodology Flowchart ---------- 39

Figure 4-1: Study Area ---------- 41

Figure 4-2: Land Use Classification of Study Area ---------- 42

Figure 4-3: Streamflow Vs Rainfall of Three Stations for 2018 Flood event ---------- 46

Figure 4-4: Thiessen Polygon for Seethawaka Watershed ---------- 47

Figure 4-5: Thiessen Average Rainfall Vs Streamflow for Deraniyagla Catchment for 2014 Storm Event ---------- 48

Figure 4-6: Thiessen Average Rainfall Vs Streamflow for Deraniyagla Catchment for 2016 Storm Event ---------- 48

Figure 4-7: Thiessen Average Rainfall Vs Streamflow for Deraniyagla Catchment for 2017 Storm Event ---------- 49

Figure 4-8: Thiessen Average Rainfall Vs Streamflow for Deraniyagla Catchment for 2018 Storm Event ---------- 49

Figure 5-1: Developed Basin Model ---------- 60

Figure 6-1: Parameter Sensitivity to Peak Discharge (Combination 01) ---------- 67

Figure 6-2: Parameter Sensitivity to Runoff Volume (Combination 01) ---------- 67

Figure 6-3: Parameter Sensitivity to Peak Discharge (Combination 02) ---------- 68

Figure 6-4: Parameter Sensitivity to Runoff Volume (Combination 02) ---------- 68

Figure 6-5: Parameter Sensitivity to Peak Discharge (Combination 03) ---------- 69

Figure 6-6: Parameter Sensitivity to Runoff Volume (Combination 03) ---------- 69

Figure 6-7: Parameter Sensitivity to Peak Discharge (Combination 04) ---------- 70

Figure 6-8: Parameter Sensitivity to Runoff Volume (Combination 04) ---------- 70

Figure 6-9: Parameter Sensitivity to Peak Discharge (Combination 05) ---------- 71

Figure 6-10: Parameter Sensitivity to Runoff Volume (Combination 05) ---------- 71

Figure 6-11: Parameter Sensitivity to Peak Discharge (Combination 06) ---------- 72

Figure 6-12: Parameter Sensitivity to Runoff Volume (Combination 06) ---------- 72

Figure 6-13: Observed and Simulated Hydrographs for Combination 01 during Calibration w.r.t. PEP ---------- 74

Figure 6-14: Observed and Simulated Hydrographs for Combination 01 during Calibration w.r.t. PEV ---------- 74

Figure 6-15: Observed and Simulated Hydrographs for Combination 02 during Calibration w.r.t. PEP ---------- 75

Figure 6-16: Observed and Simulated Hydrographs for the Combination 02 during Calibration w.r.t. PEV ---------- 75

Figure 6-17: Flow Duration Curve for Combination 01 w.r.t. PEP (Normal Scale) ---------------------- 76

Figure 6-18: Flow Duration Curve for Combination 01 w.r.t. PEP (Log Scale) -------------------------- 76

Figure 6-19: Flow Duration Curve for Combination 01 w.r.t. PEV (Normal Scale) --------------------- 77

Figure 6-20: Flow Duration Curve for Combination 01 w.r.t. PEV (Log Scale) -------------------------- 77

Figure 6-21: Observed and Simulated Hydrographs for Combination 01 during Validation using 2017 event w.r.t. PEP -- 80

Figure 6-22: Observed and Simulated Hydrographs for Combination 01 during Validation using 2017 event w.r.t. PEV-- 80

Figure 6-23: Observed and Simulated Hydrographs for Combination 01 during Validation using 2016 event w.r.t. PEP -- 81

Figure 6-24: Observed and Simulated Hydrographs for Combination 01 during Validation using 2016 event w.r.t. PEV-- 81

Figure 6-25: Observed and Simulated Hydrographs for Combination 01 during Validation using 2014 event w.r.t. PEP -- 82

Figure 6-26: Observed and Simulated Hydrographs for the Combination 01 during Validation using 2014 event w.r.t. PEV--- 82

Figure 6-27: Flow Duration Curve for Combination 01 w.r.t. PEP (Normal Scale) ---------------------- 83

Figure 6-28: Flow Duration Curve for Combination 01 w.r.t. PEP (Log Scale) -------------------------- 83

Figure 6-29: Flow Duration Curve for Combination 01 w.r.t. PEV (Normal Scale) --------------------- 83

Figure 6-30: Flow Duration Curve for Combination 01 w.r.t. PEV (Log Scale) -------------------------- 84

Figure 6-31: Flow Duration Curve for Combination 01 w.r.t. PEP (Normal Scale) ---------------------- 84

Figure 6-32: Flow Duration Curve for Combination 01 w.r.t. PEP (Log Scale) -------------------------- 84

Figure 6-33: Flow Duration Curve for Combination 01 w.r.t. PEV (Normal Scale) --------------------- 84

Figure 6-34: Flow Duration Curve for Combination 01 w.r.t. PEV (Log Scale) -------------------------- 85

Figure 6-35: Flow Duration Curve for Combination 01 w.r.t. PEP (Normal Scale) ---------------------- 85

Figure 6-36: Flow Duration Curve for Combination 01 w.r.t. PEP (Log Scale) -------------------------- 85

Figure 6-37: Flow Duration Curve for Combination 01 w.r.t. PEV (Normal Scale) --------------------- 86

Figure 6-38: Flow Duration Curve for Combination 01 w.r.t. PEV (Log Scale) -------------------------- 86

LIST OF TABLES

Table 2-1: Literature Summary of Hydrological Model Classification 10

Table 2-2: Literature Summary of Computing methods of HEC-HMS model 16

Table 2-3: Literature Summary of Objective Function 23

Table 2-4: Literature summary of selection of most suitable modelling methods in HEC-HMS......... 32

Table 4-1: Locations of gauging stations in Seethawaka Catchment used for the study...................... 43

Table 4-2: Land Use Classification of Seethawaka Watershed 43

Table 4-3: Data Sources and Resolutions.. 44

Table 4-4: Storm Event Details 45

Table 4-5: Thiessen weights for each rainfall gauging station 47

Table 4-6: Combination of Methods used in the Study.. 51

Table 5-1: Weighted Curve Number Calculations for each Sub-basin in Seethawaka Catchment 55

Table 5-2: Values assigned for parameters of Initial and Constant loss method................................. 56

Table 5-3: Calculation of Time of Concentrations and Lag time for Subbasins 57

Table 5-4: Calculations of Storage Coefficient for each Sub-basin 58

Table 5-5: Calculation of Standard Lag time 59

Table 5-6: Calculations of Lag time in River Reaches... 60

Table 5-7: Theissen Weight for Each Sub-basin 61

Table 6-1: Results of model sensitivity to changes in Initial Abstraction parameter 66

Table 6-2: Results of model sensitivity to changes in Curve Number parameter 66

Table 6-3: Results of model sensitivity to changes in Impervious (%) parameter 66

Table 6-4: Results of model calibration with respect to PEP objective function 73

Table 6-5: Results of model calibration with respect to PEV objective function................................ 73

Table 6-6: Results of model validation using 2017 event w.r.t. PEP objective function 77

Table 6-7: Results of model validation using 2017 event w.r.t. PEV objective function..................... 78

Table 6-8: Results of model validation using 2016 event w.r.t. PEP objective function 78

Table 6-9: Results of model validation using 2016 event w.r.t. PEV objective function..................... 78

Table 6-10: Results of model validation using 2014 event w.r.t. PEP objective function 79

Table 6-11: Results of model validation using 2014 event w.r.t. PEV objective function................... 79

Table 7-1: Final Results of the Validation 90

CHAPTER 1

1 INTRODUCTION

1.1 General

Sufficient knowledge regarding the runoff of a particular watershed and a correct estimation of runoff volume and peaks are very important in water resources management and associated projects (Zelelew & Melesse, 2018). The hydrology of any watershed highly depends upon climatic conditions, mainly rainfall (Ouedraogo, Raude, & Gathenya, 2018). Available water in a particular watershed can be sustainably managed only when there is sound data regarding the rainfall-runoff and other hydrological determinants which affect the water resources (Ibrahim-Bathis & Ahmed, 2016). As it is incapable to have prior knowledge of project hydrology, plans, designs and management of water resources development projects should have to be done using a hypothetical set of future hydrologic conditions (Oleyiblo & Li, 2010). Oleyiblo and Li (2010) further said that in view of the prediction of the response of watersheds to various natural and anthropogenic hydrologic and hydraulic phenomena, a number of hydrologic models have been developed.

Hydrological modelling plays a significant role in understanding the hydrological system of any watershed and providing reliable data in order to direct the water resources of the relevant watershed in a sustainable manner (Ayana & Vargheese, 2013). Hydrological modelling is a demonstration of the real world in a simplified way and it is a complex task. Besides, hydrologic models should be calibrated properly to enhance the efficiency of the model and the confidence of the user (Roy, Begam, Ghosh, & Jana, 2013). There is a wide range of applications of hydrological models like flood forecasting, water resources planning, water resources development and management, coupled systems modelling (ex: water quality, hydro-ecology and climate), etc. (Pechlivanidis, Jackson, Mcintyre, & Wheater, 2011). The selection of a suitable hydrological model depends on the function that the model needs to serve (Wickramaarachchi, Ishidaira, & Wijayaratna, 2012).

1.1.1 Hydrological Modelling in Sri Lanka

Hydrological modelling has become a vital component in numerous water resource projects in Sri Lanka (Kanchanamala, Herath, & Nandalal, 2016). Wijesekara (2010) reviewed 91 of selected literature to identify and assess the research work which had been concluded on surface water and climate change of Sri Lanka. Author summarized that, with regard to river basin, there were 13 studies for Mahaweli river, 10 for Walawe river, 8 for Kelani River, 5 each for Kalu and Nilwala rivers, 2 for Daduru Oya and Gin river 1 each for Bolgoda and Manik river. Besides, with respect to the spatial extent, 28 studies were based on basins, 22 studies were based on small basins and 09 studies were based on reservoirs. It had been identified that only 58% of sub components of surface water resources were covered by researches.

Ellawidana and Navaratne (2017) developed a SWAT (Soil and Water Assessment Tool) model, in order to simulate the streamflow of the Gin river. The performance of the calibration was evaluated using 05 objective functions including Nash-Sutcliff efficiency, R-factor etc. The author recommended that the model can be further used for various water resources analysing like flood risk management.

Another study based on the Gin river was conducted by Wickramaarachchi, Ishidaira, and Wijayaratna (2012) to carry out a study in order to identify the applicability of YHyM/BTOPMC which is a distributed model, used for major characteristics simulation of the hydrology in Gin river basin. It used global data sets available in the public domain with the locally available rainfall and discharge data and model performance was assessed by Nash-Sutcliff Efficiency and volume ratio of computed and observed discharges.

MIKE 11 (NAM model) was also applied to the Gin river basin by Jayapadma, Wickramaarachchi, Silva and Ishidaira (2018) focusing on determining the performance of the MIKE 11 NAM lumped conceptual hydrologic model to simulate the hydrological parameters of the Gin river basin. Locally available field data and public domain data were used for the model development. As the conclusion, the author said that the developed model can be successfully applied for hydrological simulations because the simulated hydrographs depicted a reasonable agreement with the observed.

Nandalal and Ratnayake (2010) developed an event-based model for Kalu river basin using HEC-HMS to verify the applicability of the HEC-HMS under two types of sub basin scales, one model with four sub basins and another model with ten sub basins. The results showed the HEC-HMS software suitability in the modelling of the Kalu river basin and further, it showed there is no effect of sub basin scale.

Another study was carried out based on Kalu river by Kanchanamala, Herath and Nandalal (2016) using lumped HEC-HMS model, in order to identify the most appropriate modelling methods among various different methods presented in HEC-HMS and to evaluate the effect of number of sub basins. The results showed that different methods presented for loss, transform and baseflow models performed differently.

Sampath, Weerakoon and Herath (2015) developed a continuous HEC-HMS model based on part of Daduru Oya river basin to demonstrate the potential HEC-HMS application in flow valuation, with intra-basin diversion and storage irrigation system. The developed model is able to use as a tool which supports to water management in Daduru Oya river basin.

De Silva, Weerakoon and Herath (2014) carried out a study of event and continuous hydrologic modelling in the Kelani river basin with HEC-HMS. Results showed that the calibrated parameters by event-based modelling which used acute field data, can be used to develop for continuous hydrological modelling.

1.1.2 Why HEC-HMS?

There are several hydrological models which are widely being used all over the world like SWAT (Soil Water Assessment Tools) (Daofeng, Ying, Changrning, & Fanghua, 2004), HEC-HMS (Ali, Khan, Aslam, & Khan, 2011), ReAF (Revitalised Flood Hydrograph) (Joo, Kjeldsen, Kim, & Lee, 2013), KINEROS2 model (Canfield & Goodrich, 1966), YHyM/BTOPMC model (Wickramaarachchi, Ishidaira, & Wijayaratna, 2012), Mike Basin, SWMM (Storm Water Management Model) (Zhang, Wang, Wang, Li, & Wang, 2013), NAM model (Jayapadma, Wickramaarachchi, Silva, & Ishidaira, 2018), Streamflow Synthesis and Reservoir Regulation (SSARR) (Kim, et al., 2018) SHER, ABCD model etc.

Among those numerous types of hydrological models, HEC-HMS which is developed by the US Army Corps of Engineers is available for free to use by anyone, while most of the other models are commercial models marketed for expensive prices (Jayadeera, 2016). As a practical rainfall-runoff model, HEC-HMS model is widely used in most countries (Joo, Kjeldsen, Kim, & Lee, 2013).

HEC-HMS is a mathematical watershed model which includes various methods to compute watershed runoff forecasting flow and stage disparity with time (Ratnayake, Sachindra, & Nandalal, 2010). HEC-HMS is user friendly, easy to operate, able to simulate runoff events which are both short and long term and used common methods (Tassew, Belete, & Miegel, 2019). Besides, the model is applicable to perform event-based simulations and continuous simulations as well (Kaatz, 2014) and it supports lumped modelling and distributed modelling (Sampath, Weerakoon, & Herath, 2015). Due to the above-mentioned factors and mainly due to free availability, HEC-HMS has become very popular among hydrologic modellers.

Sampath, Weerakoon and Herath (2015) said that HEC-HMS has been effectively applied to most of the river basins in Sri Lanka. When it is referred to in Section 1.1.1, the above factor can be further affirmed. Considering its obtainability in the public domain, user-friendliness, and availability of adequate literature for the selected project area, HEC-HMS hydrological model is selected for this study.

HEC-HMS mainly consists of four components as basin model which specifies the general characteristics of the basin, the meteorological model which calculates the precipitation input required by sub-basin elements, the control specification which specifies the time step and the simulation period and finally input data to give the observed hydrological variables to the model (Zema, Labate, Martino, & Zimbone, 2016; Ali, Khan, Aslam, & Khan, 2011). As the foundation of the model, the basin model represents the physical watershed (Ali, Khan, Aslam, & Khan, 2011) and it offers a variety of model options to compute losses of water, runoff transformation and baseflow rates which are necessary to simulate runoff production (Zhang, Wang,

Wang, Li, & Wang, 2013). Model allows the user to select suitable ones among various calculation methods to compute each part of the hydrologic process (Kaatz, 2014).

1.1.3 Kelani River Basin

Kelani river basin was selected for this study. This basin is topographically of two distinct types. The upper basin is mountainous while the lower basin below Hanwella is almost flat and the river basin receives an annual rainfall varying from 2,300 mm to 5,700 mm, respectively, over the elevation range of the basin. With its catchment area of 2,340 km^2, the Kelani river basin is the seventh largest river basin in the country and is very rich in water resources (Hettiarachchi & Priyan, 2019) Around 80 % of the water supply to Colombo is supplied by the Kelanir river besides supporting many livelihoods such as fishing and sand mining apart from being used for hydropower generation and transportation making the people very much dependent on the Kelani river for their living. The Kelani river act as a key source of water supply for drinking and industries in the Gampaha District as well.

Seethawaka river is an upper tributary of the Kelani river and it has been based for this study. Seethawaka river basin is located in a mountainous region and due to that, downstream areas of the basin like Deraniyagala area frequently face floods during heavy rainy periods. Even though hydrodynamic models have been developed for Kelani river from Glencourse hydrometric station to sea outfall for the purpose of flood warning, no model is available for the upper reaches above Glencourse (Hettiarachchi & Udowita, 2015). Hence, it will be very important, if there is a hydrological model to forecast the outflows of the downstream, for the purpose of early flood warnings within the Seethawaka river basin. Hence, the Seethawaka river basin was selected for this study.

1.2 Problem Statement

HEC-HMS is a precipitation based runoff and routing modelling system used to create and analyse hydrologic relationships of a watershed. When developing a model, the outflow is calculated from meteorological data by deducting losses, transforming excess precipitation and baseflow. Various methods are presented to select those components in HEC-HMS aimed at event-based simulation. Selection of appropriate method among different available methods should be performed according to the objective of the study and it acts as a key part of the performance of the model**.**

1.3 Overall Objective

The overall objective of the study is to select the most suitable loss and transform methods for Kelani river basin based on Seethawaka sub basin, comparing different combinations of selected loss and transform methods available for event-based simulations. Model performance will be compared with respect to the two objective functions and the most sensitive parameters of the selected methods will also be identified.

1.4 Specific Objectives

The specific objectives which used to fulfil aforementioned overall objective are listed below.

1. To study present basin conditions and literature/status of modelling.
2. To develop a rainfall-runoff model for the Seethawaka watershed, Kelani river basin using HEC-HMS.
3. To calibrate and validate the developed model for different combinations of selected loss methods and transform methods.
4. To compare the model performance with reference to selected objective functions.
5. To identify the best combination of loss and transform methods with regard to objective functions.
6. To carry out a sensitivity analysis in order to determine the most sensitive parameters of selected loss and transform methods.

CHAPTER 2

2 LITERATURE REVIEW

2.1 Hydrological Modelling

Hydrological modelling is the most important component in a hydrological study (Kanchanamala, Herath, & Nandalal, 2016) and it supports an understanding of the conversion process of rainfall into runoff (Ouedraogo, Raude, & Gathenya, 2018). McCuen (1973) said that hydrological modelling is a procedure of representing one or more phases of the hydrologic cycle by a simplified system. It is a mathematical illustration of natural phenomena that affect the energy and water balances of a watershed (Ayana & Vargheese, 2013) and it include a set of parameters to represent different hydrological processes, which need to be calibrated (Kamali & Mousavi, 2014). The output of a hydrological model is a hydrograph, which is a graph of the river flow over time at a specified location (Kaatz, 2014).

Water resources planners are commonly using hydrological modelling tools to compute the hydrological reactions in a basin due to precipitation, for the purpose of basin water handling sustainably (Sampath, Weerakoon, & Herath, 2015). Ayana and Vargheese (2013) said that the main purpose of hydrological modelling is to knowledge regarding hydrological structure to give presumptive information to control water resources in a sustained manner. Numerous types of hydrological models have been developed and employed in the hydrological field (Joo, Kjeldsen, Kim, & Lee, 2013).

Modelers can select event-based modelling or time-series modelling (continuous modelling), depending on the application (Chu & Steinman, 2009). To simulate individual events, event-based models are designed and to simulate long-term data series, time series models are designed (Duhan & Kumar, 2017). Duhan and Kumar (2017) further said that event-based models define the response of a relevant basin to a selected rainfall event and it calculates basin characteristics like peak discharges, total runoff volume, etc., on the basis of the selected event, while time-series modelling integrates the hydrologic processes and the cumulative effects of the number of rainfall events calculating soil moisture content.

2.2 Classifications of Hydrological Modelling

Numerous types of hydrological models are available from black box models to physically based models. The basin type and the purpose of the hydrological prediction are the factors on which the selection of the model depends (Sampath, Weerakoon, & Herath, 2015).

According to the process distribution (Wickramaarachchi, Ishidaira, & Wijayaratna, 2012), hydrological models can be classified as metric models, conceptual models, physics-based models and hybrid models. Metric models are mainly based on observations and seek to characterize the system response from available data (Pechlivanidis, Jackson, Mcintyre, & Wheater, 2011) and they are called as data-based, empirical or black box models (Joo, Kjeldsen, Kim, & Lee, 2013). Pechlivanidis, Jackson, Mcintyre and Wheater (2011) defined conceptual models as they indicate all the elements in hydrological processes proved to be significant in watershed scale input-output relationships. They are based on two criteria as the structure of the model is illustrated before modelling is performed and not all the parameters of the model have a direct physical clarification because they are not individually assessable (Ud Din, 2018). Joo, Kjeldsen, Kim and Lee (2013) said that many river management tools have been formed using comparatively simple conceptual models including HEC-HMS, Revitalized Flood Hydrograph (ReFH) etc. In order to restrain deficits of the conceptual models, physically based hydrologic models are focused on. Physics-based models represent the components of the hydrological cycle related to the land phase such as interception, snowmelt, evaporation, subsurface runoff etc (Islam, 2011). Pechlivanidis, Jackson, Mcintyre and Wheater (2011) said that even though many models are labelled as one of the above-mentioned types, most of the models are a combination of two or more types. They are called hybrid models.

Nandalal and Ratnayake (2010) said that hydrological models can be classified as physical, electrical analogue or mathematical. They further stated that even though analogue and physical models were significant in the past, now the mathematical models have become more convenient, commonly applicable and widely-spread types. It has had a fast improvement with regard to the scientific base. Mathematical models are based on a basic representation of physical mechanisms to the extent possible, state of the art sense of the problem (Bobba, Singh, & Bengtsson, 1999).

According to the spatial description of the watershed process (Islam, 2011; Wickramaarachchi, Ishidaira, & Wijayaratna, 2012), hydrological models are able to be classified as distributed models, semi-distributed and lumped models. Distributed models simulate both spatial variability and physical procedures occurring within a watershed (Ud Din, 2018). Semi-distributed models partially permitted to change in space, dividing the whole basin into a number of sub-basins and lump models assess the catchment reaction at the outlet without counting for an individual sub-catchment response (Tassew, Belete, & Miegel, 2019). In a lumped hydrologic model, with its representative parameters (land use, soil type, etc), the watershed is considered to be homogenous (Kamran, 2017). Kanchanamala, Herath and Nandalal (2016) said that distributed modelling is more accurate than lumped modelling. But due to higher time consumption, the requirement for more data, more effort, etc., lumped hydrological models have become widespread among modellers as it is less inconvenient.

Hydrologic models can also be classified as deterministic and stochastic models (Pechlivanidis, Jackson, Mcintyre, & Wheater, 2011). Nandalal and Ratnayake (2010) said that deterministic models use data presented as it is whereas the other type uses the statistical nature of presented data. Stochastic models are black box type models based on data and they apply mathematical and statistical techniques like regression, transfer functions, neural networks, etc., to link some input to the output of the model (Kamran, 2017).

Based on the time scale, hydrologic models can be categorised as time-series simulation models and event-based models. Event-based hydrological models disclose how a basin responds to a single storm event as the volume of surface runoff, peak discharge, time to peak, etc., while continuous hydrological models disclose how a basin responds to a series of storm events and their accumulative effects over an extensive period of time including both dry and wet condition (Chu & Steinman, 2009). Modellers can select event base or continuous, depending on the application of the model and the selection process may base on many factors like properties of the catchment, characteristics of rainfall, availability of rainfall data, completeness of rainfall and stream monitoring observation (De Silva, Weerakoon, & Herath, 2014). According to Nandalal and Ratnayake (2010), event-based models need preliminary conditions while time-series models require data at an advanced level (ex: soil type to compute soil moisture content, atmospheric data to compute evaporation losses). Unlike event-based models, continuous models compute for a soil moisture balance of a watershed over a long time duration and it is appropriate for pretending daily, monthly and seasonal streamflow (Fleming & Neary, 2004).

Table 2-1: Literature Summary of Hydrological Model Classification

Classification type	**Types of Model**	**Description**
Base on process distribution	Metric	- Called as data-based, empirical or black box models. - Mainly based on observations. - Find to characterize the system response from existing data.
	Conceptual	- Most of the operational river management tools are conceptual models (ex: HEC-HMS, ReFH) - Demonstrate all of the element in hydrological procedures proved to be significance. - Based on two criteria.
	Physics-based	- Represent the components of hydrological cycle associated with the land phase (ex: interception, evaporation)
	Hybrid	- Most of the models are combination of two or more types. They are called as hybrid models.
Physical and mathematical	Physical (Laboratory scale)	- Capable to clearly symbolise spatial variance of important land surface characteristics (ex: slope, aspect)

Classification type	Types of Model	Description
	Electrical analogue or Mathematical	- Most easily and universally applicable, wide spreaded. - Based on basic representation of physical mechanisms to the extent possible, state of the art sense of the problem.
Based on spatial description of the watershed process	Distributed	- Simulate both spatial variability and physical processes occurring within a watershed
	Semi-distributed	- Partly legalised to alter in space, dividing the whole catchment into some sub-catchments.
	Lumped	- Most popular one. - Evaluate the catchment reaction at the outlet neglecting discrete sub-catchment response. - Watershed is treated to be homogenous.
Deterministic and Stochastic	Deterministic	- Use data presented as it is.
	Stochastic	- Use the statistical nature of presented data. - Black box type model based on data. - Use mathematical techniques to connect some input to the output of the model
Based on time scale	Continuous simulation	- Reveal how a basin respond to a number of rainfall events and their accumulative effects over a longer period of time including both dry and wet condition.
	Event based	- Disclose how a basin respond to a single storm event as runoff volume, peak discharge, time to peak.

2.3 HEC-HMS Model

The Hydrologic Modelling System (HEC-HMS) is a physically based, semi-distributed hydrological model (Tassew, Belete, & Miegel, 2019; Zhang, Wang, Wang, Li, & Wang, 2013) developed by the US Army Corps of Engineers, Hydrologic Engineering Center (HEC). It is an integrated hydrologic modelling tool which can compute all hydrological processes of dendritic watershed systems (Ud Din, 2018).

Due to user-friendliness, ability to compute both short and long-time runoff events and common methods used, HEC-HMS has been very prevalent and used in a number of hydrological studies (Tassew, Belete, & Miegel, 2019). Besides, the model is capable of performing event-based simulations and continuous simulations (Kaatz, 2014) and it can be used for both lumped simulation and distributed simulation (Sampath, Weerakoon, & Herath, 2015). HEC-HMS is used for the simulation of a single watershed as well as multiple hydrologically connected watersheds (Ibrahim-Bathis & Ahmed, 2016). It requires different datasets like weather data, digital elevation model (DEM), soil type and land use (Ibrahim-Bathis & Ahmed, 2016).

The HEC-HMS model is created to compute rainfall-runoff processes in an extensive range of geographic areas (Tassew, Belete, & Miegel, 2019) and it can be applied to urban flood analysis, flood frequency analysing, planning of flood warning systems, determination of spillway capacity, stream restoration, etc. (Ford, Pingel, & DeVries, 2008). De Silva, Weerakoon and Herath (2014) revealed the capability of applying HEC-HMS in flood control, mitigation of disaster and water management in medium-sized river basins in tropical countries, based on a study in the Kelani river basin, Sri Lanka. Sampath, Weerakoon and Herath (2015) said that HEC-HMS has been successfully applied to many river basins in Sri Lanka.

2.3.1 HEC-HMS Model Structure

The basic role of the HEC-HMS model is to determine what volume of the precipitation which is being given as input to the model, percolates the ground and what volume converts surface runoff, to route this runoff towards the river, and lastly to route the flow down the river to find the total outflow downstream (Kaatz, 2014).

HEC-HMS model contains an analytical model to compute surface runoff and stream routing, an advanced graphical user interface to demonstrate hydrologic system elements, a system for keeping and handling data and a means for showing model outputs (Zema, Labate, Martino, & Zimbone, 2016). Concerning the above context, there are mainly four input components in HEC-HMS as the basin model, the meteorological model, the control specifications and time series data (Pujara, Joshipura, & Joshi, 2015; Ali et al. 2011; Ouedraogo et al., 2018; Zema et al., 2016)

The basin model is a graphical representation of various elements of the watershed including sub basin, reach, source, junction etc (Kaatz, 2014). It represents the actual objects with parameters describing their deportment in a hydrologic system (Sampath, Weerakoon, & Herath, 2015). The Basin model estimates hydrological losses, the transformation of rainfall to runoff, river routing, and baseflow and specifies the common characteristics of the basin (Zema, Labate, Martino, & Zimbone, 2016). It consists of loss models, direct runoff models, baseflow models and routing models to compute previously mentioned dissimilar components in the runoff procedure (Joo, Kjeldsen, Kim, & Lee, 2013) and the user can select a calculation method among several to represent each process (Kaatz, 2014). Each model component will be described in the section below.

The second major element of the HEC-HMS model is the meteorological component which accounts for the precipitation input needed by a sub-basin element (Zema, Labate, Martino, & Zimbone, 2016). Sampath et al. (2015) say the meteorological component is amenable for making the boundary conditions of a watershed that act on the watershed during a computation. It is composed of the precipitation, evapotranspiration and snowmelt processes (Kaatz, 2014). According to Ali et al., 2011, both point and gridded precipitation can be utilized by meteorological model. It supports eight different precipitation methods as frequency storm, specified hyetograph, gridded precipitation etc.

Control specification of the HEC-HMS model specifies the time step, the inception and the computation period (Zema, Labate, Martino, & Zimbone, 2016). It consists of a starting date and time, an ending date and time and a time interval. Sampath, Weerakoon and Herath (2015) said that the input time-series and other paired value data are kept in HEC's Data Storage System (DSS). Output data of HEC-HMS include peak flow and total volume and they are also stored in DSS (Feldman, 2000).

2.3.2 Precipitation Loss Model

According to Tassew, Belete and Miegel (2019), to compute runoff volume, direct runoff and baseflow, HEC-HMS uses separate models within the basin model. They are the loss model, direct runoff model, baseflow model and routing model.

The loss model in HEC-HMS determines what percentage of precipitation infiltrates through the ground and what percentage becomes runoff contributing to river flow (Kaatz, 2014). It subtracts the volume of water, which is infiltrated, intercepted, stored, evaporated, etc., from the precipitation (Zelelew & Melesse, 2018). HEC-HMS program considers that all the land and water in a catchment can be categorized as either directly connected impervious surface or pervious surface. Precipitation on pervious surfaces in watersheds is subjected to losses as infiltration, evaporation or other volume losses (Nandalal & Ratnayake, 2010). Considering dissimilar modelling theories on the relationships of precipitation and runoff trigging factors like soil properties, land cover etc, there are around 11 kinds of loss estimation methods in HEC-HMS (Zelelew & Melesse, 2018) such as the Green & Ampt method, Initial & Constant method, SCS Curve Number method, Soil Moisture Accounting method, etc.

Only two methods (Soil Moisture Accounting method, Deficit & Constant method) among those various methods have been designed for time-series modelling, while other methods are designed for event-based modelling (De Silva, Weerakoon, & Herath, 2014). Among remaining loss methods, the SCS-CN method which is developed by Soil Conservation Services is popular for un-gauged watersheds (Kaatz, 2014) and it requires only 02 parameters named curve number and initial abstraction. SCS-CN method assumes that the accumulative precipitation, land use, soil type and prior moisture conditions are the factors on which accumulated rainfall excess depends. The initial and Constant loss method is also commonly used for event-based studies considering its simplicity and practicability as it needs only a few parameters (initial loss, constant rate, impervious area) (Halwatura & Najim, 2013). Green and Ampt loss method is a conceptual method (Nandalal & Ratnayake, 2010) that can be used for event-based simulation, which calculates precipitation loss on permissible surfaces and it requires 04 parameters as initial loss, conductivity, wetting front suction and volume moisture deficit (Sardoii, Rostami, Khalighi, & Taheri, 2012)

According to Ud Din (2018), to estimate the runoff accurately, the selection of a suitable loss method plays an essential role.

2.3.3 Transform Model

This process transforms the excess precipitation into point runoff (Nandalal & Ratnayake, 2010) and it simulates the procedure of the runoff of surplus precipitation on the catchment (Zelelew & Melesse, 2018).

HEC-HMS provides a total of 07 dissimilar transformation methods including Clark unit hydrograph method, Kinematic wave method, SCS unit hydrograph method and Snyder unit hydrograph method. According to Halwatura and Najim (2013), some of these methods are complicated since they necessitate a number of input parameters which are not available for many un-gauged watersheds.

The Clark unit hydrograph method uses for both event simulation and continuous simulation studies and it requires a few input parameters such as time of concentration and storage coefficient (De Silva, Weerakoon, & Herath, 2014). It utilizes an instantaneous unit hydrograph (Nandalal & Ratnayake, 2010). Besides the Clark unit hydrograph method, the Snyder unit hydrograph method is also a synthetic unit hydrograph method and it is capable of calculating the peak flow as a unit of precipitation (Halwatura & Najim, 2013).

Kaatz, 2014 used the SCS unit hydrograph method as the transform method in the HEC-HMS model development for a flood early warning system in Uganda. According to Kaatz (2014), the SCS unit hydrograph method is an accepted empirical method based on the findings of many studies performed in the United Estates. Further, he said that 'lag time' is a common parameter for both the Snyder method and the SCS unit hydrograph method.

2.3.4 Baseflow Model

Baseflow is the temporarily stored runoff in the watershed from previous precipitation and delayed subsurface runoff from the current storm (Feldman, 2000). The baseflow component is not very much important in the formation of flood hydrographs when modelling of short rainfall-runoff events. But it plays an important role when modelling the recession limb of flood hydrographs and evaluating accurate flood volumes (Cunderlik & Simonovic, 2004).

Five methods available for simulating baseflow in HEC-HMS are Bounded Recession, Constant Monthly, Linear reservoir, Nonlinear Boussinesq and Recession method. De Silva et al. (2014) said, among various baseflow methods, the Recession method can be used for both event simulation and continuous simulation because it produced the best fit against observations.

Nandalal and Ratnayake (2010) said that the recession method is one fitted well for the Kalu Ganga basin, Sri Lanka. Initial flow, the recession ratio and the threshold flow are the input parameters of this model. The linear reservoir model is another baseflow method, but it is only capable to use for simulation purposes in combination with the Soil moisture accounting loss method (Ud Din, 2018).

Table 2-2: Literature Summary of Computing methods of HEC-HMS model

Model	Method	Remarks
Loss Model	Soil Moisture Accounting	Have been designed for continuous simulations.
	Deficit & Constant	Designed for continuous simulations. To account for continuous changes in moisture content; uses a single soil layer.
	SCS-CN	Popular for un-gauged watersheds. It assumes that the collective precipitation, land use, type of the soil and prior wet conditions are the factors on which accumulated rainfall excess depends.
	Initial and Constant	Commonly used for event-based simulation studies considering its simplicity and practicability
	Green and Ampt	Conceptual method that can be used for event-based simulation, which calculates precipitation loss in permissible surfaces
Transform Model	Clark unit hydrograph	Uses for event simulation and continuous simulation studies.
	Snyder unit hydrograph	Synthetic method and it has been established to calculate the peak flow as a unit of precipitation
	SCS unit hydrograph	Good empirical method based on the findings of many studies carried out in the United Estates.
Baseflow Model	Recession	Capable of use for both event-based modelling and time-series modelling
	Linear reservoir	It is only capable of use for simulation purposes in combination with Soil moisture accounting loss method

2.4 Model Optimization, Calibration and Validation

The efficiency of a model becomes higher when model parameters are optimized and once the parameters are optimized, they represent the catchment characteristics fairly in a better way. The objective of the parameter optimization is to maximize the model efficiency and fit the peak flow discharge (Rathod, Borse, & Manekar, 2015).

As deterministic and stochastic, HEC-HMS has two distinct methods to model optimization. In deterministic optimization, first estimates the primary parameter and then changes them until computed results match as closely as possible with observed streamflow. In stochastic optimization, a gathering of similarly-probable parameter sets was produced which symbolises a sample from the parameter population (Fleming & Brauer, 2018). To measure the goodness of fit between the compute and observed parameters, a multiplicity of objective functions in different ways has been provided.

Parameter optimization is a trial and error type method to fine-tune the values of variables and optimization trial is the component which calculates the results (Pujara, Joshipura, & Joshi, 2015). Pujara et al. (2015) further stated that each optimization trial is consist of all the data regarding the model and it also consists of the search method, objective function and parameters which should be adjusted with the purpose of finding an optimized model.

Hydrological models including HEC-HMS are calibrated by matching computed parameter values with observed ones. The comparison is carried out in an optimization procedure using an objective function selected for a relevant purpose (Kamran, 2017). By calibration process, optimal parameter values are found which minimize the objective function (Cunderlik & Simonovic, 2004). Validation is the process which verifies the calibrated model. Further details about calibration and validation processes will be discussed in Section 2.5.2.

2.4.1 Selection of Events

In event-based modelling, rainfall events selection is an important step for model calibration and validation processes (Chu & Steinman, 2009). The selection of rainfall events depends upon factors like characteristics of the rainfall (duration, intensity, magnitude etc.), properties of the watershed (land use, soil type etc.), availability and completeness of rainfall and streamflow data (De Silva, Weerakoon, & Herath, 2014). The selection of fine-scale time steps is also an important factor in event-based modelling (Duhan & Kumar, 2017). For small basins, storm event data which are small scale and in high resolution, identify the model parameters more correctly (Chu & Steinman, 2009).

Nandalal and Ratnayake (2010) selected four (04) high rainfall events which have 20 days of average duration for each event, for their study based on the Kalu River. One event has been used for the calibration process and others have been used for validation. In his study, De Silva et al. (2014) also used four (04) extremely heavy rainfall events as one event for the calibration process and three events for the validation process. Saleh, Ghobad and Rostami (2011) and Sardoii et al. (2012) who are modellers in Iran, used seven (07) precipitation events respectively which have a duration of 2 or 3 days for their event-based studies. Among those events, six (06) were used for the calibration process and one (01) was used for the validation process. Chu and Steinman (2009) developed an HEC-HMS model by combining event and time-series modelling and four (04) rainfall events (05 mins time step) were used to calibrate and validate the event-based model. In their study, Choudhari, Panigrahi and Paul (2014) randomly selected twenty four (24) storm events covering four (04) years data to conduct rainfall-runoff model and out of those, twelve (12) events were used to calibrate and other twelve (12) storm events were used to validate.

2.4.2 Objective Function

Objective function is the quantifiable measure of the matching between the calculated result and the observed data of a model. As well, each objective function quantity the amount of deviation among calculated and observed values in different ways (Fleming & Brauer, 2018). Modelers can select the objective function according to the objective of the model, such as flood control, water resources planning and management (Ud Din, 2018). As an example, in evaluating a flood event, the most significant feature is the peak flow (Kaatz, 2014).

Guinot, Cappelaere, Delenne and Ruelland (2011) studied about two types of objective functions as distance-based and weak form-based (integral). Many objective functions which are used in hydrological modelling fall under distance-based objective function category and distance may be defined for the original or transformed variables. A weak form-based type is used to find the statistical properties of model residuals among the predicted and observed data.

There are a number of objective functions which are capable of finding the goodness of fit of any simulation (Kamran, 2017). The latest version of the HEC-HMS model provides around 14 objective functions to be selected. Commonly used objective functions by modellers are;

1. Percent Error in Peak (PEP)

$$PEP = \frac{Q_s(peak) - Q_o(peak)}{Q_o(peak)} \times 100$$

where; Q_s *(peak)* – Simulated peak discharge, Q_o *(peak)* – Observed peak discharge (USACE, 2000)

2. Percent Error in Volume (PEV)

$$PEV = \frac{V_s - V_o}{V_o} \times 100$$

where; V_s – Simulated volume, V_o – Observed volume (USACE, 2000)

3. Sum of Square Residual (SSR)

$$SSR = \sum (Q_o - Q_s)^2$$

where; Q_s – Simulated discharge, Q_o – Observed discharge (Jayadeera, 2016)

4. Sum of Absolute Residual (SAR)

$$SSR = \sum ABS(Q_o - Q_s)$$

where; Q_s – Simulated discharge, Q_o – Observed discharge (Jayadeera, 2016)

5. Nash-Sutcliffe Efficiency (NSE)

$$NSE = 1 - \frac{\sum_{i=1}^{n}(Q_{oi} - Q_{si})^2}{\sum_{i=1}^{n}(Q_{oi} - Q_a)^2}$$

where; Q_{oi} – Observed flow at time i, Q_{si} - simulated flow at time i, Q_a - an average observed flow, n – the number of data points (Romali, Yusop, & Ismail, 2018).

6. Root Mean Square Error (RMSE)

$$RMSE = \sqrt{\sum_{i=1}^{n} \frac{(Q_{si} - Q_{oi})^2}{n}}$$

Where; Q_{oi} – Observed flow at time i, Q_{si} - simulated flow at time i, n – the number of data points (Rauf & Ghumman, 2018)

Percent error in Volume (PEV) value quantifies the difference between the computed and observed volume of streamflow while Percent Error in Peak (PEP) value measures the percent deviation between the simulated and observed peak flow (Roy, Begam, Ghosh, & Jana, 2013). PEV values less than or equal to 10% are to be considered a very good performance while PEP values less than or equal to 15% are to be considered a very good performance in the model (Ouedraogo, Raude, & Gathenya, 2018).

Nash-Sutcliffe Efficiency (NSE) is a widely used objective function which gives the proportion of the difference in the data given by the model (Pechlivanidis, Jackson, Mcintyre, & Wheater, 2011). NSE value varies from -∞ (negative infinity) to 1 (Kanchanamala, Herath, & Nandalal, 2016) and with 1 indicating a perfect fit of the data (Kamran, 2017). In common practice, if the NSE value is greater than or equal to 0.75, computed results are taken to be good while NSE values between 0.36 and 0.75 are taken to be satisfactory (Roy, Begam, Ghosh, & Jana, 2013).

Sum of Squared Residual (SSR) measures the sum of the squared differences among simulated and observed flow and it gives greater and lesser weights to large and small errors respectively (Zhang, Wang, Wang, Li, & Wang, 2013). It also compares the magnitudes of the volumes, peaks and time to peak of two hydrographs (Feldman, 2000). Root Mean Square Error (RMSE) minimizes the average distance between observed and calculated, with a larger weight for larger errors (Fleming & Brauer, 2018). The absolute error index represented by the RMSE ranges from 0 to 0.5 (very good performance) rating for the calibration period as well as validation period (Ouedraogo, Raude, & Gathenya, 2018). Zema et al. (2016) said that the model performs well if RMSE and CRM (Coefficient of Residual Mass) are equal to 0 and the Coefficient of Determination (R^2) equals 1.

Sampath, Weerakoon and Herath (2015) used Normalized Objective Function (NOF), Nash Sutcliff Efficiency (R^2_{NS}), Percentage bias (δ_b) and Root Mean Square Error (RMSE) values in his study as quantifiable measures for the skill of simulation and he stated that the reason for selecting those parameters was, past researchers have shown that those parameters were productively used to analyse.

Jayadeera (2016) compared different four objective functions (Peak Weighted Root Mean Square Error, Sum of Absolute Residuals, etc.) in her study, based on four criteria (mass balance error, ratio of calculated flow, Nash-Sutcliff error, MRAE). As a result, it was identified that in the error values for all objective functions, there were no significant changes.

Roy et al. (2013) used Nash-Sutcliffe Efficiency (NSE), Percent error in Volume (PEV), and Percent Error in Peak (PEP) objective functions for the performance evaluation of his HEC-HMS model developed considering a river basin in India and it showed results range from (0.72 to 0.84), (4.39% to 19.47%) and (1.9% to 19%) , respectively, showing good performance of the model.

Tassew et al. (2019) developed a HEC-HMS model for flow simulation in a Lake Tana basin in Ethiopia and the results of the model validation revealed a sensible alteration in peak flow (Relative Error in peak =1.49%) and total volume (Relative Error in Volume = 2.38%). Besides, Nash-Sutcliffe Efficiency (NSE) value showed as 0.884 and their correlation showed as 0.925, indicating that the model is applicable for hydrological simulation in the relevant study area.

2.4.3 Selection of objective function based on the study purpose

Selection of the objective function in a model depends upon the purpose of the modelling exercise (Green & Stephenson, 1986; Oleyiblo & Li, 2010; Ud Din, 2018) such as flood forecasting, water resources planning and management, intra-basin diversion, irrigation etc (Jayadeera, 2016). As the selected objective function should amply reflect the intended hydrologic characteristics, the selection of objective function is a very crucial decision (Kim, et al., 2018; McCuen, 1973).

Flood hydrograph has different components like time to peak, peak discharge, and runoff volume (Kamali & Mousavi, 2014). A single objective function cannot assess to fit all the components between computed and observed hydrograph because each objective function is weighed in favour of different hydrograph components (Green & Stephenson, 1986; Pechlivanidis, Jackson, Mcintyre, & Wheater, 2011). Pechlivanidis et al. (2011) said that selection of multiple objective functions for a model is important, as the results based on a single objective function are biased to an individual component of the hydrograph.

Kaatz (2014) said that when evaluating a flood event, the peak flow of the hydrograph is the most important component, as it relates to the maximum flooding in downstream. Hence in his study related to flood analysis, he selected Percent Error in Peak (PEP) and Peak Weighted Root Mean Square (RMS) objective functions, because they give greater weight to matching the peak of the hydrograph. The Percent Error in Peak (PEP) method focuses on only the fit between the magnitude of the computed and observed peak discharges, not on the errors in peak timing or runoff volume. The Peak-Weighted RMS method also accounts mainly the peak of the hydrograph; however, it considers the volume and peak timing as well.

If the modeller is interested in routing effects, the rising and falling limbs of hydrographs are important (Jayadeera, 2016). For the studies which are focused on the runoff volumes, the Percent Error in Volume objective function can be used. It calculates the variance between the computed and the observed volume of the streamflow (Roy, Begam, Ghosh, & Jana, 2013).

Ud Din (2018) selected the Nash Sutcliff index and Mean Ratio Absolute Error (MRAE) as objective functions in his study due to the aim of the study was matching of overall flow. He stated that the MRAE shows more sensitivity in medium and low flow regions compared to the high flow region while Nash Sutcliff shows the opposite.

Table 2-3: Literature Summary of Objective Function

Research	Objective Functions Used	Remarks
HEC-HMS model for runoff simulation in a tropical catchment with intra-basin diversions (Sampath,Weerakoon, & Herath, 2015)	- Normalized Objective Function (NOF) - Nash Sutcliff Efficiency - Percentage bias (δb) - Root Mean Square Error (RMSE)	- Reason for selecting those parameters was, past researchers have revealed that those parameters were effectively used to assess goodness of fit.
Development of a rainfall-runoff model for Kalu Ganga basin of Sri Lanka Using HEC-HMS Model. (Jayadeera, 2016)	- Peak Weighted Root Mean Square Error - Sum of Absolute Residuals - Sum of Squared Residuals - Percent Error in Volume	- Compared those 04 objective functions based on four criteria as mass balance error, ratio of calculated flow, Nash-Sutcliff error, MRAE. - It was identified that in the error values for all objective functions, there were no significant changes.
Calibration and validation of HEC-HMS model for a river basin in Eastern India. (Roy et al., 2013)	- Nash-Sutcliffe Efficiency (NSE) - Percent error in Volume (PEV) - Percent Error in Peak (PEP)	- The studies focused on the runoff volumes use PEV. - PEV measures the variance between computed and observed volume of the streamflow. - PEP measures the percent deviation among the calculated and observed peak flow.
Application of HEC-HMS model for flow simulation in the Lake Tana Basin (Tassew et al., 2019)	- Relative Error in Peak - Relative Error in Volume - Nash-Sutcliffe Efficiency (NSE)	- Sometimes Nash Sutcliff over-estimates the model performance in high flow and it has low sensitivity to low flow periods.
Development of a HEC-HMS model to inform river gauge placement for a flood early warning system (Kaatz, 2014)	- Percent Error in Peak (PEP) - Peak Weighted Root Mean Square (RMS)	- PEP gives greater weight to match the peak of the hydrograph. - The most significant feature of the hydrograph is the peak flow when analysing a flood event.
Analysis of the effect of loss and baseflow methods on the performance of the HEC-HMS model (Ud Din, 2018)	- Mean Ratio Absolute Error (MRAE)	- Reason for selecting MRAE is the aim of the study was the overall matching of the total flow.

Research	Objective Functions Used	Remarks
The effect of watershed scale on HEC-HMS calibrated Parameters (Zhang et al., 2013)	- Sum of Squared Residual (SSR)	- Measure the sum of the squared differences among simulated and observed flow and it compares the amount of the volumes, peaks and time to peak of two hydrographs.

2.4.4 Calibration and Validation Process

Calibration of a model is a process that adjusts the parameters of the model until simulation results become nearly the same as the observed result taken from the field (Pujara, Joshipura, & Joshi, 2015). Pujara et al. (2015) further stated that the success of a hydrological model depends on how well it is calibrated and its technical dependability on the input data. Zelelew and Langon (2019) said that calibration is the fundamental task for the selection of sensitivity parameters of a relevant hydrological model, by means of sensitivity analysis. A calibrated model provides an assurance to the modeller that the model is an accurate representation of the relevant watershed (Kaatz, 2014).

The primary stage in model calibration is, using the trial and error method and manually adjusting the model parameters. It allows the modeller to create a particular tuning of parameters that gives a proper fit among computed and observed hydrographs (Zhang, Wang, Wang, Li, & Wang, 2013).

There are two methods to calibrate a model as manual calibration and automatic calibration (Ud Din, 2018). In manual calibration, the modeller can adjust the model parameter values by hand using the trial and error method, until the output of the model and observed data closely matches (Pechlivanidis, Jackson, Mcintyre, & Wheater, 2011). Visual judgment, by comparing simulated and observed hydrographs, is the factor that the goodness of fit of the manually calibrated model is based on (Jayadeera, 2016). Successful manual calibration needs an expert hydrologic knowledge and a good understanding of the physical and response characteristics of the watershed, as well as a good understanding of the structure and functioning of the model components and parameters (Yilmaz, Vrugt, Gupta, & Sorooshian, 2010). Pechlivanidis et al. (2011) further said that problem of manual calibration is that it consumes a lot of time.

Automatic calibration is a computer based process (Jayadeera, 2016) which refers to an algorithm that finds the best parameter set (Kamran, 2017). Kamran (2017) further said that an automatic process gives more trustworthy results and it reduces the necessity of expertise. The automatic calibration process has four elements as the selected objective function, optimization algorithm, termination criteria and calibration data (Pechlivanidis et al., 2011). A possible disadvantage of automatic calibration is if not properly designed, the model results are to be hydrologically unrealistic (Yilmaz et al., 2010). In practice, most of the models are calibrated using a combination of both manual and automatic methods (Ud Din, 2018).

Sudheer, Chaubey, Garg and Migliaccio (2006) conducted a study to assess the effect of the calibration time-scale on model predictive capability. They calibrated their model at two-time scales as monthly and daily, and the results showed that the model performance under a smaller time scale cannot be guaranteed by calibrating them under a larger time scale. In conclusion, they suggested that model calibration should be carried out on a daily time scale to keep the hydrological behaviour of the catchment properly.

Kim et al. (2018) said that due to uncertainties of input data, measured data, non-optimized parameters and incomplete model structure, a difference between simulated and observed results may occur. And he further stated that however by the calibration process, non-optimized parameters are only capable of controlling.

The validation process of a model is, testing the ability of a calibrated model to simulate separate observed data sets not used for the calibration process, without changing the calibrated model parameters by keeping their values constant. The degree of deviation among computed and observed hydrographs is the quantifiable measure of the match, like in the calibration process (Cunderlik & Simonovic, 2004).

Assessing the available data is the largest difficulty of the validation process (Ibrahim-Bathis & Ahmed, 2016). For the calibration and validation process of a model, the modeller should use two data sets separately. Oleyiblo and Li (2010) used ten flood events and six flood events , respectively to calibrate and to validate their event-based model developed for two catchments in China. Ouedraogo et al. (2018) carried out a manual calibration using streamflow data of four years (1988-1991) and they used another data set of four years (1992-1995) for the validation process in continuous modelling of a river catchment in Kenya.

2.5 Sensitivity Analysis

Sensitivity analysis is a vital element of hydrological modelling which helps to find prominent parameters (Ouedraogo, Raude, & Gathenya, 2018) and it is possibly useful in all phases of the modelling process like model formulation, calibration and verification (McCuen, 1973). Ouedraogo et al. (2018) further said that among optimized parameters of a model some of them are more sensitive and a minor change in their value can make a vast dissimilarity in the simulated flow. Therefore estimating the most sensitive parameters of a model is very important.

According to Pechlivanidis et al. (2011), two types of sensitivity analysis are available as local and global. The local sensitivity analysis targets to evaluate the influence of change in the values of a parameter within the local region while global sensitivity analysis tries to inquire about the full parameter space within pre-defined feasible parameter ranges.

Kamran (2017) carried out a sensitivity analysis to find the suitable range of parameters for calibration of their HEC-HMS model developed for the Maha Oya basin, Sri Lanka. They selected initial parameters from literature (from a previous study which was carried out for Kelani basin, Sri Lanka) and the sensitivity analysis was performed after trying manual and automatic adjustments to the parameters.

Saleh, Ghobad and Rostami (2011) carried out a sensitivity analysis during their study of comparing three different loss methods for a developed HEC-HMS model and it shows Constant loss rate, Conductivity and Initial Deficit are the most sensitive parameters for Initial & Constant method, Green & Ampt method and Deficit & Constant method , respectively. In another study which was conducted by Sardoii, Rostami, Khalighi and Taheri (2012) to compare different loss methods, a sensitivity analysis was carried out and results showed that among the required parameters of three methods (Initial & Constant method, Green & Ampt method and SCS-CN method), Initial loss, Wet Front Potential Suction and Curve Number were the most sensitive parameters.

Rathod, Borse and Manekar (2015) in their study carried out a sensitivity analysis on lag time and Green Ampt parameters (5 parameters). Parameters were changed from +20% to -20% with the interval of 5% as well by altering only one parameter per time and keeping all other parameters constant, simulated peak flow values were determined. Results showed that percentage imperviousness is the least sensitive parameter and lag time and suction head are the most sensitive parameters. Then model parameters were optimized depending on the sensitivity analysis results by ignoring the least sensitive parameters.

2.6 Selection of Most Suitable Modelling Methods in HEC-HMS

This section discusses the various studies related to selecting the most suitable modelling methods (baseflow, loss, and transform methods) in HEC-HMS, performed by researchers all over the world.

Saleh, Ghobadm and Rostami (2011) developed a HEC-HMS model for **Kan Watershed, Iran** to compare various methods for estimation of rainfall losses (Green & Ampt method, Initial & Constant method, Deficit & Constant loss method) considering two objective functions (Percent error in peak, Percent error in volume). According to each method's performance with respect to two objective functions, the Initial & Constant method showed better results (70% of events had fewer changes of computed to observed discharge) than Green & Ampt and Deficit & Constant methods.

In **Iran**, another study was carried out based on the **Amirkabir dam watershed** by Sardoii, Rostami, Khalighi and Taheri (2012) to compare various methods for evaluation of surface runoff loss, their evaluation and priorities in HEC-HMS. They used Initial & Constant, Green & Ampt and SCS Curve Number methods and results were checked with respect to two objective functions (Percent error in peak flow, Peak-weighted Root Mean Square). Results showed that the Green & Ampt method caused better performance than the other two methods (Initial & Constant and SCS

Curve number). This study showed different results than the previous study conducted by Saleh, Ghobad and Noredin (2011) for another watershed in **Iran**.

Another researcher in Iran, Razmkhah (2016) developed an event-based HEC-HMS model based on the **Hendijan-Jarrahi watershed, Iran** to compare the performance of different loss methods. He used 07 various loss methods in the study including the SCS-CN method, Green and Ampt method, Initial Constant method, Deficit Constant method, Constant Fraction method, Exponential method and Soil Moisture Accounting method. The Soil Moisture Accounting (SMA) method was selected as the best method with max average Nash-Sutcliff and min peak Weighted Root Mean Square Error (PWRMSE) in calibration and verification. As second appropriate methods in sub daily (2 h) event simulation, the SCS-CN method and Exponential method were selected with similar Nash-Sutcliff and PWRMSE.

Zema, Labate, Martino and Zimbone (2016) did a study based on the Mesima Torrent watershed in **Italy** to evaluate the performance of three infiltration methods of HEC-HMS (SCS Curve Number method, Green & Ampt method, Initial & Constant method) in predicting runoff volume and peak flow. According to the results, it was concluded that an adequate accuracy in forecasting runoff volume was accomplished using the SCS-CN method, thanks to calibration of the Initial CN parameter and the Initial & Constant method was better to estimate peak flow after calibrating 'Constant Rate' parameter.

Zelelew and Langon (2019) carried out a study to select an appropriate model set combination fit to the targeted un-gauged catchment and to determine the resultant sensitive parameter values. The Dodigne catchment in **Northern Ethiopia** was the selected study area for the study. Considering the simplicity of applicability and low data requirement they used two methods for the loss model (SCS Curve Number method, Initial and Constant method) with the SCS Unit Hydrograph transform method. According to the results and conclusion, the Initial and Constant loss method with the SCS Unit Hydrograph method was the most suitable model set (NSE of 88% and R^2 of 0.89) for the selected study area.

Another study was carried out by Zelelew and Melesse (2018) considering an un-gauged catchment (Angreb sub basin, Abbay River) in **Northwest Ethiopia** to select the best loss and transform methods and to determine the most sensitive parameter in the selected methods. In that study, they used two loss models (Initial and Constant method, SCS-CN method) and two transform models (SCS Unit Hydrograph, Clark Unit Hydrograph). Best results were acquired in the model set with the Initial & Constant loss method and SCS Unit Hydrograph method with Nash-Suteliff efficiency (NSE) of 82.8%, R^2 of 0.83 and 10.71% of relative bias errors. When comparing these two studies, the most suitable loss method and transform method in the HEC-HMS model for Northern Ethiopia and Northwest Ethiopia were found same.

Pujara, Joshipura and Joshi (2015) applied the HEC-HMS model as a case study for **Hadamtala basin, India** to estimate sensitive parameters. They used the Initial & Constant method, Synthetic Snyder Hydrograph method as loss model and transform model respectively with smaller baseflow. Results of the study showed that Snyder hydrograph method expresses higher sensitivity of parameters in the range of 0 to 28%. It means that the discharge of the basin is more sensitive to a smaller value of lag time and the peaking coefficient for the basin.

Rathod, Borse and Manekar (2015) developed a HEC-HMS model based on the **Tapi River, India** with the objective of matching the peak discharges and enhancing the Nash-Sutcliffe coefficient. Further, SCS Unit Hydrograph and Snyder Unit Hydrograph methods were compared by keeping all parameters constant and best suitable methods for the study area were chosen. For that model, the Green-Ampt method was used as the loss model. According to the results of the study, the SCS method gave the better peak discharge but at the same time base time became smaller while Snyder's method gave the low peak discharge but at the same time, base time was larger than the SCS method. The SCS Unit Hydrograph method was selected for the estimation of runoff in that catchment, considering the safe side of selecting the higher peak discharges. According to the sensitivity analysis, the most sensitive parameter and least sensitive parameter of the Green-Ampt method were suction head and imperviousness, respectively. As well, the most sensitive parameter for the SCS Unit hydrograph method was lag time.

In **Sri Lanka**, Kanchanamala, Herath and Nandalal (2016) developed a model for the **Kalu Ganga basin** using HEC-HMS to identify the most suitable modelling method among various alternative methods. They used Clark Unit Hydrograph, Snyder Unit Hydrograph and SCS Unit Hydrograph methods as transform model, Constant monthly method and Recession method as the baseflow model and Initial Constant, SCS Curve Number and Deficit Constant methods as loss model. Then they created 18 different combinations using the above loss, baseflow and transform methods and for each combination, optimization trials have been run separately. To compare the model performance Nash-Sutcliffe Coefficient was used. They concluded the results, as the most suitable sets of parameter methods for the Kalu Ganga upper basin are the Deficit Constant method as the loss model, Snyder Unit Hydrograph method as the transform model and the Recession method as the baseflow model.

Halwatura and Najim (2013) developed a HEC-HMS model to select the most suitable loss and transform method for the **Aththanagalu Oya basin**. They used the SCS Curve Number method and Deficit Constant methods as loss model and Snyder Unit Hydrograph and Clark Unit Hydrograph methods as transform model. The study was concluded by recommending that Snyder Unit Hydrograph transform method and Deficit Constant loss method for Aththanagalu Oya Basin. Halwatura further stated that the SCS-CN method may not useable for urban watersheds and it suit for agricultural and natural watersheds.

Ud Din (2018) developed a HEC-HMS model for the **Glencourse watershed in the Kelani river basin** in order to discover the best loss and baseflow methods for computing rainfall runoff. Two dissimilar combinations of baseflow and loss methods were considered. As the first combination, Deficit & Constant loss method and Recession baseflow method were used while Soil Moisture Accounting and Linear Reservoir methods were used as the second combination. Among the above two combinations, the second combination (Soil Moisture Accounting loss method and Linear Reservoir baseflow method) was selected as the best combination. Further, in the conclusion of the study, it was stated that the selection of appropriate method in HEC-HMS should be carried out, according to the objective of the study to get an accurate estimation of runoff. According to the sensitivity analysis, for Deficit &

Constant method and Recession method, Impervious area (%) and Recession constant was the most sensitive parameters , respectively while Groundwater1 coefficient and Groundwater1 percolation are the most sensitive parameters when Soil Moisture Accounting was used with linear reservoir method.

Ratnayake, Sachindra and Nandalal (2010) carried out a study to develop a flood prediction tool for the **Nilwala river basin** using WRF (Weather Research and Forecasting) and HEC-HMS models. WRF model was used to predict rainfall over the basin 24 hours into the future and the output of the WRF model was coupled with HEC-HMS to generate river discharge. In their study, they used three transform models (Clark's UH method, Snyder's UH Method and SCS UH method) with the Green Ampt loss model and Recession base flow model. They compared three transform methods and the results showed that Snyder's method acts better than the other two methods, producing Nash-Sutclif efficiencies (NSE) greater than 70% in calibration and greater than 50% in verification.

Table 2-4: Literature summary of selection of most suitable modelling methods in HEC-HMS

No.	Research Topic	Purpose	Methods	Results and Remarks
1	Evaluation of HEC-HMS Methods in Surface Runoff Simulation (Case Study: Kan Watershed, Iran)	Compare the results of different methods for estimation of runoff losses considering various objective functions.	**Loss methods**: Green & Ampt, Initial & Constant, Deficit & Constant **Objective functions**: Percent error in peak Percent error in volume	**Initial & Constant method** showed better results than Green & Ampt and Deficit & Constant methods. **Sensitive parameters:** Initial & Cons. – Constant loss rate Green & Ampt – Conductivity Deficit & Cons. – Initial Deficit
2	Calibration of loss estimation methods in HEC-HMS for simulation of surface Runoff (Case Study: Amirkabir dam watershed, Iran)	Comparison of different methods for estimation of runoff loss, their evaluation and prioritizing in HEC-HMS	**Loss methods**: Green & Ampt, Initial & Constant, SCS-CN **Objective functions**: Percent error in peak Peak Weighted RMS	**Green & Ampt method** caused better performance than the other two methods (Initial & Constant and SCS-CN) **Sensitive parameters:** Initial & Cons. – Initial loss Green & Ampt – Wet front potential SCS-CN – Curve Number
3	Comparing Performance of Different Loss Methods in Rainfall-Runoff Modeling. (Case Study: Hendijan-Jarrahi watershed, Iran)	To compare the performance of 07 different loss methods.	**Loss methods**: SCS-CN, Green & Ampt, Initial Constant, Deficit Constant, Constant Fraction, Exponential and Soil Moisture Accounting	The **Soil Moisture Accounting** (SMA) method was chosen as the best method with max average Nash-Sutcliff. Second suitable methods: SCS-CN and Exponential methods
4	Comparing Different Infiltration Methods of the HEC-HMS Model: The Case Study of the Mésima Torrent (Southern Italy)	Evaluate the three of the different infiltration methods in HEC-HMS	**Loss methods**: SCS-CN method Green & Ampt method Initial & Constant method	Best result is shown by **SCS-CN** method. SCS-CN method is recommended to estimate runoff volume. Initial & Constant method is recommended to estimate peak flow.

No.	Research Topic	Purpose	Methods	Results and Remarks
5	Selection of Appropriate Loss Methods in HEC-HMS Model and Determination of the Derived Values of the Sensitive Parameters for Un-Gauged Catchments in Northern Ethiopia.	For selecting appropriate model set combinations suitable to the targeted un-gauged catchment and sensitivity analysis.	**Loss methods**: SCS-CN method Initial & Constant method **Transform methods**: SCS UH method	**Initial & Constant** method and **SCS UH** method shoed best results. (NSE of 88% & R^2 of 0.89) **Sensitive parameters**: Curve number, Constant loss rate, Lag time
6	Applicability of a Spatially Semi-Distributed Hydrological Model for Watershed Scale Runoff Estimation in Northwest Ethiopia	To select the best loss and transform methods in the model, as well as testing the applicability of the calibrated model to un-gauged watersheds.	**Loss methods**: Initial Constant method SCS-CN method **Transform methods**: SCS UH method Clark UH method	Model set containing the **Initial & Constant** loss method and **SCS UH** transform method showed the best results. (NSE-82.8%, R^2-0.83, Relative bias error-10.71%)
7	A Critical Review on Applicability of HEC-HMS Software for Hydrological Parameter Estimation: A Case Study of India	- To study HEC-HMS and check its applicability to study area. - To estimate hydrological parameters and coefficients.	**Loss method**: Initial & Constant **Transform method**: Synthetic UH	High sensitivity of parameters was shown by the Snyder method (Range of 0-28%) Basin discharge sensitive to – lag time / peaking coefficient/ Muskingum X
8	Simulation of Rainfall - Runoff Process Using HEC-HMS (Case Study : Tapi River , India)	To fit the peak flow discharges and maximizing the Nash Sutcliffe coefficient.	**Transform methods**: SCS UH method Snyder UH method	SCS-CN : high peak discharge, small base time Snyder method: low peak discharge, large base time **SCS UH** is selected because it showed high peak discharge.
9	Impact of Catchment Scale on Rainfall Runoff Modeling: Kalu Ganga	Identification of the most suitable modelling method	**Transform methods**: Clark UH, Snyder's UH, SCS UH	Most suitable set of model combination for Kalu Ganga basin is **Deficit Constant** loss method,

No.	Research Topic	Purpose	Methods	Results and Remarks
	River Catchment upto Ratnapura	from among various alternative methods.	**Baseflow methods**: Constant monthly, Recession **Loss methods**: Initial Const, SCS-CN, Deficit	**Snyder UH** transform method and **Recession** baseflow method.
10	Application of the HEC-HMS Model for Runoff Simulation in a Tropical Catchment (Case Study: Aththanagalu Oya basin)	Select the most suitable loss and transform methods for the Attanagalu Oya basin	**Loss methods**: SCS-CN, Deficit Constant **Transform methods**: Snyder UH, Clark UH	Best for Attanagalu Oya basin; **Snyder UH** transform method and **Deficit Constant** method
11	Analysis of the Effect of Loss And Baseflow Methods And Catchment Scale on Performance of HEC-HMS Model For Kelani River Basin	In order to find the best loss and baseflow methods for simulating rainfall-runoff.	<u>Combination 01</u>; Deficit& constant **loss method** Recession **baseflow method** <u>Combination 02</u>; Soil Moisture Accounting **loss method** Linear reservoir method **baseflow method**	**Combination 02** showed the best results. **Sensitive Parameters:** Combination 01 – Recession constant & Impervious area (%) Combination 02 – GW1 Coefficient, GW1 Percolation
12	Rainfall Forecasting for Flood Prediction in the Nilwala Basin	To compare three transform methods	**Transform methods**: Clark's UH Snyder's UH SCS UH	**Snyder's method** performed better than the other two methods, producing NSE greater than 70% in calibration and greater than 50% in verification.

2.7 Summary of the Literature Survey

According to the literature survey carried out, it can be identified that the most suitable modelling method among numerous methods available in HEC-HMS depends on the study area. It varied from country to country, basin to basin and watershed to watershed. A selected appropriate model set for one basin may not be suited for another basin in the same country. In Sri Lanka, only a few studies have been undertaken for selecting the most suitable modelling methods for HEC-HMS models (evaluate the effect of modelling methods on the performance of the HEC-HMS model). Halwatura and Najim (2013) said that the HEC-HMS model is not calibrated and validated for Sri Lankan watersheds and it is been needed reliable data inputs for checking the suitability of a developed model to study location and purpose.

As mentioned in Section 2.5, Kanchanamala et al. (2016) found that Deficit Constant loss method, Snyder Unit Hydrograph transform method and Recession baseflow method were most suitable for Kalu Ganga upper basin. Halwatura and Najim (2013) said that the Deficit Constant loss method and Snyder Unit Hydrograph transform method were suitable for the Aththanagalu Oya basin. Ud Din (2018) found that Soil Moisture Accounting and Linear Reservoir method were the most suitable loss and baseflow methods , respectively for the Glencourse watershed in the Kelani river basin. Ratnayake, Sachindra and Nandalal (2010) said that Snyder's UH method was the best transform method for the Nilwala river basin.

The most suitable modelling methods are also dependent upon the simulation type of the model (ex: event-based, continuous), as some methods can be used only for one simulation type. The study which is carried out by Ud Din (2018) based on the Kelani River basin was a continuous simulation. In this study, an event-based simulation will be carried out to select the most suitable loss and transform methods for the Kelani Ganga basin using the Seethawaka sub-catchment, with respect to various objective functions and to identify the most sensitive parameters of the selected methods.

CHAPTER 3

3 METHODOLOGY

3.1 Methodology Outline

The methodology used in this study is shown in Figure 3-1. As the first step of the study, the research need was identified considering the hydrological modelling and water resources planning in Sri Lanka. After that, the overall objective and the specific objectives were finalized which are aimed to be fulfilled through the study. Then a comprehensive literature review was carried out to identify the current status of the relevant research area and it has been summarized in Chapter 02.

Model selection and the data collection were carried out simultaneously. Due to the free availability, user friendliness and the availability of sufficient literature for the selected project area, HEC-HMS hydrological model was selected for this study. Rainfall and streamflow data were collected from Irrigation Department for four (04) extreme storm events which occurred in the recent past. Among them, one (01) storm event was used for the calibration process while the other three (03) storm events were used for the validation process.

The selection of computing methods was accomplished according to the literature review, data availability and ease of applicability. From the possible methods given in the HEC-HMS, two loss methods and three transform methods were selected for this study and six (06) different combinations using those loss and transform methods were tried out to evaluate the performance of the model. Model development is the next significant step of the study and the process of the model development, estimation of initial parameter values as well as the objective function selection has been described in Chapter 05. To fulfil the objective of this study, two objective functions (Percent Error in Peak and Percent Error in Volume) were selected to determine the best fit between observed and simulated hydrograph related to each combination. After the model development, sensitivity analysis was carried out to estimate the most sensitive parameters of the model in order to use for the model calibration process. Then the model was calibrated and validated using above mentioned rainfall and streamflow data. These steps were applied for all the six (06) combinations of computing methods.

In addition to the two objective functions, three performance indicators (Nash-Sutcliff Index, RMSE and Percentage bias) were used as to assess the performance of the model. Values of the above mentioned indicators which were achieved after calibration and validation processes were tabulated under the results section (Chapter 06). Objective function values for each option as well as other performance indicator values were analysed and the best combination was selected with regard to each objective function which shows the least value, for overall matching of flow.

The final steps of the study were discussion, conclusion and recommendations and they are presented in Chapter 07, Chapter 08 and Chapter 09 , respectively.

3.2 Methodology Flowchart

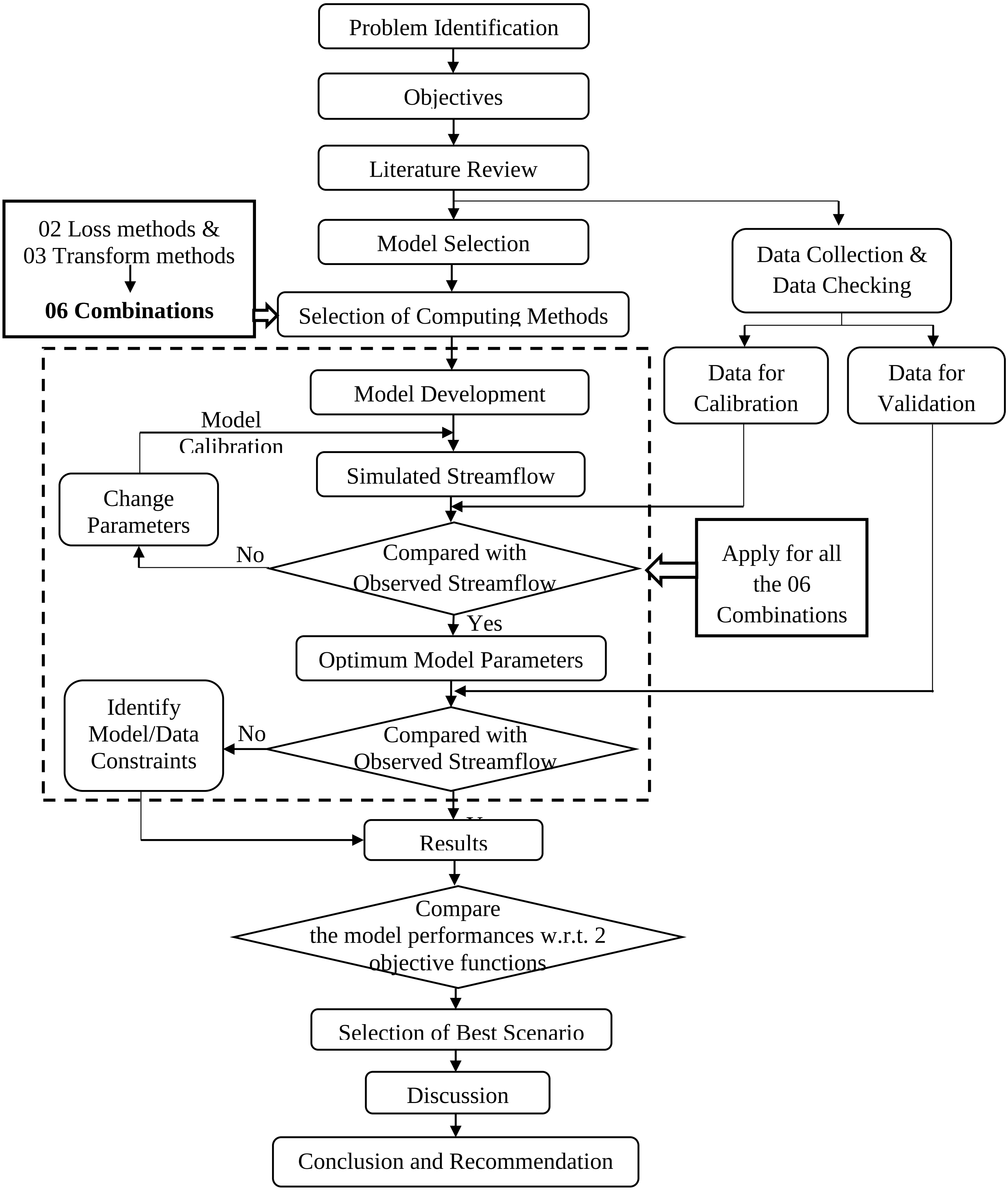

Figure 3-1: Methodology Flowchart

CHAPTER 4

4 DATA CHECKING AND ANALYSIS

4.1 Study Area

Seethawaka sub basin of Kelani river basin which is based on the Seethawaka river was selected for this study. Seethawaka river which is an upper tributary of the Kelani river is supplemented by a number of tributaries at its upper reaches and it has 180 km^2 of catchment area up to Deraniyagala. This region of the country is mountainous and the elevation of the catchment area ranges from 56 m to 1,600 m MSL. The upper catchment is covered by virgin dense tropical rainforest and receives an average annual rainfall of about 4,600 mm (Source: Meteorological Department, Sri Lanka). The lower catchment of about 18% of the total area extent has a relatively mild slope and receives an average annual rainfall of about 3,825 mm. The lower catchment is under varying land use including tea, rubber, paddy cultivation and home gardens.

Deraniyagala stream gauging station and three rainfall gauging stations (Deraniyagala, Kitulgala and Norwood), which are lying in the Seethawaka catchment and outside of the catchment but contributing to the catchment rainfall were considered in this study. The coordinates of the rainfall gauging stations as well as the stream gauging station used for this study are mentioned below in Table 4-1. The study area map with the locations of gauging stations is shown in below Figure 4-1.

Land use map (1:50,000) obtained from Survey Department, Sri Lanka was classified into six (06) classes as shown in Figure 4-2. Composition values of each land use pattern are shown in Table 4-2.

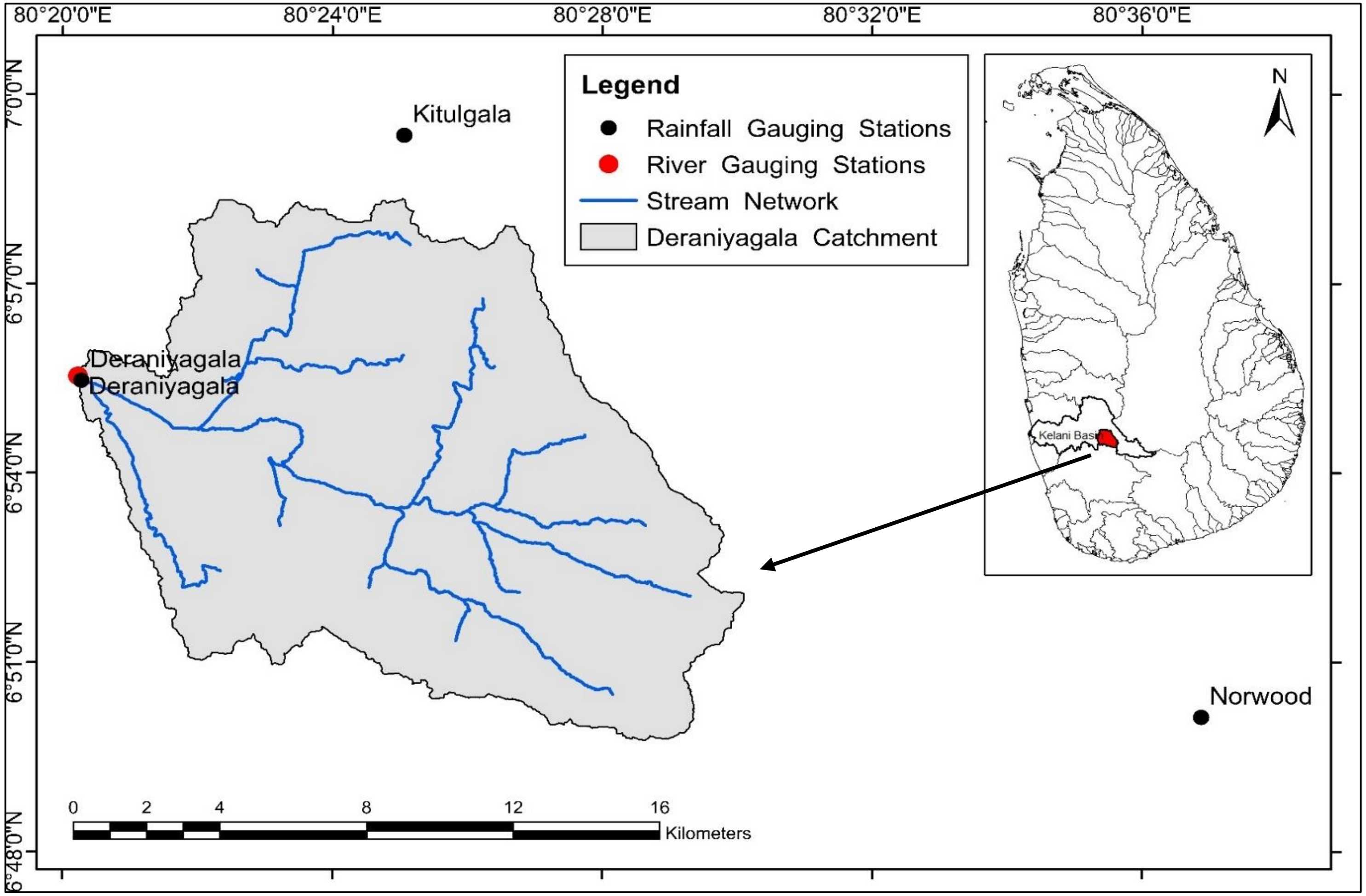

Figure 4-1: Study Area

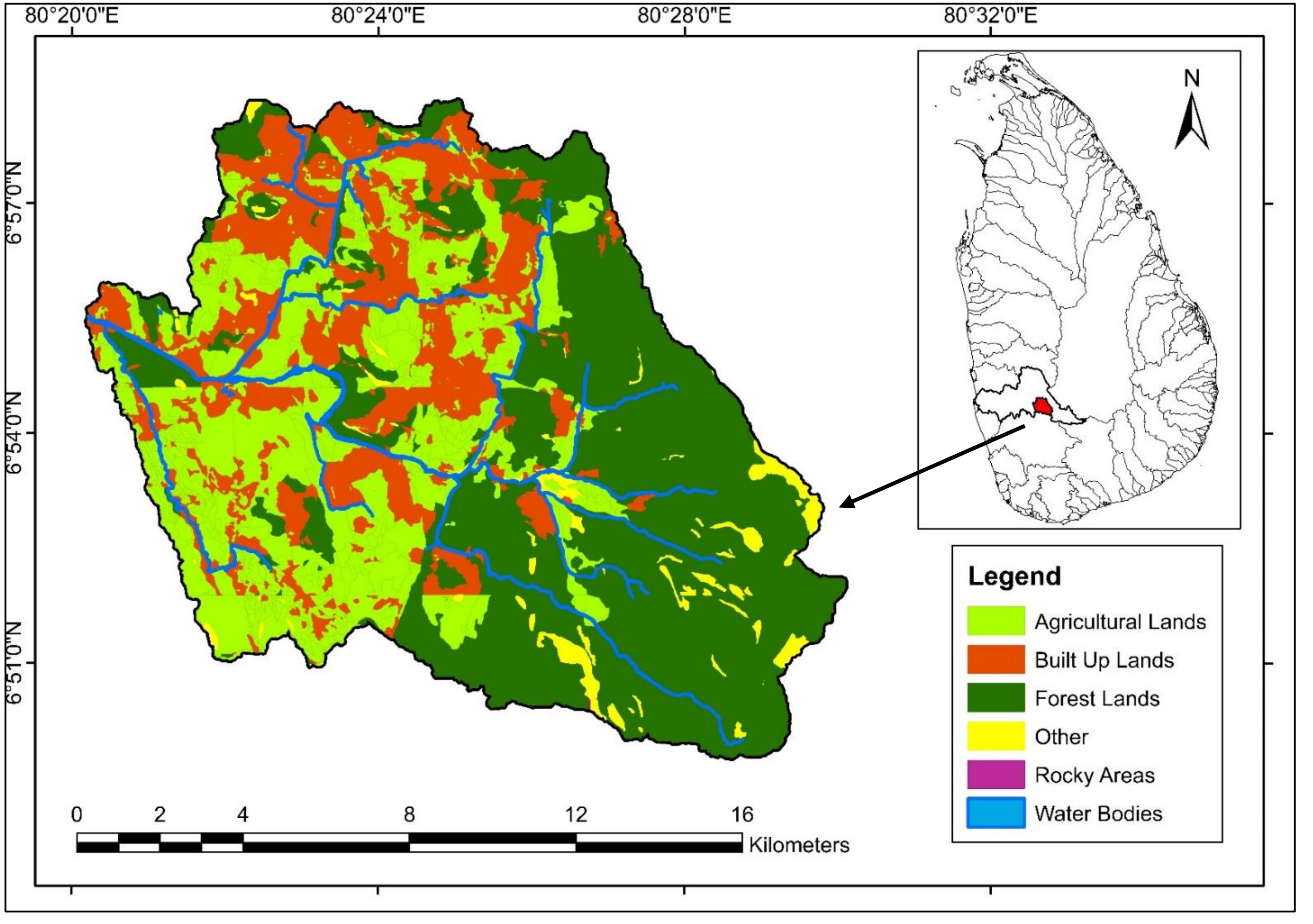

Figure 4-2: Land Use Classification of Study Area

Table 4-1: Locations of gauging stations in Seethawaka Catchment used for the study

Gauging Station	**Location**	
	N	**E**
Deraniyagala stream gauge	6° 55' 33.2"	80° 20' 21.2"
Deraniyagala rain gauge	6° 55' 29.2"	80° 20' 24.2"
Kitulgala rain gauge	6° 59' 27.6"	80° 25' 10.0"
Norwood rain gauge	6° 50' 09.4"	80° 37' 0.10"

Table 4-2: Land Use Classification of Seethawaka Watershed

Land Use Pattern	**Area (km^2)**	**Percentage of total area (%)**
Agricultural Lands	53.46	29.65
Build-up Lands	38.78	21.50
Forest	81.06	44.95
Other	4.99	2.77
Rocky	19.91	0.01
Water Bodies	2.03	1.13
Total	**180.34**	**100.00**

4.2 Data Collection

Key data which was used for this study are rainfall, streamflow and topographic data. Rainfall and streamflow data were collected from the Irrigation Department, Sri Lanka. Digital Elevation Model (DEM) developed for the whole Kelani basin was obtained from Survey Department. Table 4-3 shows the details of relevant data sources and data resolutions.

Since the study area (Seethawaka catchment) is relatively small, the time of concentration of the area takes a considerably low value. Meteorological data with higher resolution is preferred for event based modelling based on such small catchments. Hence, hourly rainfall and streamflow data were used for the calibration and validation processes of this study.

Table 4-3: Data Sources and Resolutions

Data type	**Resolution**	**Data period**	**Source**
Rainfall	Hourly	May 2014, May 2016, May 2017, May 2018	Irrigation Department
Streamflow	Hourly	May 2014, May 2016, May 2017, May 2018	Irrigation Department
Land use	1:50000	N/A	Survey Department
DEM	4 m Grid	N/A	Survey Department

Since the two rainfall stations out of three stations are located outside the catchment, they were checked against the isohyetal map to make sure that a representatively reasonable rainfall distribution is adopted for the study. Dearniyagala catchment and gauging station locations within the Average Annual Rainfall map of Sri Lanka are shown in Annexure 1. According to that, it can be identified that a reasonable rainfall distribution can be expected from those three gauging stations.

4.2.1 Storm Events

As indicated in the literature review, for small catchments, storm event data which are small scale and in high resolution, identify the model parameters more accurately on a fine time scale (Chu & Steinman, 2009). Hence, hourly rainfall data of four (04) storm events were collected for the above three rainfall gauging stations from

Irrigation Department, as this study is an event based simulation. Those events were the most extreme rain events which happened during the relevant year. Hourly streamflow data of the same storm events for the Deraniyagala stream gauging station were also collected. The details of storm events are shown in below Table 4-4.

Table 4-4: Storm Event Details

Storm Event	**Time Period**	**Rainfall Duration**	**Total Rainfall (mm)**	**Total Streamflow (mm)**	**Peak Flow (m^3/s)**
2014 event	02/06/2014 – 05/06/2014	04 days	447.3	146.94	353.00
2016 event	15/05/2016 – 19/05/2016	05 days	1,317.7	311.46	427.45
2017 event	25/05/2017 – 29/05/2017	05 days	659.3	221.30	572.00
2018 event	20/05/2018 – 23/05/2018	04 days	1,006.0	232.22	511.78

4.3 Data Checking

4.3.1 Visual Data Checking

To find out if there are any discrepancies in data visual checking was carried out. To identify the abnormalities in available hydrological data, it should be carefully checked prior to model development. Therefore, the first step of the data checking was visual checking. For each rainfall event, streamflow against rainfall was plotted in the same graph for each gauging station and the response of streamflow against rainfall was checked.

Figure 4-3 shows the observed Deraniyagala streamflow with respect to the rainfall of all three gauging stations Deraniyagala, Kitulgala and Norwood during the 2018 storm event. In accordance with those plots, rainfall of all three gauging stations well responds and corresponds to Deraniyagala streamflow during the 2018 storm event. Kitulgala gauging station has received more rainfall than the other two stations while Norwood gauging station receives the lowest rainfall. Deraniyagala streamflow with respect to the rainfall in each rainfall gauging station for other storm events are shown in Annexure 2.

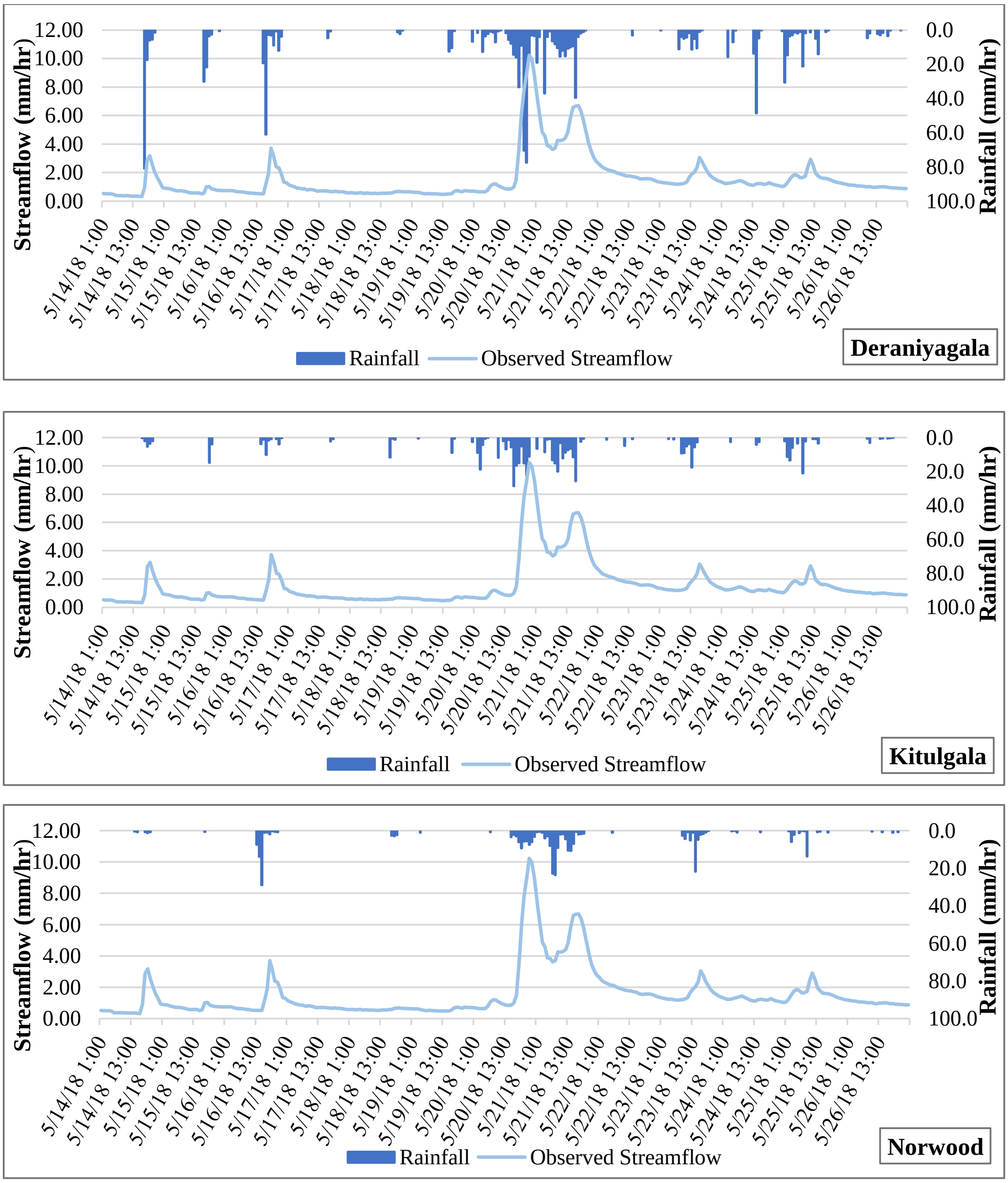

Figure 4-3: Streamflow Vs Rainfall of Three Stations for 2018 Flood Event

4.3.2 Thiessen Average Rainfall

To find the average rainfall of the catchment, the Thiessen polygon method was used. ArcGIS 10.3 (ESRI, USA) was used to develop Thiessen polygons for each rainfall gauging station in Seethawaka watershed and the developed Thiessen polygon is shown in Figure 4-4 while the Table 4-5 also shows the Thiessen weights determined for each rainfall gauging station. The rainfall of each station was multiplied by relevant Thiessen weight to obtain the Thiessen average rainfall.

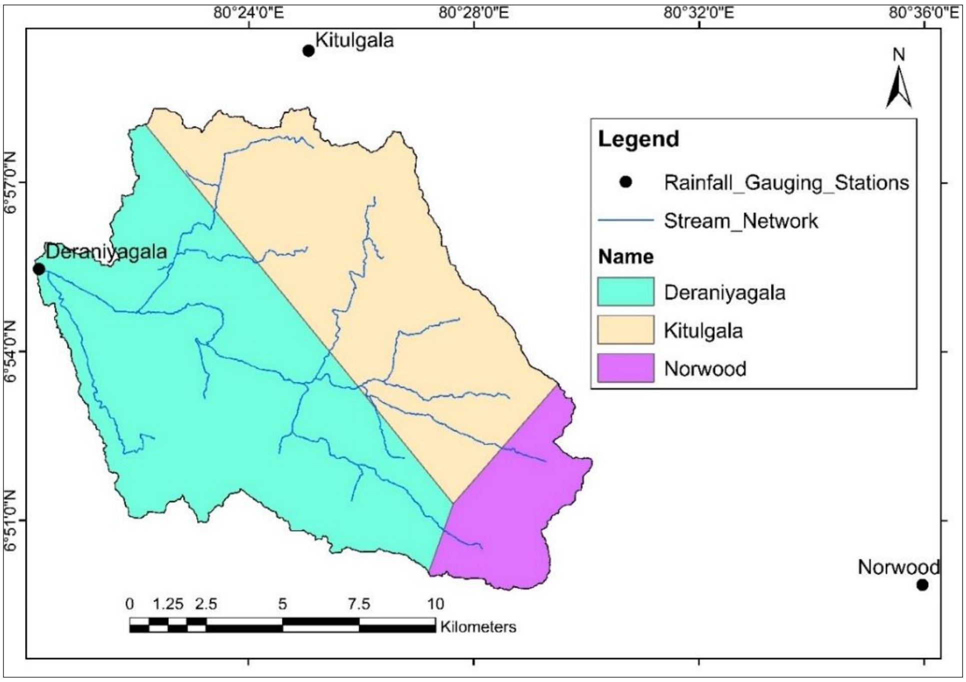

Figure 4-4: Thiessen Polygon for Seethawaka Watershed

Table 4-5: Thiessen weights for each rainfall gauging station

Rainfall Station	Area (km^2)	Thiessen Weight
Deraniyagala	91.68	0.51
Kithulgala	70.96	0.39
Norwood	17.77	0.10
Total	**180.41**	**1.00**

Thiessen average rainfall and observed streamflow were plotted in the same plot for each event and they are presented in Figure 4-6 to Figure 4-9. According to those plots, it can be identified that Thiessen rainfall well responds to the observed streamflow in each event.

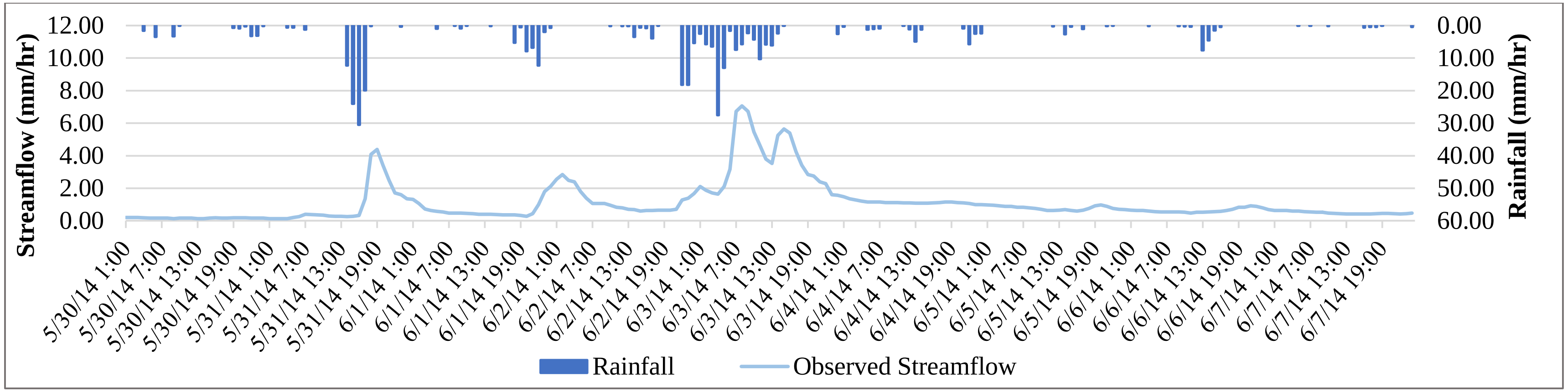

Figure 4-5: Thiessen Average Rainfall Vs Streamflow for Deraniyagla Catchment for 2014 Storm Event

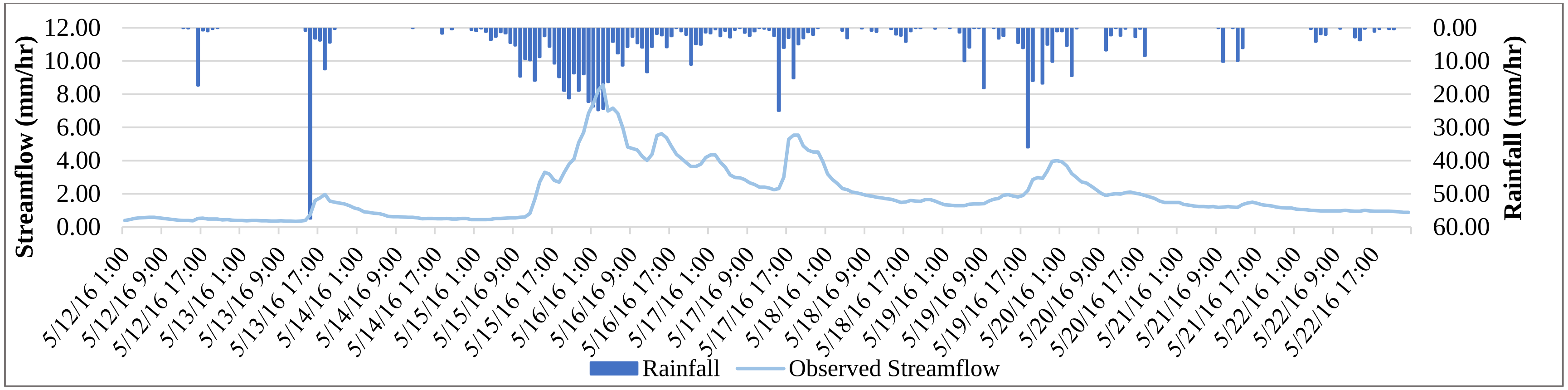

Figure 4-6: Thiessen Average Rainfall Vs Streamflow for Deraniyagla Catchment for 2016 Storm Event

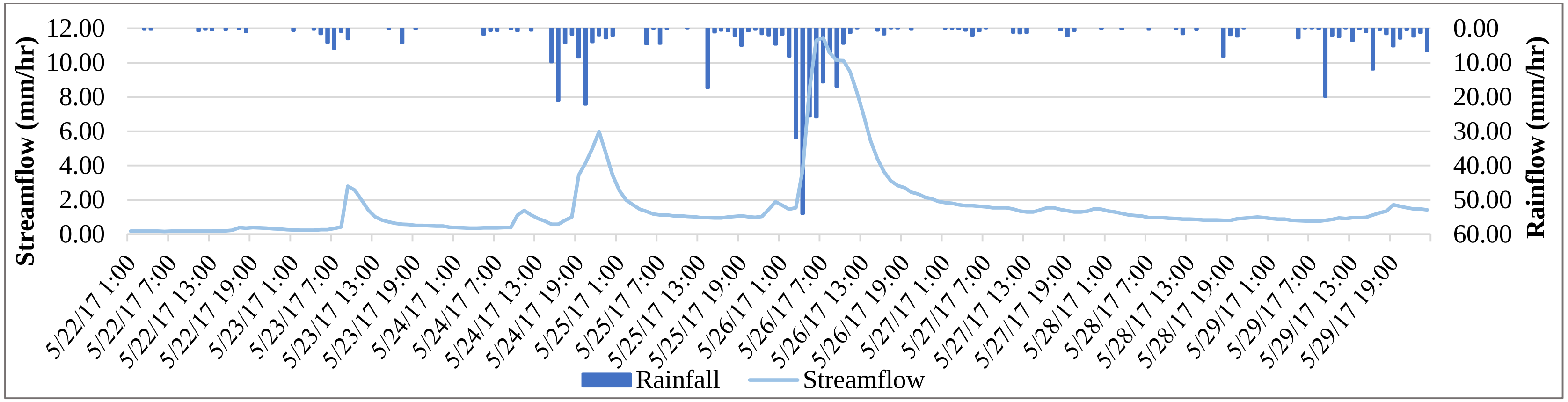

Figure 4-7: Thiessen Average Rainfall Vs Streamflow for Deraniyagla Catchment for 2017 Storm Event

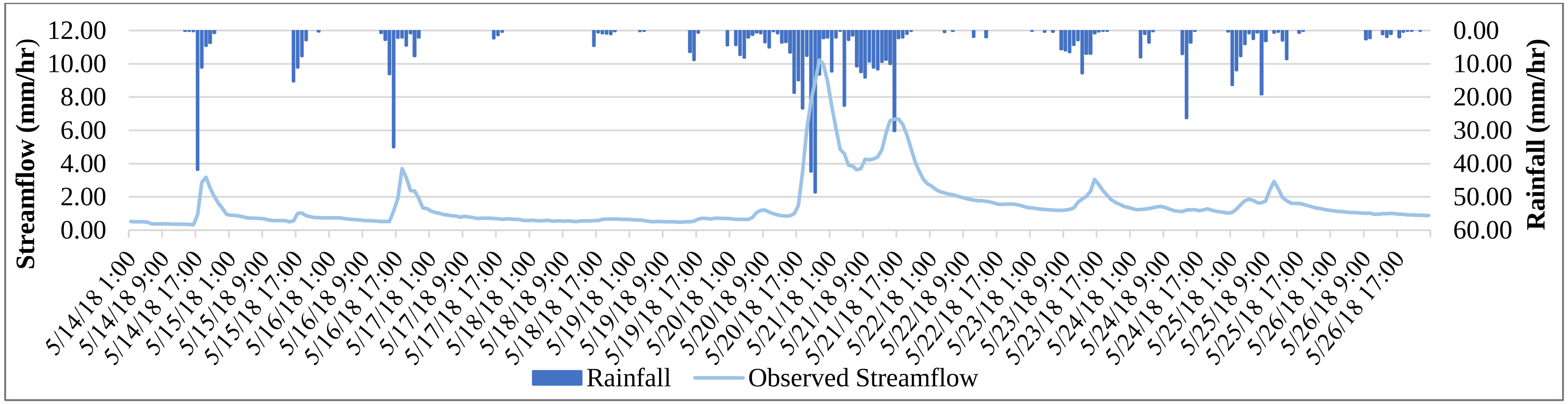

Figure 4-8: Thiessen Average Rainfall Vs Streamflow for Deraniyagla Catchment for 2018 Storm Event

4.4 Selection of Computing Methods

To compute runoff volume, direct runoff and baseflow, HEC-HMS uses separate models within the basin model. They are the loss model, direct runoff model, baseflow model and routing model. HEC-HMS provides a number of various methods for each model to select by the user. Selection of appropriate method among different available methods for each model act a significant part in the performance of the model.

According to the literature review, among eleven dissimilar loss methods available in HEC-HMS for calculating precipitation loss, all other methods can be used for event based simulation except Deficit & Constant rate method and Soil Moisture Accounting method. To transforms the excess precipitation into point runoff, HEC-HMS provides a total of seven different transformation methods.

From the possible methods given in the HEC-HMS, two loss methods namely **SCS Curve Number method**, **Initial Constant method** and three transform methods namely **SCS Unit Hydrograph method**, **Clark Unit Hydrograph method** and **Snyder Unit Hydrograph method** were selected for this study. The corresponding methods were chosen by considering literature review, data availability and ease of applicability. Six dissimilar combinations of loss and transform methods as shown in Table 4.6 were used to estimate the performance of the model.

Recession baseflow method was selected for each combination of this study because it is usually more appropriate for shorter duration periods for watersheds where the precipitation event effect to the baseflow volume and timing. As the routing method, the lag model was used in this study because that method is suitable for steeper reaches like Seethawaka Ganga.

Table 4-6: Combination of Methods used in the Study

Combination	Loss method		Transform method		
	SCS-CN	Initial Constant	SCS UH	Clark UH	Snyder UH
1	√	-	√	-	-
2	√	-	-	√	-
3	√	-	-	-	√
4	-	√	√	-	-
5	-	√	-	√	-
6	-	√	-	-	√

CHAPTER 5

5 MODEL DEVELOPMENT AND APPLICATIONS

5.1 HEC-HMS Model Development

This section will explain how the HEC-HMS model is created and it describes how parameters are derived and then applied to the different calculation methods used in the model. The basin model, the meteorological model and control specifications were created before running the model.

5.1.1 Development of Basin Model

Basin model estimates hydrological losses, the transformation of rainfall to runoff, river routing, baseflow and it specifies the general characteristics of the basin. It is a graphical representation of the different elements of the watershed including sub basin, river reaches, etc. It consists of loss models, direct runoff models, baseflow models and routing models to analyse various elements in the runoff process.

The basin model should be created either by HEC-GeoHMS with DEM (Digital Elevation Model) or by feeding data into HEC-HMS itself, at first in the procedure of model development. In this study, the basin model was developed by HEC-GeoHMS using the DEM of the study area. HEC-GeoHMS which is an extension tool of ArcGIS is selected for this study because of its ease of use with HEC-HMS.

5.1.2 Development of Loss Model

In order to determine what percentage of precipitation infiltrates through the ground and what percentage becomes runoff contributing to river flow, the loss calculating method should be added to each sub basin. For this study, the SCS Curve Number method and Initial Constant method were selected as precipitation loss methods.

SCS Curve Number method

This method was developed by the Soil Conservation Service (SCS), United States (Feldman, 2000) and it estimates precipitation excess using cumulative precipitation, soil cover, land use and antecedent moisture as indicated in the following equation;

$$P_e = \frac{(P - I_a)^2}{P - I_a + S}$$

where P_e = accumulated precipitation excess at time t; P = accumulated rainfall depth at time t; I_a = Initial abstraction and S = potential maximum retention.

The method requires three parameters as Curve Number (CN), Initial Abstraction (I_a) and Percent Imperviousness. The Curve Number is the main parameter of this method and it is estimated as a function of land use, antecedent watershed moisture and soil type. Since different land use patterns can be found in the study area, weighted curve number was derived using initial curve numbers obtained from the book Applied Hydrology (Chow, Maidment, & Mays, 1988) and Appendix A - Technical Manual of HEC-HMS. According to the Chow et al. (1988) and Feldman (2000), based on the minimum filtration rate, soils are categorized into four groups as A,B,C and D. Among them, soil group C was used in this study to calculate the CN values as that type is used for soil for usually high in clay. Seethawaka river basin is located in the wet zone of the country and it mainly consists of forest and agricultural lands. As this basin is very small one, same soil type was considered for the whole catchment. Weighted CN calculations for each subbasin are shown in Table 3-7.

Initial Abstraction (I_a) is computed as a fraction of the potential maximum retention (S) which is the maximum total amount of precipitation that can be absorbed by the ground and is a function of the curve number. The US Army Corps of Engineers has given the relationship of curve number, and potential maximum retention and initial abstraction as;

$$S = \frac{25400}{CN} - 254$$

$$I_a = 0.2 \times S$$

According to the above equations, maximum potential retention (S) and Initial abstraction (I_a) were obtained as 62.37 mm and 12.47 mm, respectively. Percent imperviousness defines the percentage of the impervious surface of a sub basin. It was adjusted by comparing simulating and observed streamflow volumes during the calibration process.

Table 5-1: Weighted Curve Number Calculations for each Sub-basin in Seethawaka Catchment

Sub Basin	**Land Use Type**	**Area%**	**Soil Group C**		
			Individual CN	**Weighted CN**	**CN**
Sub basin-1	Agricultural Lands	11.94	88	10.51	78.10
	Build-up Lands	7.81	74	5.78	
	Forest	74.53	77	57.39	
	Water Bodies	0.90	79	0.71	
	Scrub	4.81	77	3.71	
Sub basin-2	Agricultural Lands	10.54	88	9.28	78.05
	Build-up Lands	4.29	74	3.17	
	Forest	80.44	77	61.94	
	Water Bodies	0.71	79	0.56	
	Rocky	0.04	95	0.04	
	Scrub	3.99	77	3.07	
Sub basin-3	Agricultural Lands	52.96	88	46.60	81.93
	Build-up Lands	31.13	74	23.03	
	Forest	13.11	77	10.10	
	Water Bodies	2.01	79	1.59	
	Scrub	0.79	77	0.61	
Sub basin-4	Agricultural Lands	60.94	88	53.62	82.87
	Build-up Lands	28.25	74	20.91	
	Forest	9.48	77	7.30	
	Water Bodies	0.64	79	0.51	
	Scrub	0.69	77	0.53	
Sub basin-5	Agricultural Lands	63.07	88	55.50	83.24
	Build-up Lands	24.41	74	18.06	
	Forest	10.00	77	7.70	
	Water Bodies	1.52	79	1.20	
	Rocky	0.03	95	0.03	
	Scrub	0.98	77	0.75	

Initial Constant method

The theory of the Initial and Constant loss method is that the maximum possible rate of precipitation loss, f_c is constant throughout an event. This method necessitates two input parameters as the Initial Loss and the Constant Rate which show the physical features of soil, land use and antecedence conditions of the basin. If the basin is in a saturated condition, the initial loss will approach zero while in dry condition initial loss enhances and shows the maximum height of rainfall that cannot be changed into the runoff. Feldman (2000) indicated that initial loss may vary from 10% - 20% of the total rainfall for forest areas to 0.1 inch – 0.2 inches for urban areas.

Zema, Labate, Martino and Zimbone (2016) indicated in their study, an initial loss value of 12.7 mm (AMC III, wet soil) for agricultural and forested areas. That value was used for this study as the Seethawaka river basin is also an agricultural and forested area. The range for constant rate suggested by Feldman (2000) was used to estimate the constant rate considering the hydrological soil group of the study area is Group ‘C’ (0.05 - 0.15). The values used for initial loss, constant rate and percent imperviousness in this study are given in below Table 5-2. The values for constant loss rate and per cent imperviousness were adjusted by comparing simulating and observed streamflow volumes during the calibration process.

Table 5-2: Values assigned for parameters of Initial and Constant loss method

Parameter	**Values**
Initial loss (mm)	12.7
Constant loss (in/hour)	0.10
Percent imperviousness (%)	20

5.1.3 Development of Transform Model

Transform model indicates how the volume of surplus rainfall is transformed into runoff at a specific point. In this study three transform methods namely the SCS Unit Hydrograph method, Clark Unit Hydrograph method and Snyder Unit Hydrograph method were used.

SCS Unit Hydrograph method

This method was developed by the Soil Conservation Service (SCS) and it is based upon averages of unit hydrographs derived from gaged rainfall and runoff for most of the small agricultural watersheds in the US.

The input parameter which is required by this method is Lag time. Lag time was obtained using time of concentration (Lag time (t_p) = 0.6×Time of concentration; Feldman, 2000). The time of concentration is the time occupied by a water particle to move to the catchment outlet from the most hydraulically remote point. It was calculated using the Kirpich formula (Subramanya, 2008).

Kirpich formula is as fallows;

$$T_c = 0.0195L^{0.77}S^{-0.385}$$

where; T_c = Time of concentration (mins)

L = Maximum length of travel of water (m)

S = Slope of the basin (m/m)

Time of concentration and lag time calculations is tabulated in Table 5-3 below.

Table 5-3: Calculation of Time of Concentrations and Lag time for Subbasins

Sub Basin	L (m)	Basin Slope (S)	T_c (h)	T_c (mins)	t_p(mins)
Sub basin-1	13,592.22	0.117	1.13	67.81	40.68
Sub basin-2	15,654.65	0.102	1.33	79.61	47.77
Sub basin-3	12,873.28	0.036	1.71	102.40	61.44
Sub basin-4	14,179.28	0.032	1.92	115.50	69.30
Sub basin-5	14,824.28	0.039	1.85	111.11	66.67

Clark Unit Hydrograph method

Clark Unit Hydrograph method is a synthetic unit hydrograph method which is not essential to create a unit hydrograph over the past observation analysing. This model derives a watershed unit hydrograph by representing two critical processes named translation and attenuation in the alteration of surplus precipitation to runoff.

This method needs two input parameters as the time of concentration and storage coefficient. Time of concentration derived for the SCS-UH method was used for this method as well. The storage coefficient (R) is an index of the temporary storage of precipitation surplus as it drains to the outlet point. Feldman (2000) stated a relationship between Time of Concentration and Storage Coefficient and it was used for this study. The relationship is;

$$R/(T_c + R) = 0.65$$

$$R = T_c(13/7)$$

where; T_c = Time of concentration (mins)

Table 5-4: Calculations of Storage Coefficient for each Sub-basin

Basin	T_c (h)	R (h)
Sub basin-1	1.13	2.10
Sub basin-2	1.33	2.46
Sub basin-3	1.71	3.17
Sub basin-4	1.92	3.57
Sub basin-5	1.85	3.44

Snyder Unit Hydrograph method

The Snyder Unit hydrograph method is also a synthetic unit hydrograph method and it has been created to calculate the peak flow as a unit of precipitation.

The two input parameters which are required by this method were Standard Lag and Peaking Coefficient. Standard lag was calculated using the equation provided by the US Army corps of Engineers. The equation is;

$$t_p = CC_t(LL_c)^{0.3}$$

where; t_p = Standard lag time (hour)

C_t = Basin coefficient (typically changes from 1.8 to 2.2; Feldman, 2000)

L= Length of the main stream from the outlet to the divide (miles),

L_c = Length along the main stream from the outlet to a point nearest the watershed centroid (miles)

C = A conversion constant (0.75 for SI, 1.00 for foot-pound system).

The calculation of standard lag (t_p) is tabulated in Table 5-5 below.

Peaking coefficient (C_p) was estimated during the calibration process by comparing observed and simulated flows. As an initial value of the peaking coefficient, 0.5 was taken because Feldman (2000) indicated that C_p ranges from 0.4 to 0.8.

Table 5-5: Calculation of Standard Lag time

Basin	Longest flow path (miles)	Longest flow path from centroid (miles)	Conversion constant C	Basin coefficient C_t	t_p (hrs)
Sub basin-1	8.44	3.53	1.00	1.8	4.98
Sub basin-2	9.72	4.45	1.00	1.8	5.57
Sub basin-3	7.99	4.49	1.00	1.8	5.27
Sub basin-4	8.81	3.38	1.00	1.8	4.98
Sub basin-5	9.21	3.45	1.00	1.8	5.08

5.1.4 Development of Baseflow Model

Baseflow is the temporarily stored runoff in the watershed from previous precipitation and delayed subsurface runoff from the current rainstorm. Literature survey was conducted to find the most appropriate baseflow method to achieve the objective of this study. Among five methods available for simulating baseflow in HEC-HMS, **Recession method** was selected for this study because it is normally more suitable to smaller periods for watersheds. Baseflow model was kept the same for all combinations.

The input parameters for the recession base flow are initial flow, recession constant and threshold ratio. Initial flow is an initial condition and it specifies the discharge before the simulation interval. The recession constant (k) depends upon the source of baseflow and it represents baseflow rate decay. Threshold ratio is the threshold flow below which baseflow happens in pursue of the recession constant. The limits given in the HEC-HMS manual for recession constant and threshold ratio are between 0 and 1. They were considered when optimizing these two parameters. For initial values, 0.54 and 0.4 were used for recession constant and ratio to peak , respectively as a previous study in the Kelani river basin carried out by De Silva, Weerakoon and Herath (2014) have found those values are suitable for Kelani river. After simulating several trials, baseflow modelling parameters were fixed.

5.1.5 Development of Routing Model

To model catchment flow from the upper catchment to the outlet, the Routing model is used. The routing methods presented in HEC-HMS are Kinematic Wave, Lag, Modified Pulse, Muskingum, Muskingum Cunge and Sraddle Stagger. In this study, the **Lag method** was used because via literature review, it was identified that the lag method is suitable for steeper reaches like Seethawaka Ganga. This method requires only one parameter and it is the lag time. For initial estimation of the lag time for each reach, the mathematical expression given in the HEC-HMS manual was used and they were optimized by manual calibration. Calculations of the lag time of reaches are shown in Table 5-6.

Table 5-6: Calculations of Lag time in River Reaches

Reach	Length of water path (m)	Slope	t_c (mins)	t_p (mins)
Reach-1	9,200.424	0.010117	128.89	77.33
Reach-2	4,044.198	0.001402	146.49	87.89

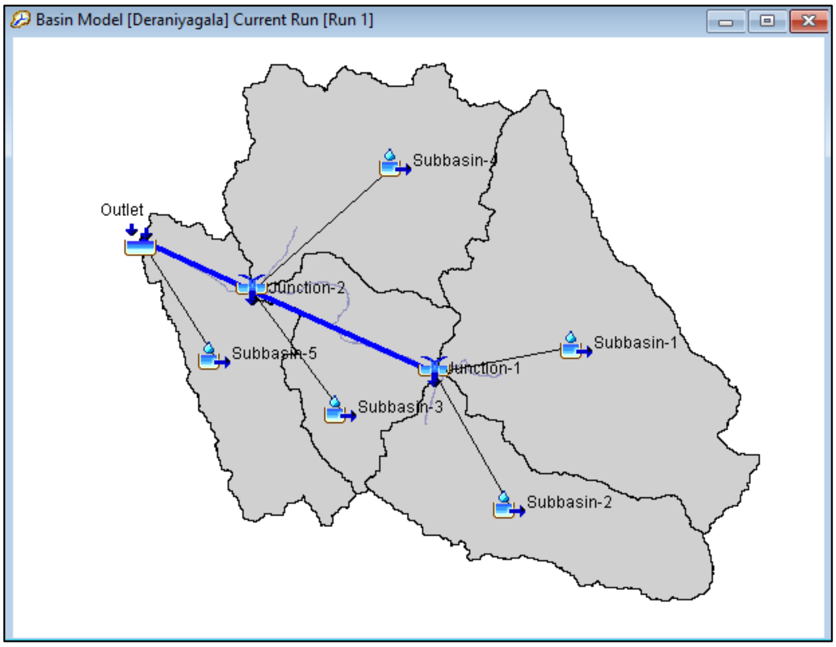

Figure 5-1: Developed Basin Model

5.1.6 Development of Precipitation Model

To determine the amount of precipitation that falls over each subbasin, the Gage Weight method was used. Theissen polygons for the Seethawaka catchment were created using ArcGIS (ESRI, USA) and Theissen weight for each sub basin is indicated in the below Table 5-7.

Table 5-7: Theissen Weight for Each Sub-basin

Sub Basin	**Theissen Weight**		
	Deraniyagala	**Kitulgala**	**Norwood**
1	0.09	0.76	0.15
2	0.70	0.01	0.29
3	1.00	-	-
4	0.40	0.60	-
5	1.00	-	-

5.1.7 Control Specifications

Control specification of the HEC-HMS model specifies the time step, the inception and the simulation period which is required to run the program. The start dates of the events were used as the model commencement dates and the end dates of the events were used as the finish dates for the calibration and validation processes of the model.

5.1.8 Simulation Time Interval

After methods and parameters are selected, the HEC-HMS model computes results at a given simulation time step. The time step can range from one day (24 hours) to 1 minute. Feldman (2000) says the simulation time interval should be less than 29% of the lag time for a subbasin. Time interval of the model was taken as 01 hour.

5.2 Selection of Objective Function

The purpose of this study is to find the best combination of loss and transform methods with regard to selected objective functions. Hence, to select the objective functions for this study, a qualitative analysis of different objective functions available in HEC-HMS was carried out. It was taken an idea regarding various objective functions used by past researchers via literature survey as well.

To fulfil the objective of this study, objective functions had to be selected which are being used to achieve dissimilar purposes in HEC-HMS models, showing different weights in favour of different hydrograph components.

Percent Error in Peak (PEP) objective function and Percent Error in Volume (PEV) objective function were selected in this study to determine the best fit between to observed and simulated hydrograph related to each loss and transform method combinations. PEP objective function only show the well-fitting of peak discharge of observed and computed hydrographs while the PEV objective function show fitting of volumes.

5.3 Sensitivity Analysis

Sensitivity analysis was performed to estimate the more sensitive parameters of the model. It was carried out for all the six (06) combinations of modelling methods, to define model performance with regard to various parameters and to find the sensitive parameters. Then those identified parameters were taken for the subsequent model calibration process.

The sensitivity analysis was carried out separately by changing each parameter from +15% to -15% from its initial value with increments of 5%. The one parameter at a time method was used for this analysis, by changing one parameter at a time and keeping other parameters fixed. To identify the sensitivity of each parameter, their impacts on peak flow and runoff volume were determined. The percentage of variation in calculated peak discharge and the percentage of variation in calculated runoff volume were plotted.

5.4 Model Calibration

Model calibration is the process of adjusting physical watershed characteristic input parameters to create a simulated hydrograph that matches an observed hydrograph as closely as possible. By matching with the observed flow at the Deraniyagala river gauging station, Seethawaka lumped model was calibrated. For the model calibration, data from the 2018 storm event was used.

Per cent Error in Peak and Percent Error in Volume were used as objective functions to assess the performance of the model. Values of the model parameters were adjusted to optimum value by altering the initial parameter values until the difference in objective function becomes the least.

Close values of simulated and observed peak discharge, the total volume of streamflow and the time to peak are the most important indicators of the performance of an event base model (De Silva, Weerakoon, & Herath, 2014). In addition to those indicators, Nash-Sutcliff Index (N.S.E.) and Percentage bias (δ_b) were also used to assess model performance.

Both automatic calibration and manual calibration approaches were used in this model. Since not all parameters are adjusted through the calibration process, individual parameters that have an effect on each other should be adjusted. For calibration procedures, the objective function tolerance was set as 0.01 and the maximum number of iterations is set as 100. Results of the calibration process are indicated in the next chapters.

5.5 Model Validation

Testing the capability of the calibrated model to simulate separate observed data sets not used for the calibration process is called the validation process. It ensures the accuracy of the model. Observed stream flow data and rainfall data for the remaining three storm events (2016 event, 2017 event and 2018 event) were used for the validation of this model. The process was performed without changing the calibrated model parameters keeping their values constant. Results of the validation process are indicated in the next chapters.

5.6 Selection of the Best Option

As the criteria for the choice of the best option, the value of the objective functions and the other three goodness of fit statistical criteria (NSE, RMSE and δ_b) were used which are recommended by most of the previous studies. De Silva et al. (2014) and Sampath et al. (2015) used NSE and δ_b as a quantitative measure in their studies based on the Kelani river basin and Daduru Oya basin , respectively. Roy, Begam, Ghosh and Jana (2013) used NSE to predict the overall performance of his HEC-HMS model along with PEV and PEP objective functions. Nandalal and Ratnayake (2010) also used NSE as the goodness of fit statistical criteria to compare their HEC-HMS model performance considering two scenarios and they further said that NSE is recommended by ASCE Watershed Management Committee (1993) for rainfall-runoff model evaluation. If NSE and δ_b values closed to 1 and 0% , respectively, it can be said that the model perform well (Sampath et al, 2015; Kanchanamala et al., 2016; Kamran, 2017). Besides, if RMSE values ranges from 0 – 0.5, that model can be taken as very well performing model (Ouedraogo, Raude, & Gathenya, 2018).

As indicated in the methodology flow chart, the calibration process for all the six options was carried out using both objective functions. Objective function values for each option as well as the N.S.E, RMSE and δ_b values were analysed and the best options were selected with regard to each objective function which shows the least value, for overall matching of flow. Objective function values and the other three goodness of fit statistical criteria (NSE, RMSE and δ_b) values for each option and their evaluation are given in the next chapters.

CHAPTER 6

6 RESULTS

6.1 General

The results which achieved in each step of the analysis part are presented in this chapter.

6.2 Results of Sensitivity Analysis

As indicated in Section 5.3, sensitivity analysis was conducted for all the six (06) combinations of modelling methods, to evaluate the model performance with regard to various parameters and to find the most sensitive parameters. The results obtained were as follows.

6.2.1 Combination 01 (SCS-CN Loss method and SCS-UH Transform method)

Sensitivity analysis was implemented for the entire set of parameters and the results for 03 parameters (Initial abstraction, Curve number, Impervious) are presented in the Tables 6-1 to 6-3 below. Plots of model results for each parameters are shown in Figure 6-1 to Figure 6-12. Curve number parameter was found as the most sensitive parameter for Combination 01 as percent change in both peak flow and volume were observed to be significantly varying from initial value to percentage variation (±15%) in the parameter value. Lag time, Impervious extent (%) and Initial Abstraction were identified as the least sensitive parameters because percent change in both peak flow and runoff volume were negligible.

Table 6-1: Results of model sensitivity to changes in Initial Abstraction parameter

Parameter changes (%)	Parameter Value	Simulated Values		Percentage of Change (%)	
		Peak flow (m^3/s)	Volume (MM)	Peak flow	Volume
-15	10.60	636.5	387.72	0.16	0.60
-10	11.22	636.2	386.86	0.11	0.37
-5	11.85	635.8	385.85	0.05	0.11
0	12.47	635.5	385.42	0.00	0.00
5	13.09	635.0	383.70	-0.08	-0.45
10	13.72	634.6	382.83	-0.14	-0.67
15	14.34	634.2	381.97	-0.20	-0.90

Table 6-2: Results of model sensitivity to changes in Curve Number parameter

Parameter changes (%)	Parameter					Simulated Values		Percentage of Change (%)	
	Sub basin 1	Sub basin 2	Sub basin 3	Sub basin 4	Sub basin 5	Peak flow (m^3/s)	Volume (MM)	Peak flow	Volume
-15	66.39	66.34	69.64	70.44	70.75	575.60	334.59	-9.41	-13.06
-10	70.29	70.25	73.74	74.58	74.92	597.00	351.27	-6.04	-8.73
-5	74.20	74.15	77.83	78.73	79.08	617.00	368.00	-2.90	-4.38
0	78.10	78.05	81.93	82.87	83.24	635.40	384.85	0.00	0.00
5	82.01	81.95	86.03	87.01	87.40	652.00	401.79	2.61	4.40
10	85.91	85.86	90.12	91.16	91.56	666.40	418.80	4.88	8.82
15	89.82	89.76	94.22	95.30	95.73	678.20	435.85	6.74	13.25

Table 6-3: Results of model sensitivity to changes in Impervious (%) parameter

Parameter changes (%)	Parameter Value	Simulated Values		Percentage of Change (%)	
		Peak flow (m^3/s)	Volume (MM)	Peak flow	Volume
-15	4.25	634.90	384.08	-0.08	-0.20
-10	4.50	635.10	384.34	-0.05	-0.13
-5	4.75	635.20	384.59	-0.03	-0.07
0	5.00	635.40	384.85	0.00	0.00
5	5.25	635.50	385.11	0.02	0.07
10	5.50	635.70	385.36	0.05	0.13
15	5.75	635.80	385.62	0.06	0.20

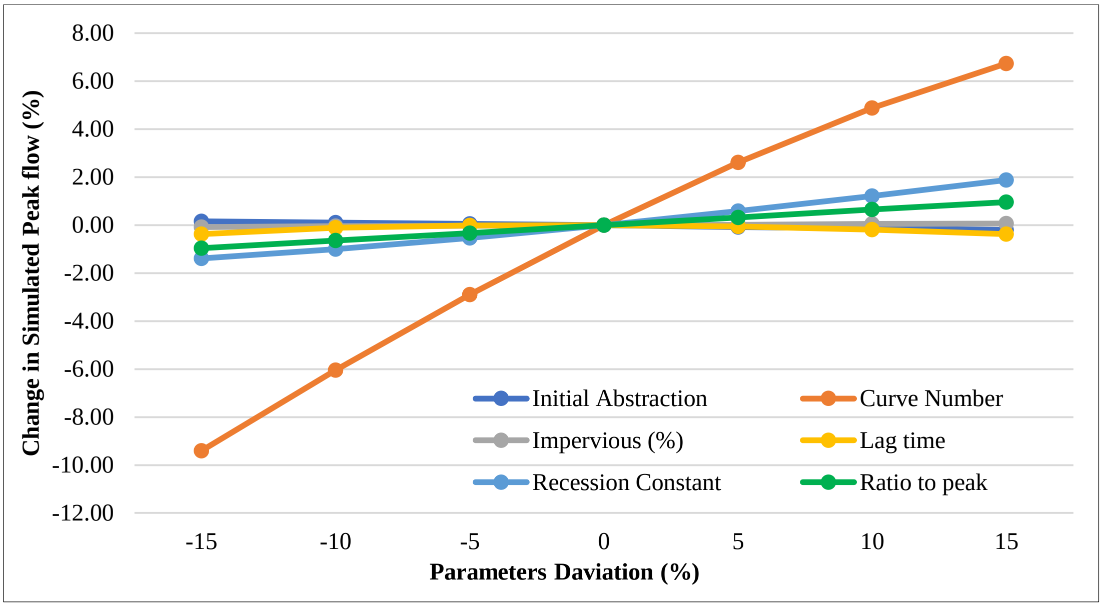

Figure 6-1: Parameter Sensitivity to Peak Discharge (Combination 01)

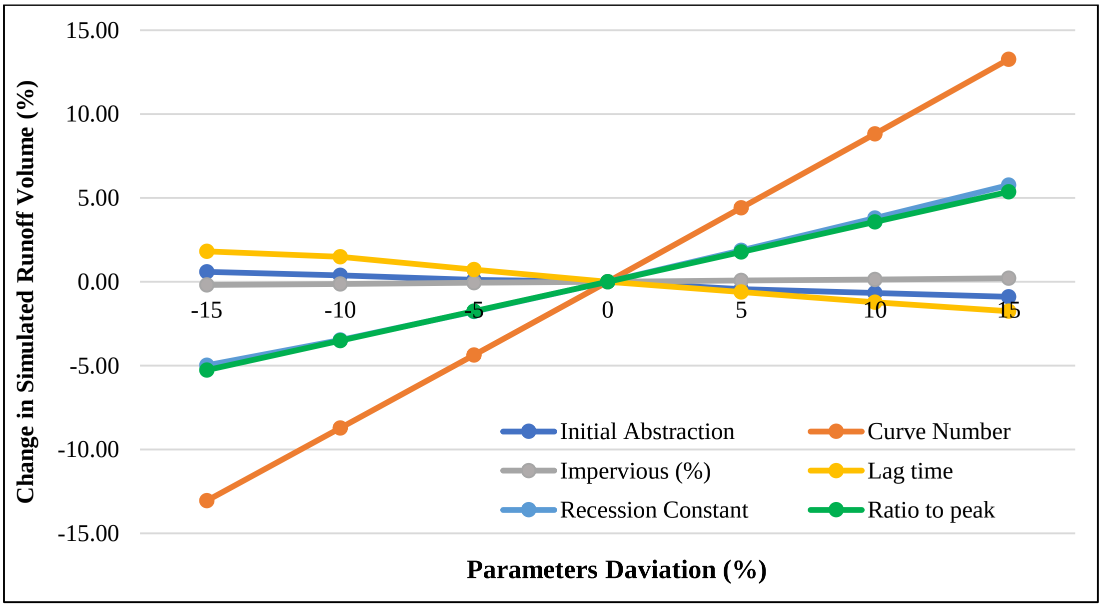

Figure 6-2: Parameter Sensitivity to Runoff Volume (Combination 01)

6.2.2 Combination 02 (SCS-CN loss method and Clark-UH Transform method)

Plot of model results for each parameter are shown in Figure 6-3 and Figure 6-4. Curve number and Storage Coefficient parameters were found as the most sensitive parameters for Combination 02 while Time of Concentration, Impervious (%) and Initial Abstraction were identified as the least sensitive parameters.

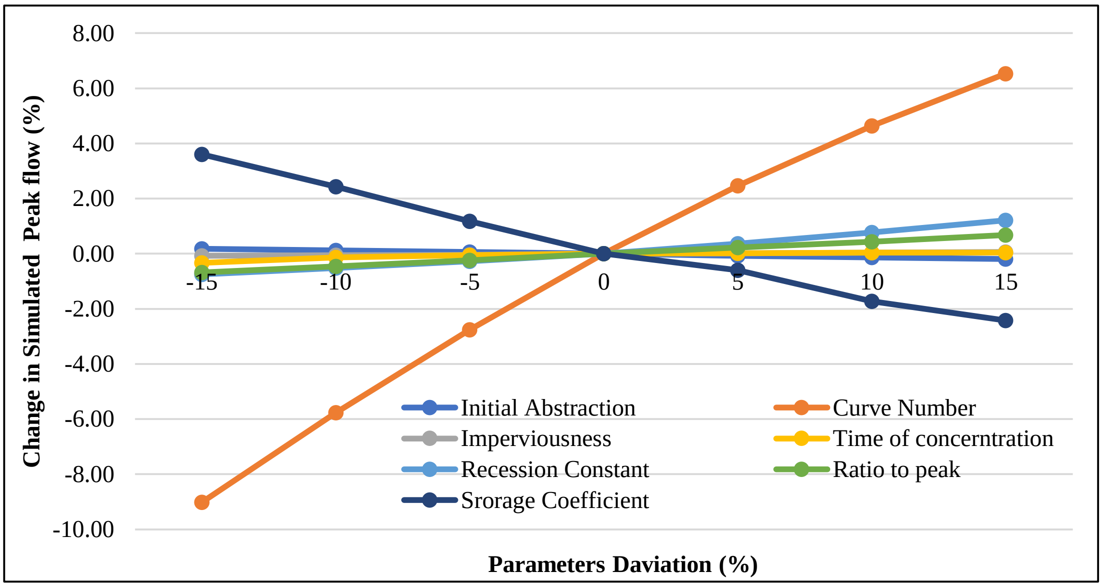

Figure 6-3: Parameter Sensitivity to Peak Discharge (Combination 02)

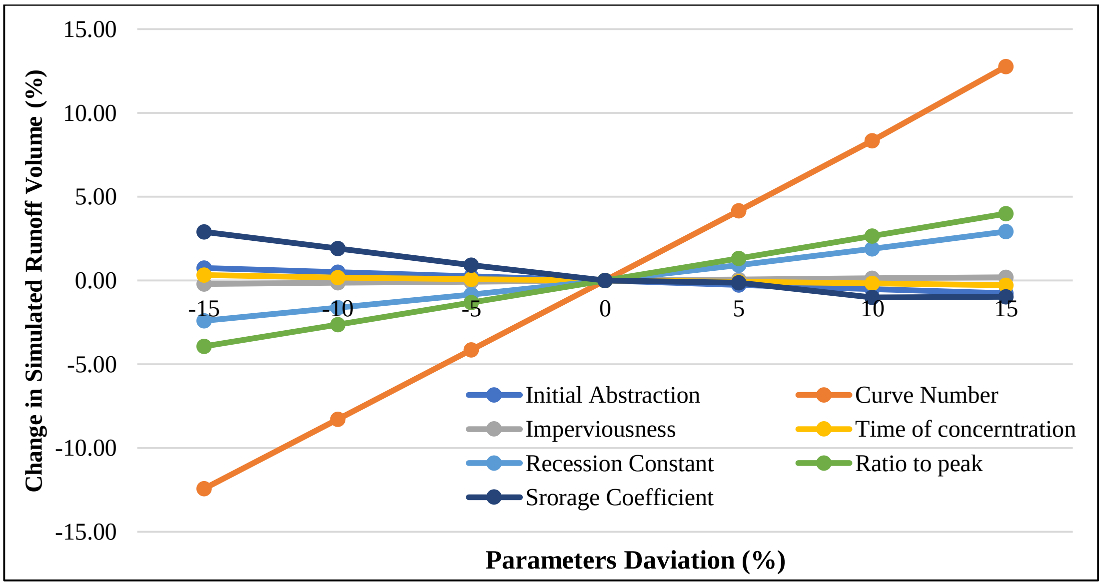

Figure 6-4: Parameter Sensitivity to Runoff Volume (Combination 02)

6.2.3 Combination 03 (SCS-CN Loss method and Snyder-UH Transform method)

Plot of model results for each parameter are shown in Figure 6-5 and Figure 6-6. Curve number, Standard Lag and Peaking Coefficient parameters were found as the most sensitive parameters for Combination 03 while Ratio to Peak, Impervious (%) and Initial Abstraction were identified as the least sensitive parameters.

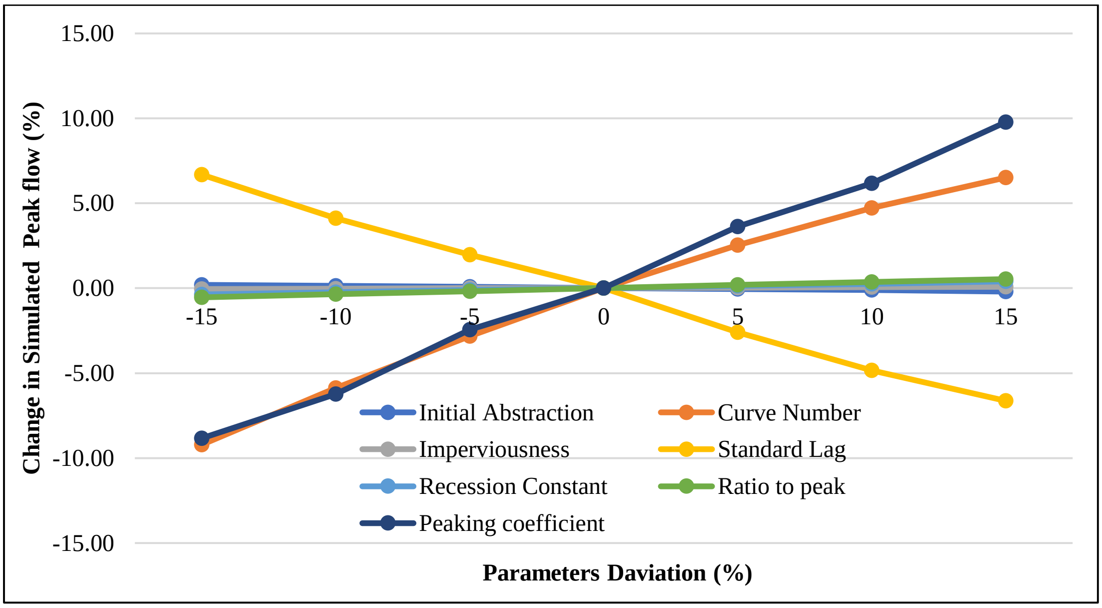

Figure 6-5: Parameter Sensitivity to Peak Discharge (Combination 03)

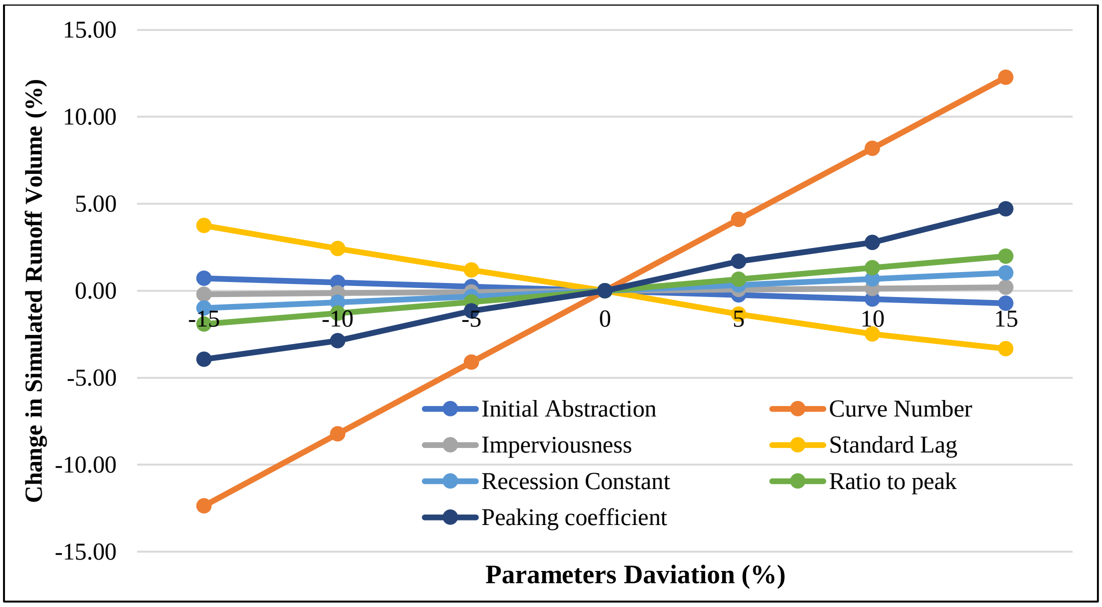

Figure 6-6: Parameter Sensitivity to Runoff Volume (Combination 03)

6.2.4 Combination 04 (Initial Constant Loss method and SCS-UH Transform method)

Plot of model results for each parameter are shown in Figure 6-7 and Figure 6-8. Initial Loss and Lag time parameters were found as the most sensitive parameters for Combination 04 while Ratio to Peak and Constant Rate were identified as the least sensitive parameters.

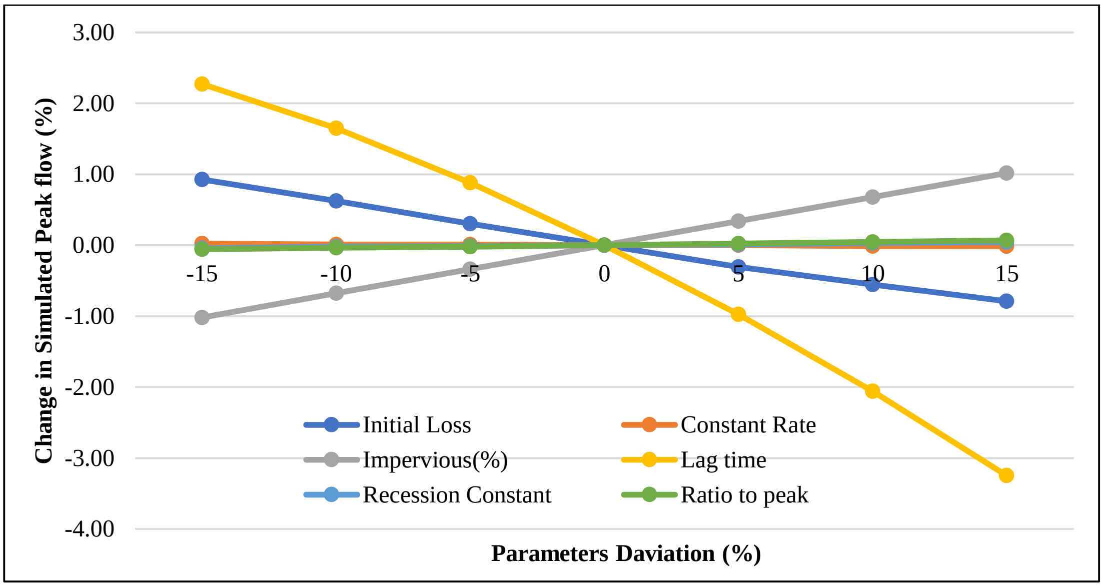

Figure 6-7: Parameter Sensitivity to Peak Discharge (Combination 04)

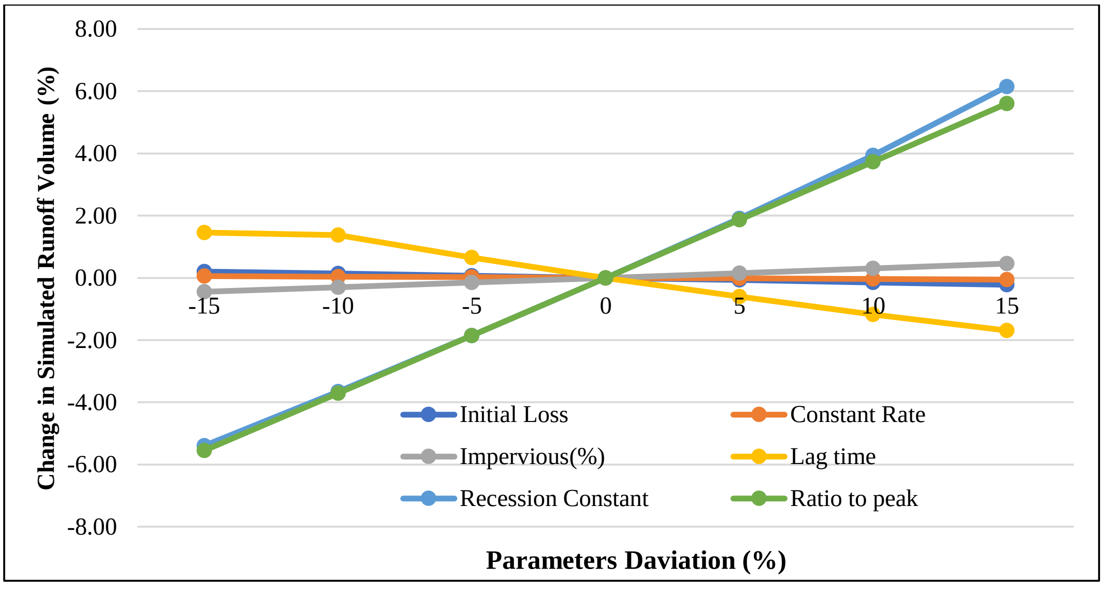

Figure 6-8: Parameter Sensitivity to Runoff Volume (Combination 04)

6.2.5 Combination 05 (Initial Constant Loss method and Clark-UH Transform method)

Plot of model results for each parameter are shown in Figure 6-9 and Figure 6-10. Storage Coefficient parameter was found as the most sensitive parameter for Combination 05 while Time of Concentration and Constant Rate were identified as the least sensitive parameters.

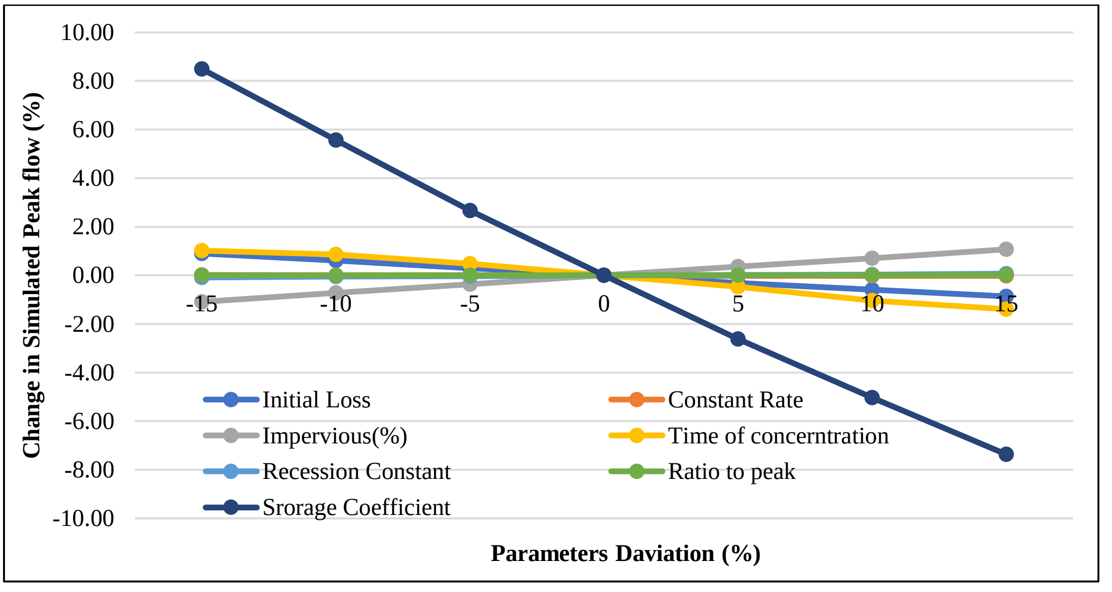

Figure 6-9: Parameter Sensitivity to Peak Discharge (Combination 05)

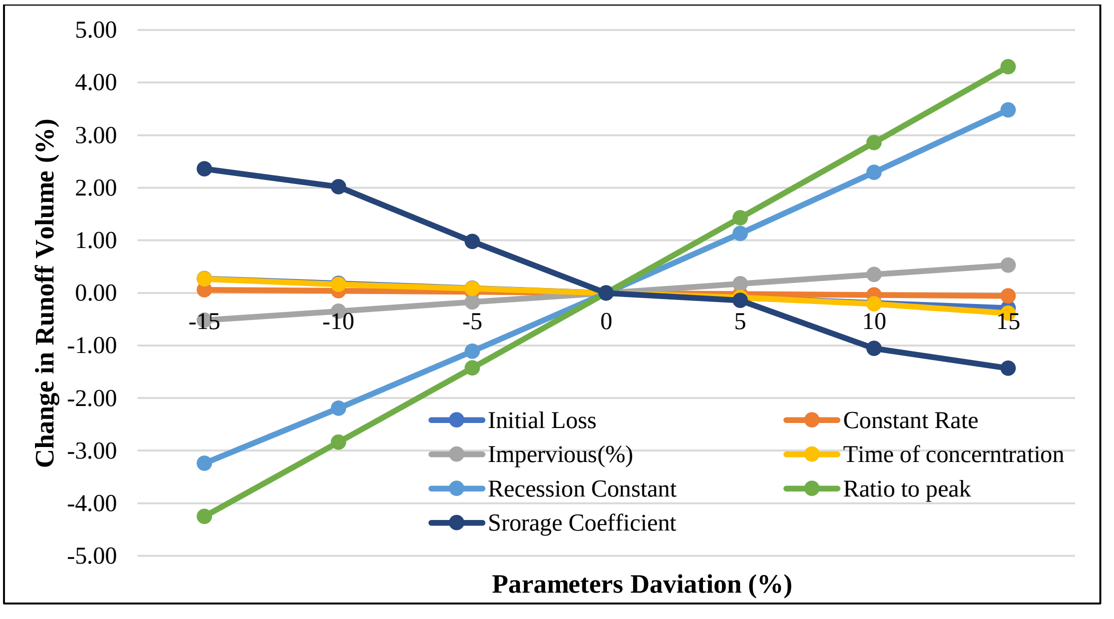

Figure 6-10: Parameter Sensitivity to Runoff Volume (Combination 05)

6.2.6 Combination 06 (Initial Constant Loss method and Snyder-UH Transform method)

Plot of model results for each parameter are shown in Figure 6-11 and Figure 6-12. Peaking Coefficient and Standard Lag parameters were found as the most sensitive parameters for Combination 06 while Initial Loss and Constant Rate were identified as the least sensitive parameters.

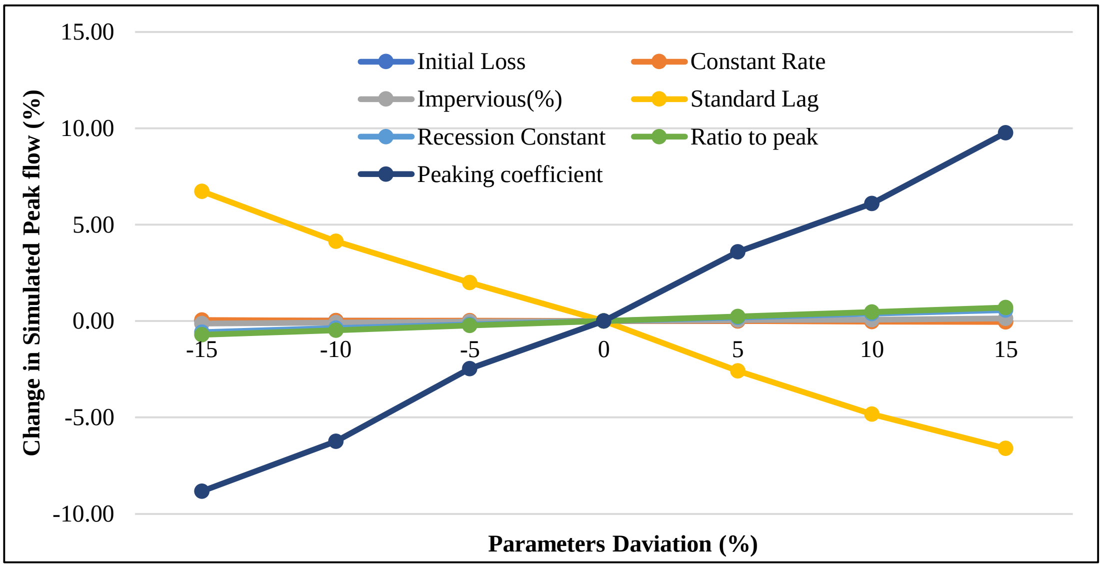

Figure 6-11: Parameter Sensitivity to Peak Discharge (Combination 06)

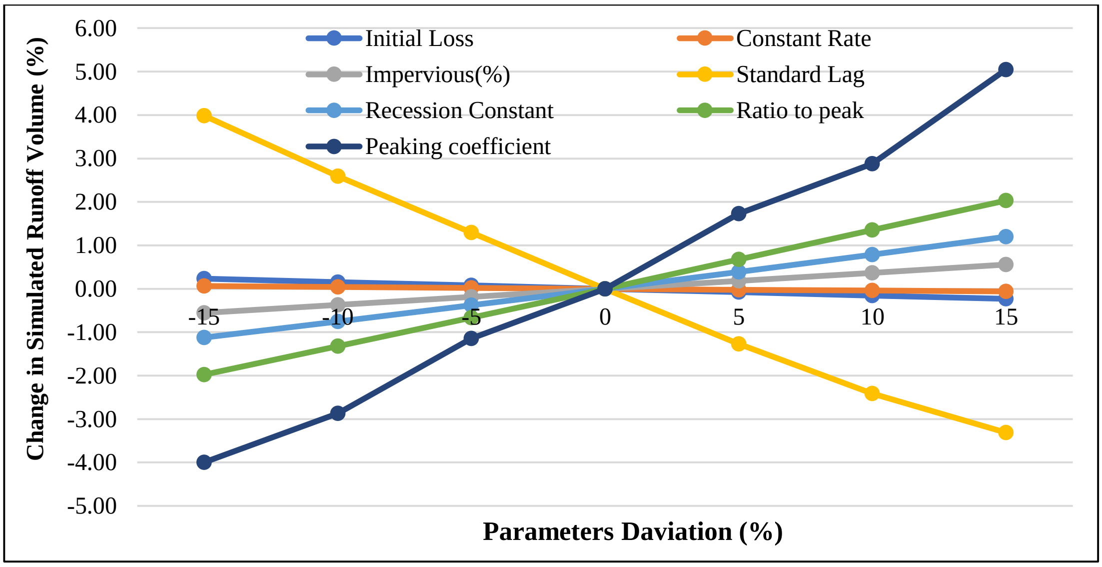

Figure 6-12: Parameter Sensitivity to Runoff Volume (Combination 06)

6.3 Model Calibration Results

The model was calibrated by considering the observed flow at the Deraniyagala stream gauge station. Calibration of the model for each combination was performed with respect to Percent Error in Peak (PEP) and Percent Error in Volume (PEV) objective functions. In addition to visual checking of the matching of observed and simulated streamflow hydrograph, Nash-Sutcliff Index (N.S.E.), RMSE and Percentage bias (δ_b) were used to evaluate model performance. For the model calibration, data from the 2018 storm event was used and Tables 6-4 and 6-5 show the results of each combination.

Table 6-4: Results of model calibration with respect to PEP objective function

Combination	**Peak Flow (m^3/s)**		**Error (m^3/s)**	**Error as a Per cent of Observed Flow (%)**	**Percentage Bias (%)**	**RMSE**	**NASH**
	Simulated	**Observed**					
C 01	513.9	511.8	-2.10	-0.41	5.43	0.4	0.816
C 02	512.5	511.8	-0.70	-0.14	8.86	0.5	0.717
C 03	511.4	511.8	0.40	0.08	5.99	0.6	0.622
C 04	532.0	511.8	-20.20	-3.95	-0.79	0.8	0.424
C 05	503.3	511.8	8.50	1.66	1.89	0.7	0.472
C 06	513.6	511.8	-1.80	-0.35	0.58	0.6	0.596

Table 6-5: Results of model calibration with respect to PEV objective function

Combination	**Total Volume (1,000 m^3)**		**Error (m^3/s)**	**Error as a Per cent of Observed Flow (%)**	**Percentage Bias (%)**	**RMSE**	**NASH**
	Simulated	**Observed**					
C 01	230.11	230.67	0.56	0.24	-0.08	0.40	0.827
C 02	230.10	230.67	0.57	0.25	-0.13	0.50	0.736
C 03	230.00	230.67	0.67	0.29	-0.17	0.50	0.719
C 04	230.02	230.67	0.65	0.28	-0.24	0.7	0.506
C 05	230.18	230.67	0.49	0.21	-0.05	0.7	0.524
C 06	229.29	230.67	1.38	0.60	-0.53	0.6	0.637

6.3.1 Outflow Hydrographs in Calibration Period

Figures 6-13 and 6-14 show the observed vs simulated hydrographs for the Combination 01 during model calibration w.r.t. PEP and PEV , respectively. Figures 6-15 and 6-16 show the observed vs simulated hydrographs for the Combination 02 during model calibration w.r.t. PEP and PEV respectively.

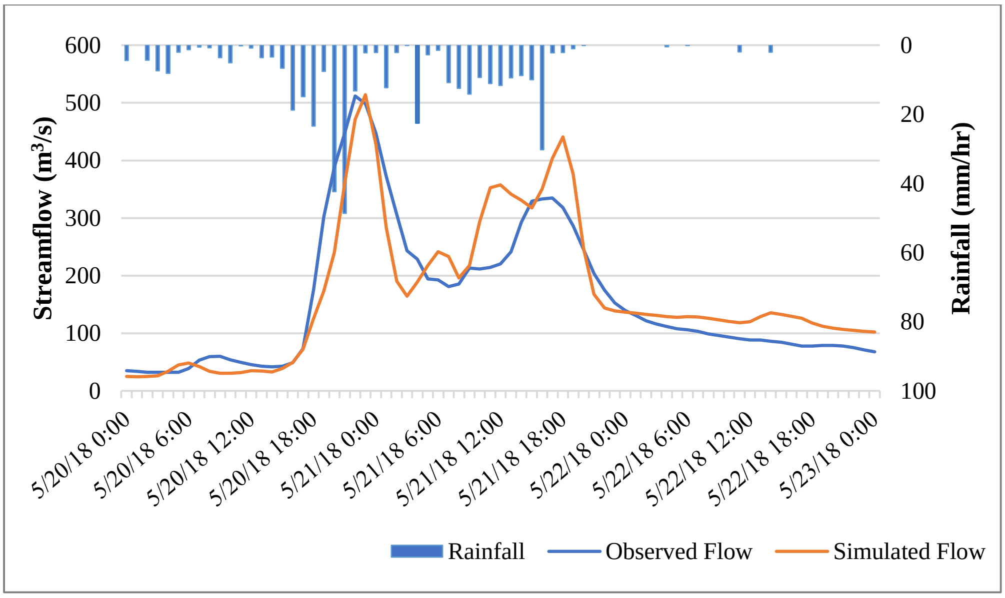

Figure 6-13: Observed and Simulated Hydrographs for Combination 01 during Calibration w.r.t. PEP

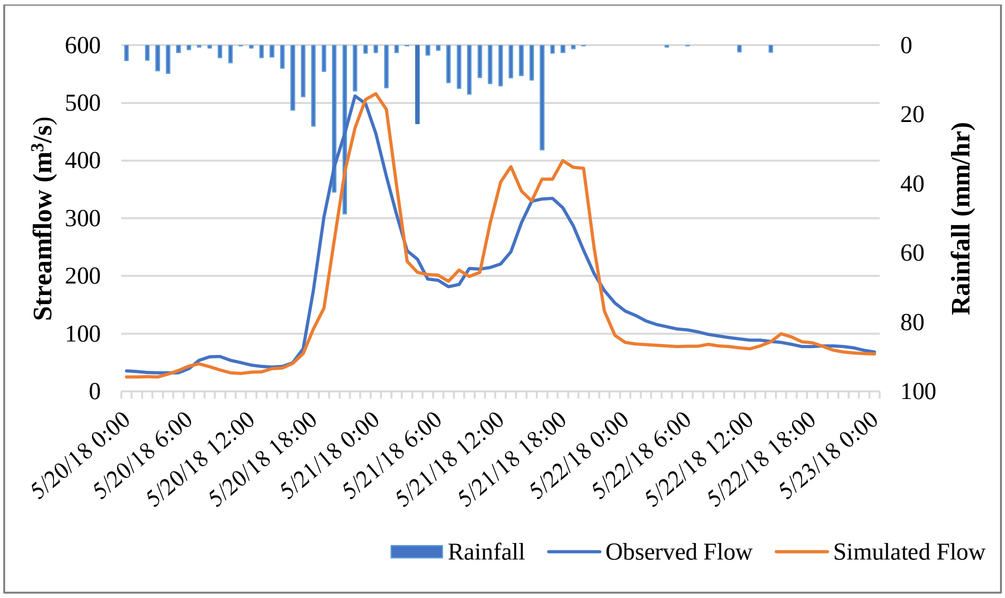

Figure 6-14: Observed and Simulated Hydrographs for Combination 01 during Calibration w.r.t. PEV

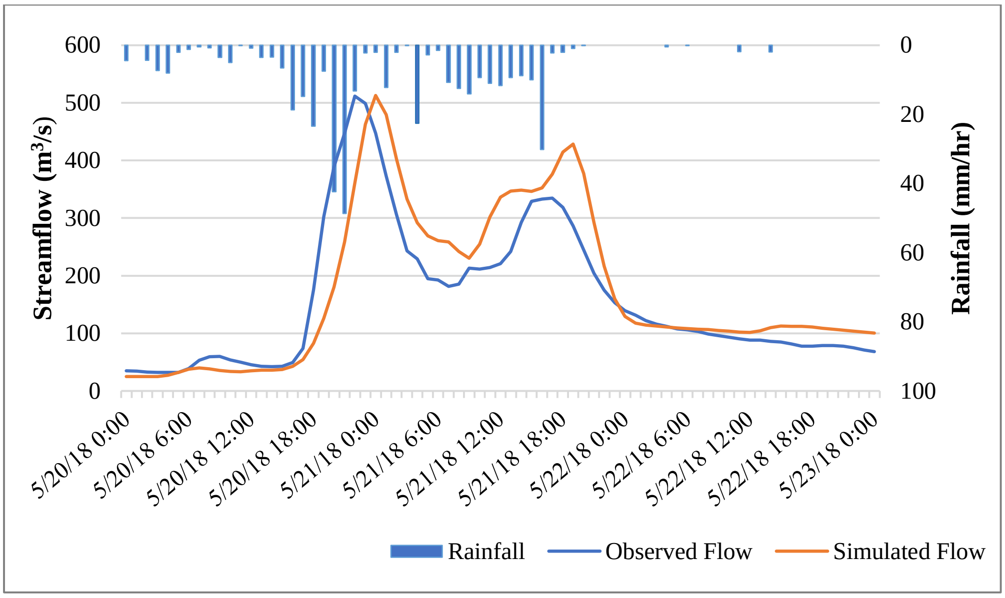

Figure 6-15: Observed and Simulated Hydrographs for Combination 02 during Calibration w.r.t. PEP

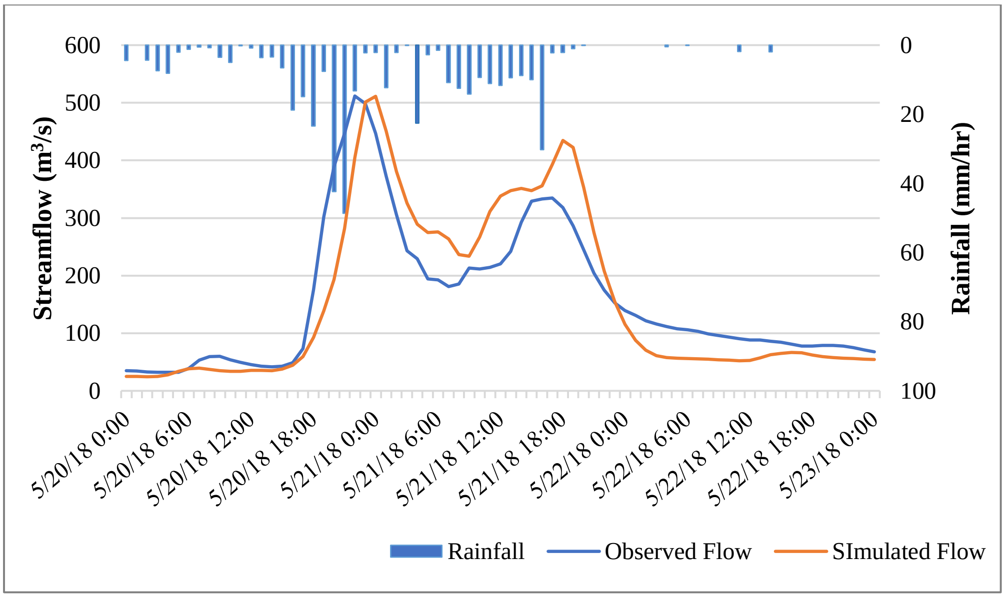

Figure 6-16: Observed and Simulated Hydrographs for the Combination 02 during Calibration w.r.t. PEV

Outflow hydrographs for other combinations during calibration process are shown in Annexure 03.

6.3.2 Flow Duration Curve for Calibration Period

Figure 6-17 to Figure 6-20 shows the flow duration curves for calibration of Combination 01 w.r.t. PEP and PEV objective functions using the 2018 storm event. Flow duration curves for other combinations have been included in Annexure 03.

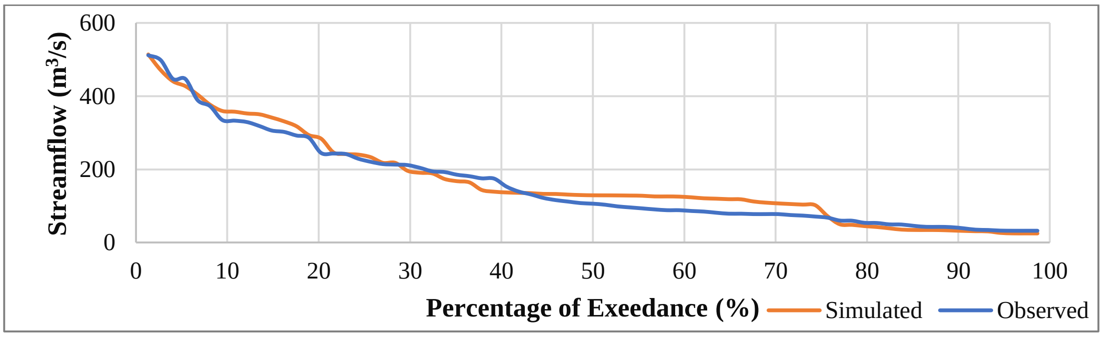

Figure 6-17: Flow Duration Curve for Combination 01 w.r.t. PEP (Normal Scale)

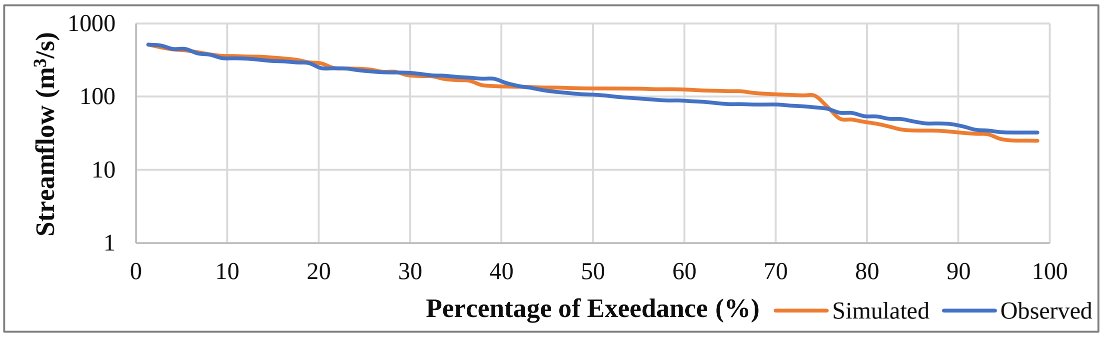

Figure 6-18: Flow Duration Curve for Combination 01 w.r.t. PEP (Log Scale)

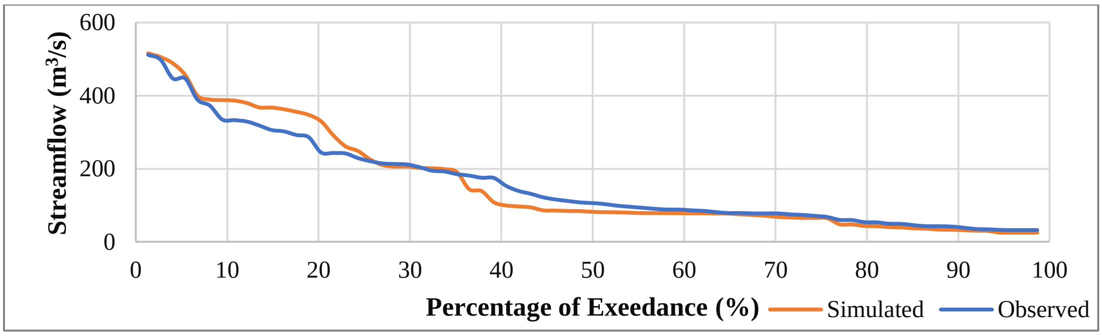

Figure 6-19: Flow Duration Curve for Combination 01 w.r.t. PEV (Normal Scale)

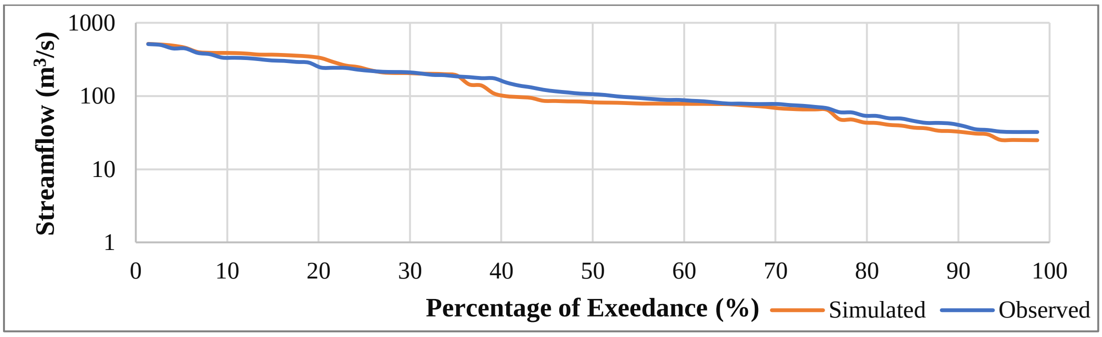

Figure 6-20: Flow Duration Curve for Combination 01 w.r.t. PEV (Log Scale)

6.4 Model Validation Results

Observed streamflow data and rainfall data for 2017, 2016 and 2014 storm events were used for the validation of the model. The process was performed without changing the calibrated model parameters keeping their values constant. Table 6-6 to Table 6-11 show the results of each combination during model validation.

Table 6-6: Results of model validation using 2017 event w.r.t. PEP objective function

Combination	Peak Flow (m^3/s)		Error (m^3/s)	Error as a Per cent of Observed Flow (%)	Percentage Bias (%)	RMSE	NASH
	Simulated	Observed					
C 01	456.6	572	115.4	20	-4.58	0.6	0.694
C 02	484.3	572	87.7	15	-6.52	0.5	0.785
C 03	487.2	572	84.8	15	-6.16	0.5	0.748
C 04	384.8	572	187.2	33	-54.95	0.7	0.563
C 05	300.1	572	271.9	48	-40.3	0.7	0.452
C 06	757.5	572	-185.5	-32	16.08	0.6	0.625

Table 6-7: Results of model validation using 2017 event w.r.t. PEV objective function

Combination	Total Volume (1,000m^3)		Error (1,000 m^3)	Error as a Per cent of Observed Flow (%)	Percentage Bias (%)	RMSE	NASH
	Simulated	Observed					
C 01	177.12	218.56	41.44	19%	-19.04	0.4	0.820
C 02	160.38	218.56	58.18	27%	-26.65	0.4	0.829
C 03	166.78	218.56	51.78	24%	-23.76	0.4	0.820
C 04	107.72	218.56	110.84	51%	-50.62	0.6	0.581
C 05	127.66	218.56	90.9	42%	-41.45	0.6	0.603
C 06	135.29	218.56	83.27	38%	-38.11	0.5	0.618

Table 6-8: Results of model validation using 2016 event w.r.t. PEP objective function

Combination	Peak Flow (m^3/s)		Error (m^3/s)	Error as a Per cent of Observed Flow (%)	Percentage Bias (%)	RMSE	NASH
	Simulated	Observed					
C 01	487.4	427.5	-59.90	-14	9.73	0.6	0.676
C 02	578.7	427.5	-151.2	-35	20.17	0.7	0.440
C 03	520.1	427.5	-92.6	-22	13.86	0.7	0.502
C 04	614.4	427.5	-186.90	-44	3.93	0.9	0.201
C 05	495.9	427.5	-68.40	-16	21.06	0.9	0.249
C 06	313.1	427.5	114.40	27	-26.82	0.6	0.657

Table 6-9: Results of model validation using 2016 event w.r.t. PEV objective function

Combination	Total Volume (1,000m^3)		Error (1,000 m^3)	Error as a Per cent of Observed Flow (%)	Percentage Bias (%)	RMSE	NASH
	Simulated	Observed					
C 01	285.42	309.81	24.39	8	-7.69	0.6	0.670
C 02	257.36	309.81	52.45	17	-16.76	0.6	0.660
C 03	229.20	309.81	80.61	26	-25.82	0.6	0.682
C 04	342.99	309.81	-33.18	-11	10.89	1	0.420
C 05	342.17	309.81	-32.36	-10	10.64	0.7	0.525
C 06	327.20	309.81	-17.39	-6	5.78	0.6	0.656

Table 6-10: Results of model validation using 2014 event w.r.t. PEP objective function

Combination	Peak Flow (m^3/s)		Error (m^3/s)	Error as a Per cent of Observed Flow (%)	Percentage Bias (%)	RMSE	NASH
	Simulated	Observed					
C 01	345.70	353.0	7.30	2	0.30	0.7	0.442
C 02	169.90	353.0	183.10	52	-44.05	0.8	0.328
C 03	318.00	353.0	35.00	10	-4.19	0.5	0.737
C 04	187.10	353.0	165.90	47	-50.12	0.9	0.127
C 05	295.00	353.0	58.00	16	-4.36	0.8	0.281
C 06	391.90	353.0	-38.90	-11	19.66	0.9	0.227

Table 6-11: Results of model validation using 2014 event w.r.t. PEV objective function

Combination	Total Volume (1,000m^3)		Error (1,000 m^3)	Error as a Per cent of Observed Flow (%)	Percentage Bias (%)	RMSE	NASH
	Simulated	Observed					
C 01	126.26	145.06	18.80	13	-12.65	0.6	0.609
C 02	123.67	145.06	21.39	15	-14.51	0.6	0.694
C 03	126.28	145.06	18.78	13	-12.80	0.5	0.745
C 04	71.86	145.06	73.20	50	-49.96	0.9	0.105
C 05	79.17	145.06	65.89	45	-44.92	0.8	0.310
C 06	85.79	145.06	59.27	41	-40.44	0.8	0.394

6.4.1 Outflow Hydrographs in Validation Period

Figure 6-21 and Figure 6-22 show the observed and simulated hydrographs for Combination 01 w.r.t. PEP and PEV objective functions respectively during the validation process using the 2017 storm event. Figure 6-23 and Figure 6-24 show the observed and simulated hydrographs for Combination 01 w.r.t. PEP and PEV objective functions, respectively during the validation process using the 2016 storm event. Figure 6-25 and Figure 6-26 show the observed and simulated hydrographs for Combination 01 w.r.t. PEP and PEV objective functions, respectively during the validation process using the 2014 storm event.

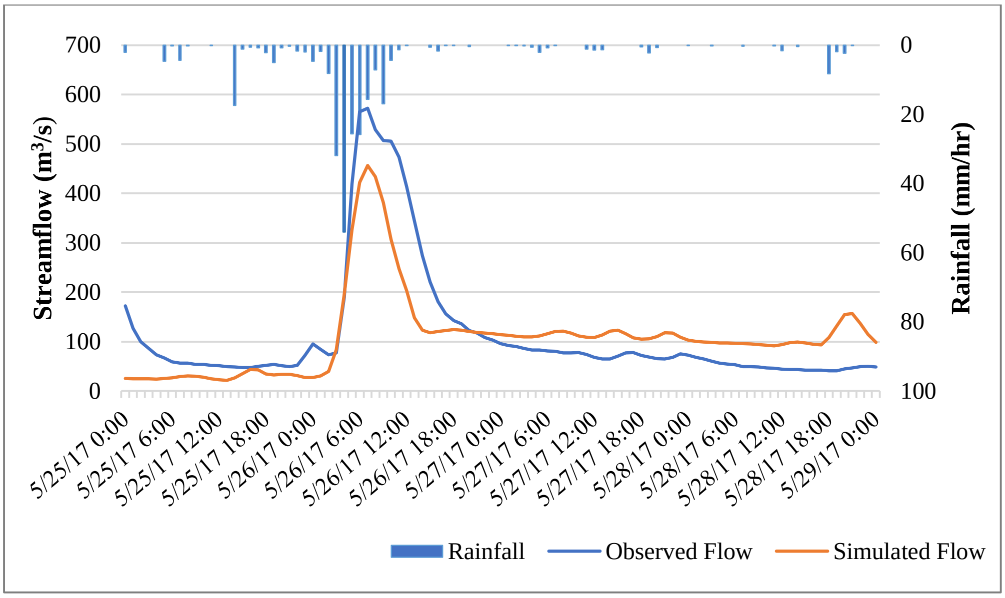

Figure 6-21: Observed and Simulated Hydrographs for Combination 01 during Validation using 2017 event w.r.t. PEP

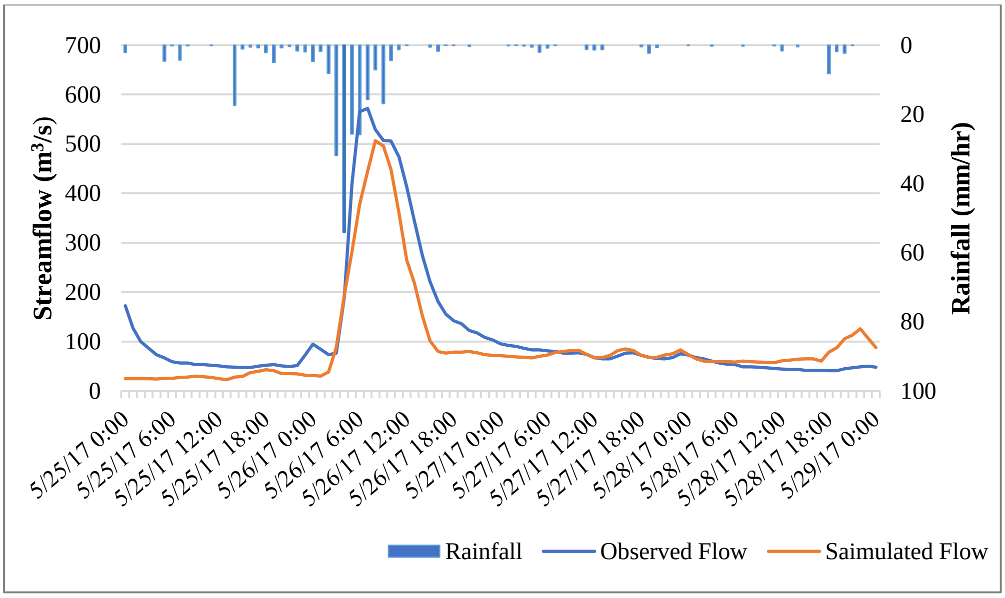

Figure 6-22: Observed and Simulated Hydrographs for Combination 01 during Validation using 2017 event w.r.t. PEV

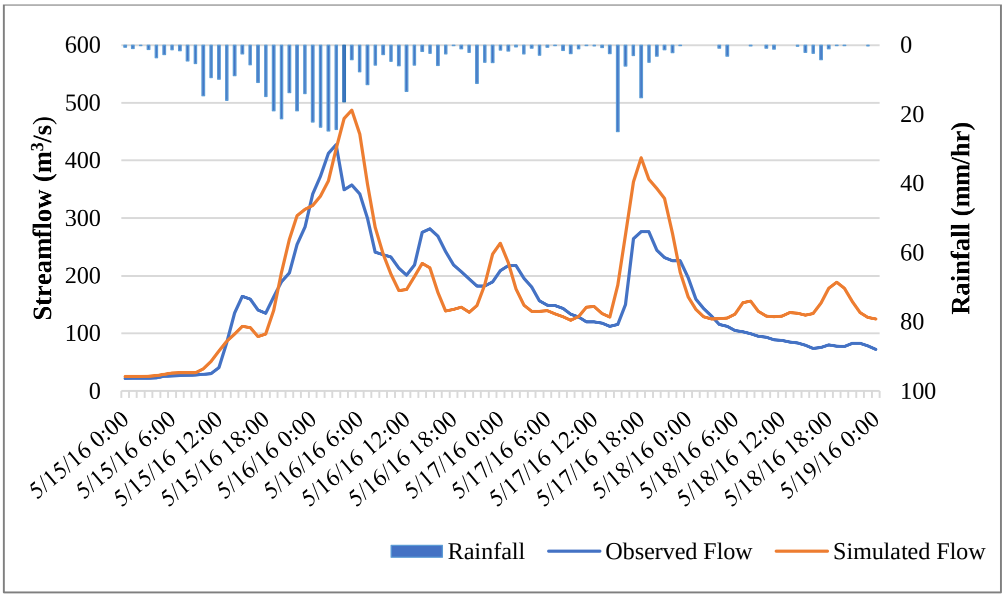

Figure 6-23: Observed and Simulated Hydrographs for Combination 01 during Validation using 2016 event w.r.t. PEP

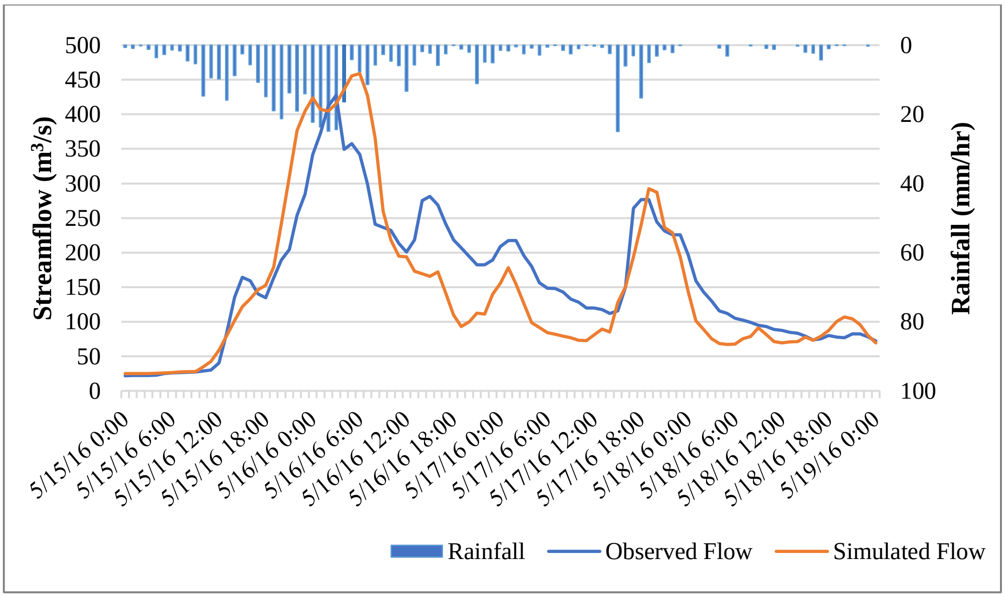

Figure 6-24: Observed and Simulated Hydrographs for Combination 01 during Validation using 2016 event w.r.t. PEV

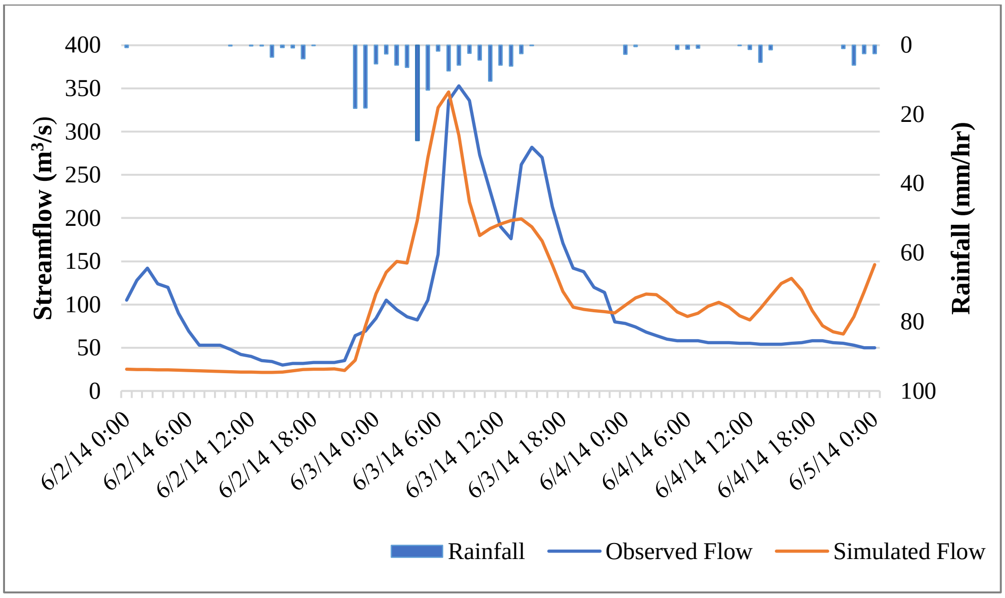

Figure 6-25: Observed and Simulated Hydrographs for Combination 01 during Validation using 2014 event w.r.t. PEP

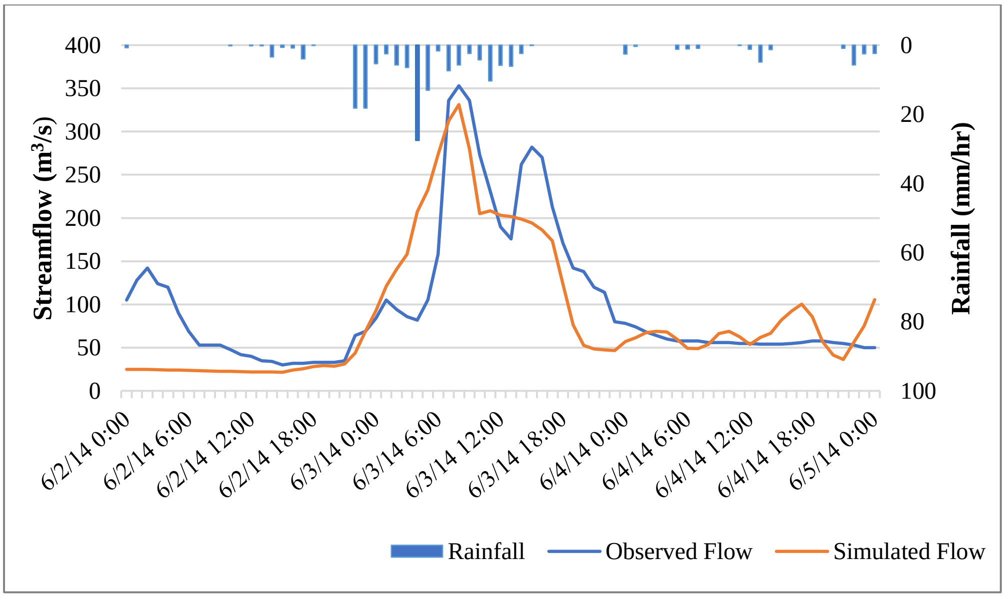

Figure 6-26: Observed and Simulated Hydrographs for the Combination 01 during Validation using 2014 event w.r.t. PEV

Outflow hydrographs for other combinations during validation are shown in Annexure 03.

6.4.2 Flow Duration Curves for Validation Period

Figure 6-27 to Figure 6-30 shows the flow duration curves for the validation process using the 2017 storm event.

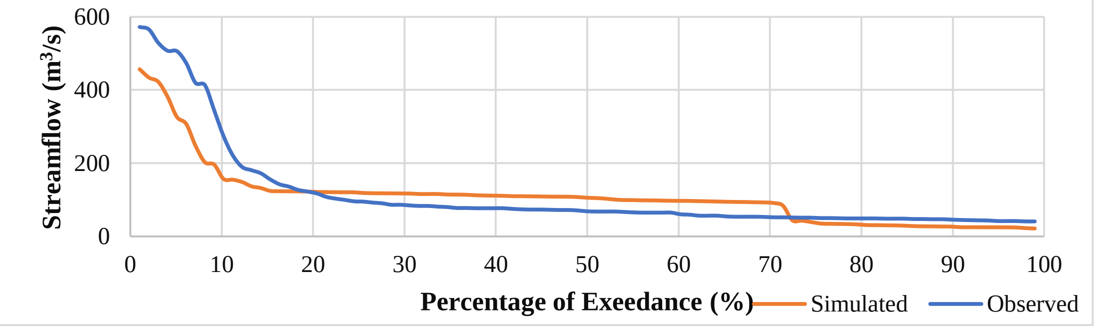

Figure 6-27: Flow Duration Curve for Combination 01 w.r.t. PEP (Normal Scale)

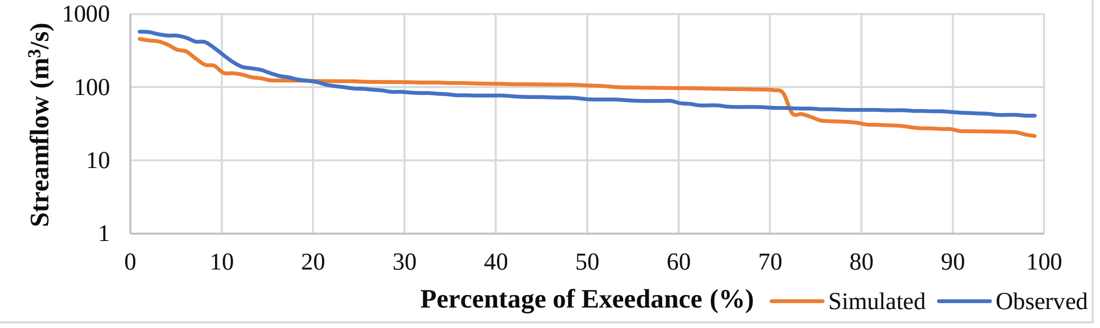

Figure 6-28: Flow Duration Curve for Combination 01 w.r.t. PEP (Log Scale)

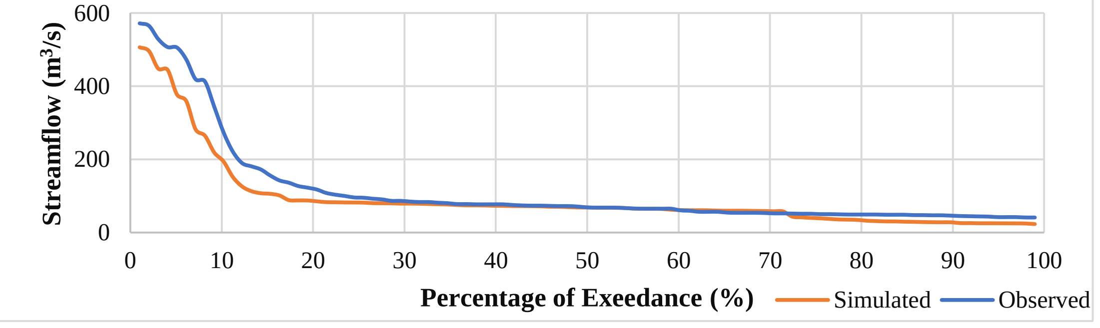

Figure 6-29: Flow Duration Curve for Combination 01 w.r.t. PEV (Normal Scale)

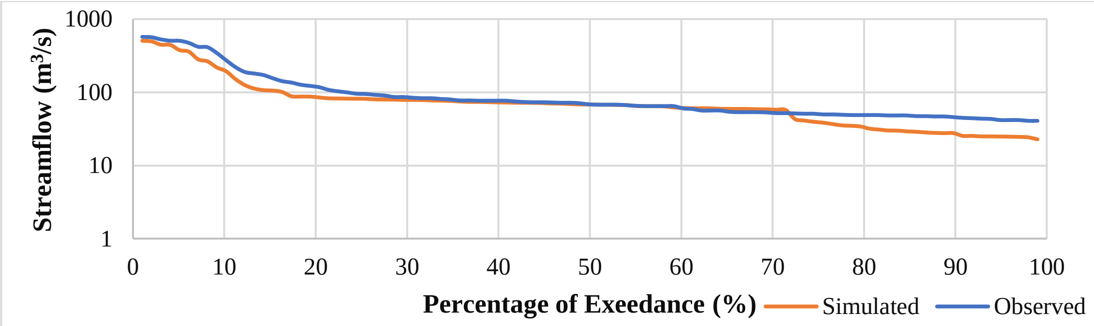

Figure 6-30: Flow Duration Curve for Combination 01 w.r.t. PEV (Log Scale)

Figure 6-31 to Figure 6-34 shows the flow duration curves for validation process using 2016 storm event.

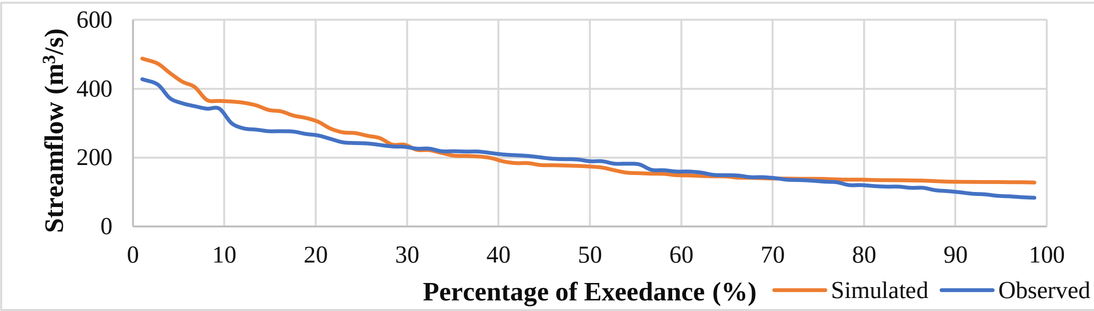

Figure 6-31: Flow Duration Curve for Combination 01 w.r.t. PEP (Normal Scale)

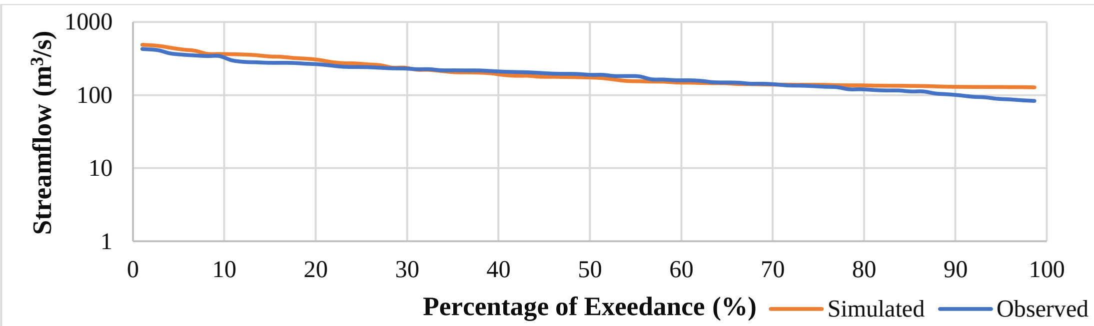

Figure 6-32: Flow Duration Curve for Combination 01 w.r.t. PEP (Log Scale)

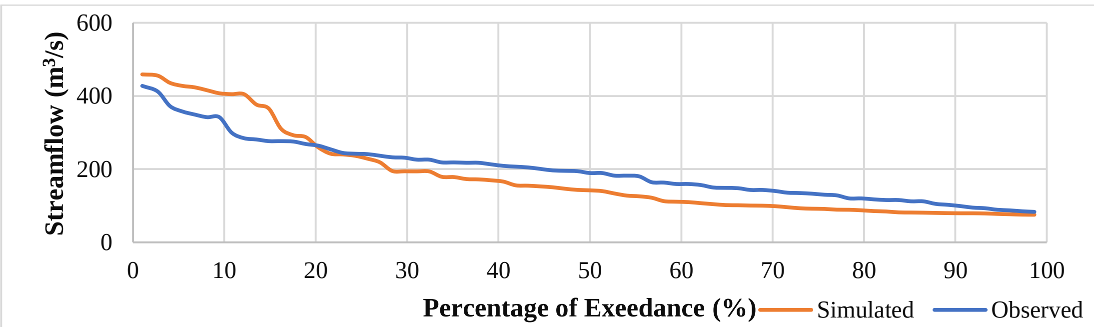

Figure 6-33: Flow Duration Curve for Combination 01 w.r.t. PEV (Normal Scale)

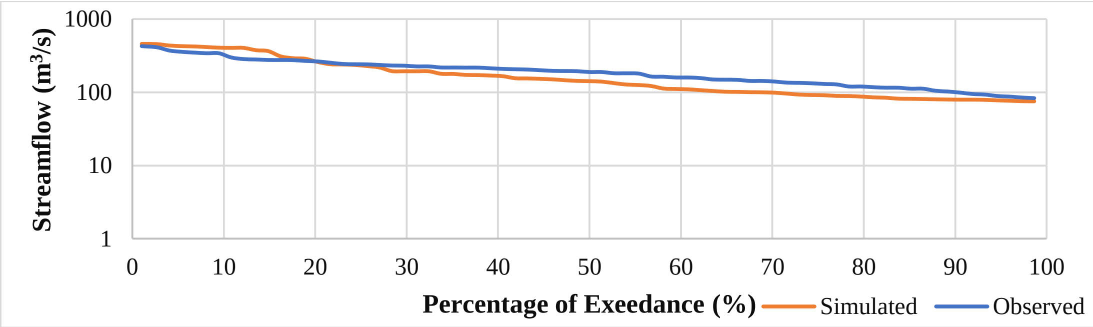

Figure 6-34: Flow Duration Curve for Combination 01 w.r.t. PEV (Log Scale)

Figure 6-35 to Figure 6-38 shows the flow duration curves for validation process using 2014 storm event.

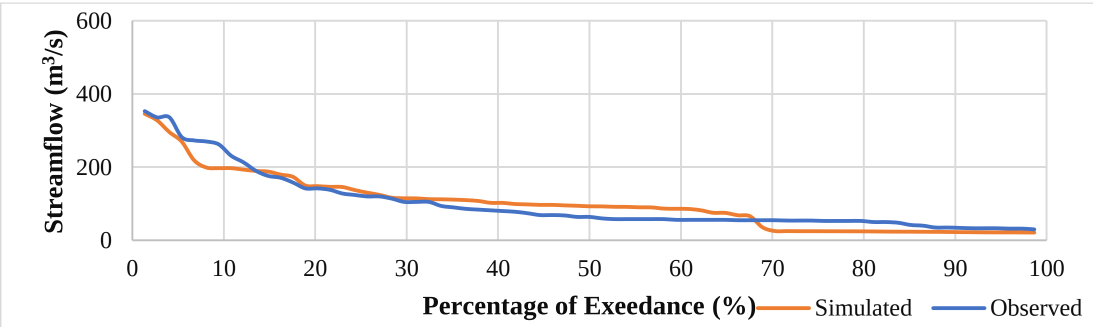

Figure 6-35: Flow Duration Curve for Combination 01 w.r.t. PEP (Normal Scale)

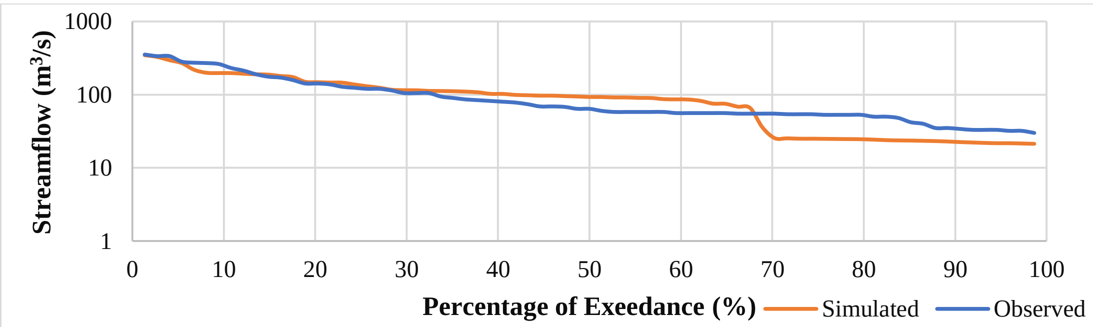

Figure 6-36: Flow Duration Curve for Combination 01 w.r.t. PEP (Log Scale)

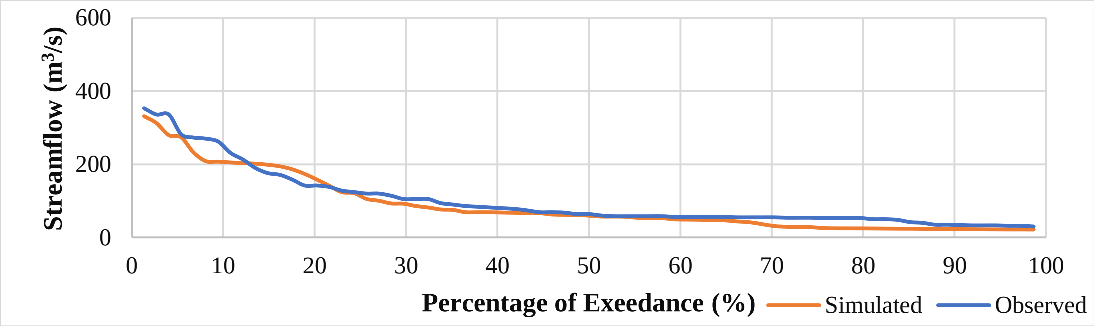

Figure 6-37: Flow Duration Curve for Combination 01 w.r.t. PEV (Normal Scale)

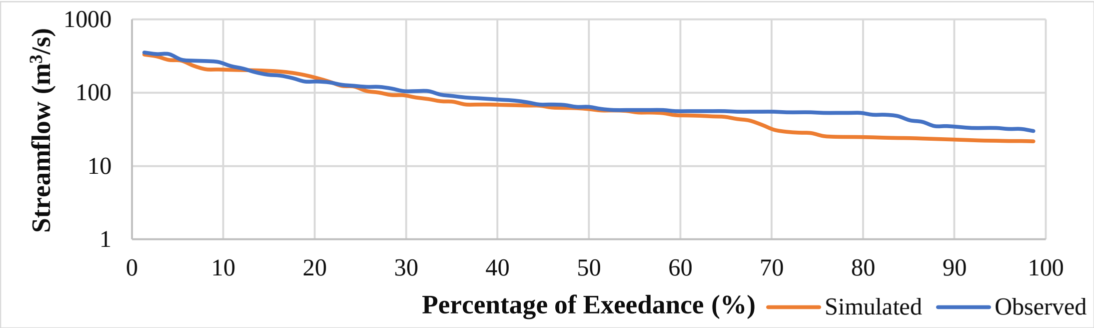

Figure 6-38: Flow Duration Curve for Combination 01 w.r.t. PEV (Log Scale)

CHAPTER 7

7 DISCUSSION

7.1 Event Selection

Seethawaka subbasin of the Kelani river basin was chosen as the study area for this study considering the data availability. De Silva et al. (2014) said that the selection of rainfall events and finer time step data are crucial factors in the event-based modelling process. Considering that, hourly rainfall and streamflow data for four (04) extreme flood events (May 2014, May 2016, May 2017, May 2018) which occurred in the recent past were used in this study as this is an event-based simulation. All of them have four (04) to five (05) days of rainfall period.

For the calibration process, the 2018 storm event was used and the other three storm events (May 2014, May 2016, and May 2017) were used for the validation process.

7.2 Data Resolution

Since the study area (Seethawaka catchment) is relatively small, the time of concentration of the area takes a considerably low value. Meteorological data with higher resolution is preferred for event-based modelling based on such small catchments.

Hence, hourly rainfall data for three rainfall gauging stations (Deraniyagala, Kitulgala, Norwood) and hourly streamflow data for one streamflow gauging station (Deraniyagala) were obtained from Irrigation Department, Sri Lanka to use for the calibration and validation processes of this study as mentioned in earlier.

7.3 Sensitivity Analysis

Sensitivity analysis was carried out to estimate the sensitive parameters of the model. It was performed for all the six (06) combinations of modelling methods, to evaluate the model performance with regard to various parameters and to find the most sensitive parameters.

It was carried out separately by changing each parameter from +15% to -15% from its initial value with increments of 5%. The one parameter at a time method was used for this analysis, by changing one parameter at a time and keeping all other parameters constant. To identify the sensitivity of each parameter, their impacts on peak flow and runoff volume were determined.

For each combination, it was identified different parameters as the most sensitive one. According to the results of the sensitivity analysis, curve number was the most sensitive parameter for Combination 01, Combination 02 and Combination 03 due to all of those combinations using the SCS Curve Number method as the loss method. In addition to curve number, storage coefficient and standard lag parameters were identified as the other sensitive parameters for Combination 02 and Combination 03, respectively. Lag time and ratio to peak parameters were found as the most sensitive parameters for Combination 04 while storage coefficient was identified for the Combination 05. For Combination 06, it was identified that peaking coefficient and standard lag are more sensitive than other parameters. Those identified parameters were used for the calibration process of the model as they are the most sensitive.

7.4 Model Calibration

Model was calibrated by considering the observed flow at the Deraniyagala stream gauge station. Calibration of the model for each combination was performed with respect to Percent Error in Peak (PEP) and Percent Error in Volume (PEV) objective functions. In addition to visual checking of the matching of observed and simulated streamflow hydrograph, Nash-Sutcliff Index (N.S.E.), RMSE and Percentage bias (δ_b) were used to evaluate model performance. For the model calibration, data from the 2018 storm event was used.

Both automatic calibration and manual calibration approaches were used in this model. Since not all parameters are adjusted through the calibration process, individual parameters should be adjusted that have an effect on each other.

During the calibration time period Combination 01, N.S.E., δ_b and RMSE values were reported as 0.816, 5.43% and 0.4 when it was calibrated with respect to PEP objective function (Table 6-4). Those values were reported as 0.830, -0.08% and 0.4 after being calibrated with respect to the PEV objective function (Table 6-5). The SCS curve number loss method and SCS-UH transform method were used with the Recession baseflow method in this combination. Combination 02, which used the SCS-CN loss method and Clark-UH transform method shows N.S.E., δ_b and RMSE values as 0.717, 8.86%, 0.4 w.r.t. PEP objective function and 0.740, -0.13%, 0.4 w.r.t. PEV objective function, respectively. Among all the six combinations, Combination 01 shows better results than the others during the calibration process with respect to both PEP and PEV objective functions. Combinations 04, 05 and 06 shows poor results compared with other combinations. Combination 04, which used the Initial Constant loss method and SCS-UH transform method shows N.S.E., δ_b and RMSE values as 0.424, -0.79% , 0.8 w.r.t. PEP objective function and 0.506, -0.24% , 0.7 w.r.t. PEV objective function, respectively. Hence, it can be identified that the SCS-CN loss method performs fairly well than the Initial and Constant loss method for the Kelani river basin.

7.5 Model Validation

Observed stream flow data and rainfall data for 2014, 2016 and 2017 storm events were used to validate the model. The process was carried out without changing the calibrated model parameters, keeping their values constant. The calibrated model was run separately using the above three events and N.S.E., δ_b , RMSE values were reported for each combination. Those values were averaged to get the overall results of the validation process. De Silva et al. (2014) and Nandalal and Ratnayake (2010) have also used three storm events for the validation process in their studies and they have obtained the final values of the goodness of fit measures (N.S.E., δ_b) by averaging their values taken w.r.t. all the three events. Table 7-1 shows the averaged N.S.E. and RMSE values for the validation process.

Table 7-1: Final Results of the Validation

Combination	Percent Error in Peak		Percent Error in Volume	
	Avg. RMSE	Avg. NASH	Avg. RMSE	Avg. NASH
C 01	0.6	0.604	0.5	0.700
C 02	0.7	0.518	0.5	0.728
C 03	0.6	0.662	0.5	0.749
C 04	0.8	0.297	0.8	0.369
C 05	0.8	0.327	0.7	0.479
C 06	0.7	0.503	0.6	0.556

7.6 Selection of the Best Combination

Calibration and validation of the model for all the six combinations were carried out and in addition to visual checking of the matching of observed and simulated streamflow hydrographs, Nash-Sutcliff Index (N.S.E.), Percentage bias (δ_b) and RMSE were used to evaluate model performance. As indicated in Section 7.4, Combination 01 shows better results than others during the calibration process with respect to both PEP and PEV objective functions. Even considering the validation results, it can be confirmed that Combination 01 (SCS-CN loss method and SCS-UH transform method) shows the best results among other combinations.

While Combinations 02 and 03 also show somewhat good results (Table 7-1), Combinations 04, 05 and 06 show relatively poor results (Table 7-1) indicating that the Initial Constant method is not much suitable for the Kelani river basin as all of those three combinations use the Initial Constant method as the loss method. Halwatura et al. (2013) said that the SCS-CN method is more suitable for agricultural lands than urban lands and it can be confirmed that the lower part of the Seethawaka Catchment consists of agricultural lands like tea, paddy, etc.

7.7 Summary of the Discussion

As the conclusion, it can be identified that the SCS-CN loss method and SCS-UH transform method along with the Recession baseflow method provide more reliable estimates compared to other loss and transform methods with respect to both PEP and PEV objective functions in streamflow forecasting in Kelani river. In a previous study carried out by Ud Din (2018), it was concluded that the Soil Moisture Accounting loss method and Linear Reservoir baseflow methods are the most suitable modelling methods for the Kelani river basin and it was a continuous model.

Seethawaka river basin is located in a mountainous region and due to that, downstream areas of the basin like Deraniyagala area frequently face floods during heavy rainy periods. According to Hettiarachchi and Udowita (2015), no hydrodynamic model is available for the upper reaches of Kelani river above Glencourse for the purpose of flood warning. Considering the ability of the model to predict the peak discharge and the time to peak, this developed model can be used to provide early flood warnings to the Deraniyagala area during extreme rainfall events. The outflow hydrographs of this model can be fed into the HEC-RAS model to identify the inundation areas during flood events as well.

This model can be used in the planning of future water resources development projects (ex: reservoirs) in the Seethawaka river. Developed flood hydrographs will be useful to evaluate the effect to the flow in Seethawaka river due to construction of hydraulic structures like dam, weir etc and it will also be useful to decide the design parameters of the reservoir structures.

Besides, this study provides a guide on how to develop a hydrological model and it can be used as the foundation for similar approaches in other watersheds in the wet zone of Sri Lanka. As future research directions it can be suggested that to check the suitability of these computing methods to river basins in other zones of the country also.

CHAPTER 8

8 CONCLUSIONS

1. Performance of different six combinations created using two loss methods (SCS Curve Number method, Initial Constant method) and three transform methods (SCS Unit Hydrograph method, Clark Unit Hydrograph method, Snyder Unit Hydrograph method) were checked separately.
2. Percent Error in Peak (PEP) objective function and Percent Error in Volume (PEV) objective function were selected in this study to determine the performance of the model. Other than those, RMSE, Percentage bias and NASH index were also used to evaluate the performance of the model.
3. Sensitivity analysis was conducted to estimate the most sensitive parameters of the model. It was carried out for all the six (06) combinations of modelling methods, to identify model performance with respect to various parameters and to find the most sensitive parameters. According to the results of the sensitivity analysis, curve number was the most sensitive parameter which shows 13.25% change in simulated volume and 9.41% change in simulated peak flow with 15% change in parameter value.
4. Curve number is the most sensitive parameter in the SCS-CN loss method and it is estimated as a function of land use, antecedent watershed moisture and soil type. An accurate estimation of the curve number is important in the performance of the model.
5. Among the different combinations of loss and transform methods, Combination 01 (SCS Curve Number loss method and SCS Unit Hydrograph transform method) shows better performance along with both Percent Error in Peak and Percent Error in Volume objective functions, than the other five (05) combinations.

6. In Combination 01, N.S.E. values after calibration were shown as 0.816 and 0.830 w.r.t. PEP and PEV, respectively. According to the literature, N.S.E. values greater than or equal to 0.75, computed results are taken to be good and these models can be taken as well calibrated models. In validation process also Combination 01 shows the N.S.E. values greater than 0.60 w.r.t. both PEP and PEV objective functions.

7. While Combinations 02 (SCS Curve Number method and Clark Unit Hydrograph method) and 03 (SCS Unit Hydrograph method and Snyder Unit Hydrograph method) also show good results, Combinations 04, 05 and 06 show poor results indicating that the Initial Constant method is not much suitable for Kelani basin. According to the Tables 6-4 and 6-5, it can be identified that N.S.E. values for Combinations 02 and 03 are greater than 0.7 while it is lower than 0.5 for Combinations 04, 05 and 06 during calibration w.r.t. both PEP and PEV. During validation, Combinations 04 and 05 show N.S.E. values lesser than 0.35 and literature says models which show N.S.E. values lower than 0.35 cannot be taken as satisfactory.

8. The SCS-CN loss method and SCS-UH transform method provide more reliable evaluations in streamflow predicting in the Kelani river basin. Visual observation of observed and simulated hydrographs and other performance indicators reveals that the developed model performs fairly well and it can simulate the streamflow accurately.

9. Considering the ability of the model to predict the peak discharge and the time consume to occur the peak, this model can be used as a flood prediction tool as the Deraniyagala area frequently face severe floods during heavy rainy periods.

CHAPTER 9

9 RECOMMENDATIONS

1. If finer resolution data can be used (ex: 05 mins), with more rainfall gauging stations and more rainfall events to calibrate and validate the model, the performance of the model can be enhanced.
2. Since the curve number is the most sensitive parameter in the loss model, it is recommended to use the latest land use maps and soil maps from a reliable source.
3. This study provides a guide on how to develop a hydrological model and it can be used as the foundation for similar approaches in other watersheds in the wet zone of Sri Lanka.
4. Due to the ability to predict peak discharge and time to peak in this model, it can be recommended that this model can be used as a flood prediction tool as an application to the early warning system in the Deraniyagala area.
5. The outflow hydrographs of this model can be used to feed the HEC-RAS model to identify the inundation areas during flood events.
6. This model can be used in the planning of water resources development projects (ex: reservoirs) in the Seethawaka river basin.
7. As future research directions it can be suggested that to check the suitability of these computing methods to river basins in other zones of the country also.

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ANNEXURE 1

ANNEXURE 01 : ISOHYETAL MAP OF SRI LANKA

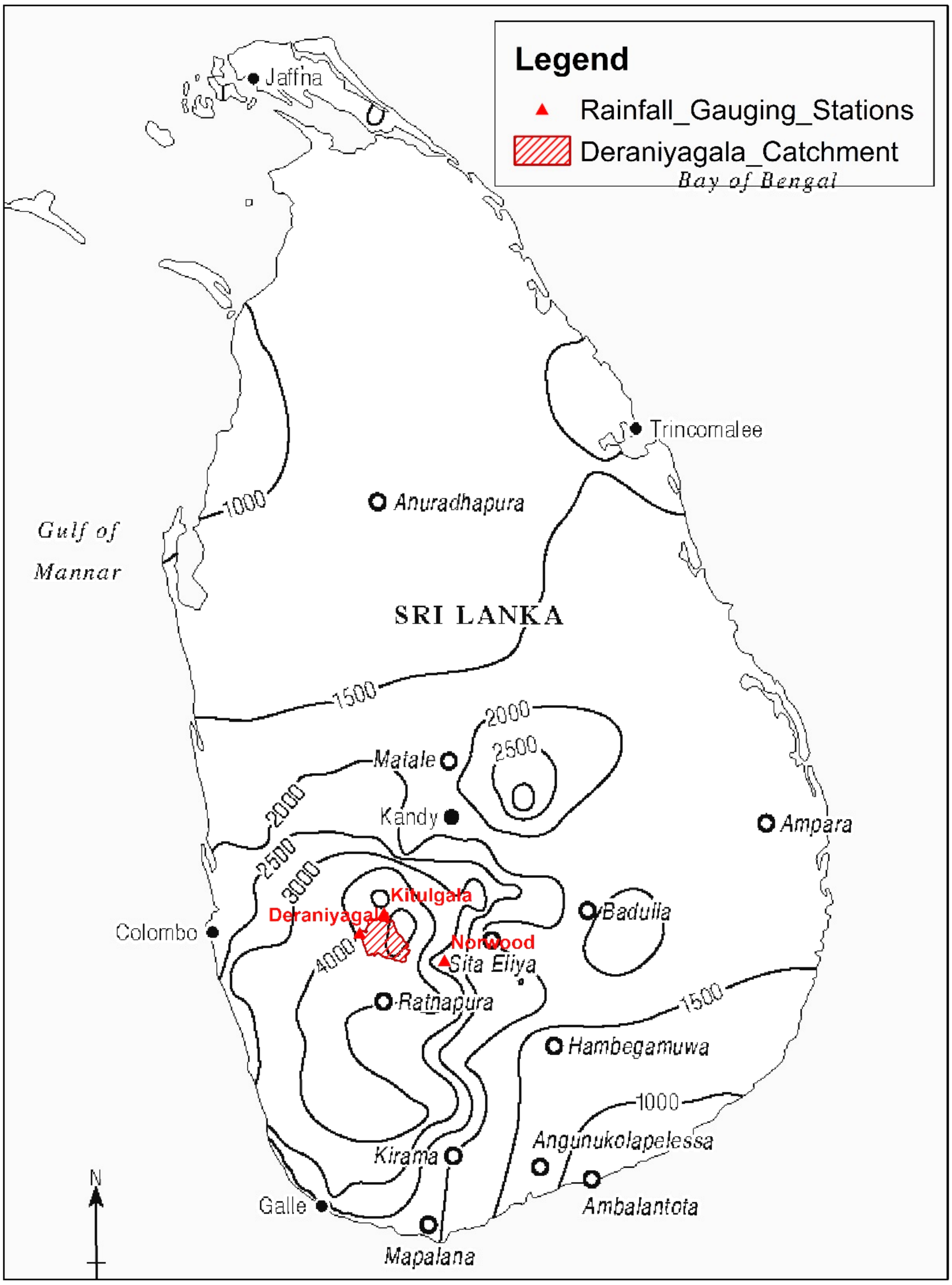

Figure A1- 1: Seethawaka Catchment and RF gauging stations within the Average Annual Rainfall Map of Sri Lanka

ANNEXURE 2

ANNEXURE 02 : VISUAL DATA CHECKING

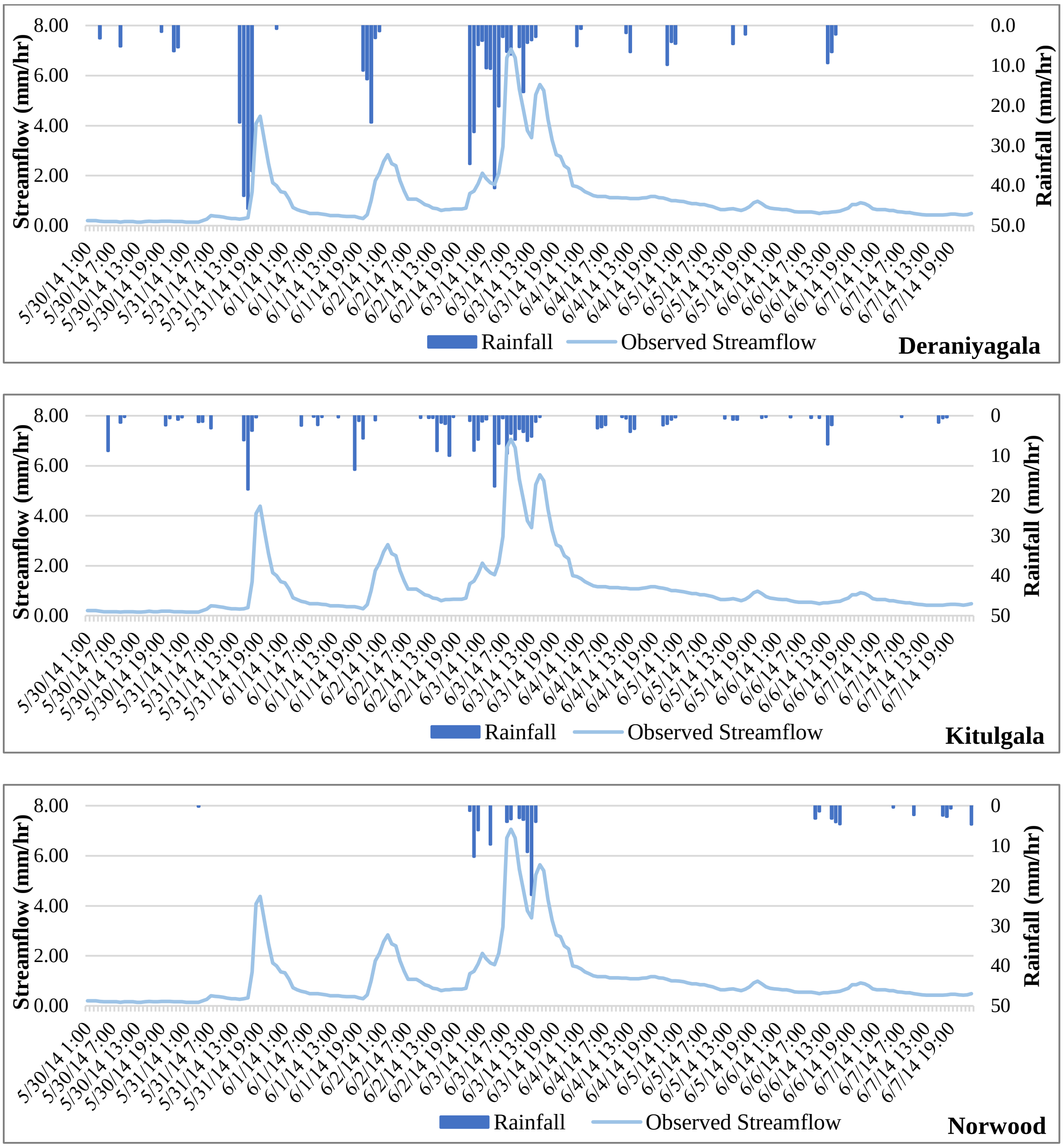

Figure A2- 1: Streamflow Vs Rainfall of Three Stations for 2014 Flood event

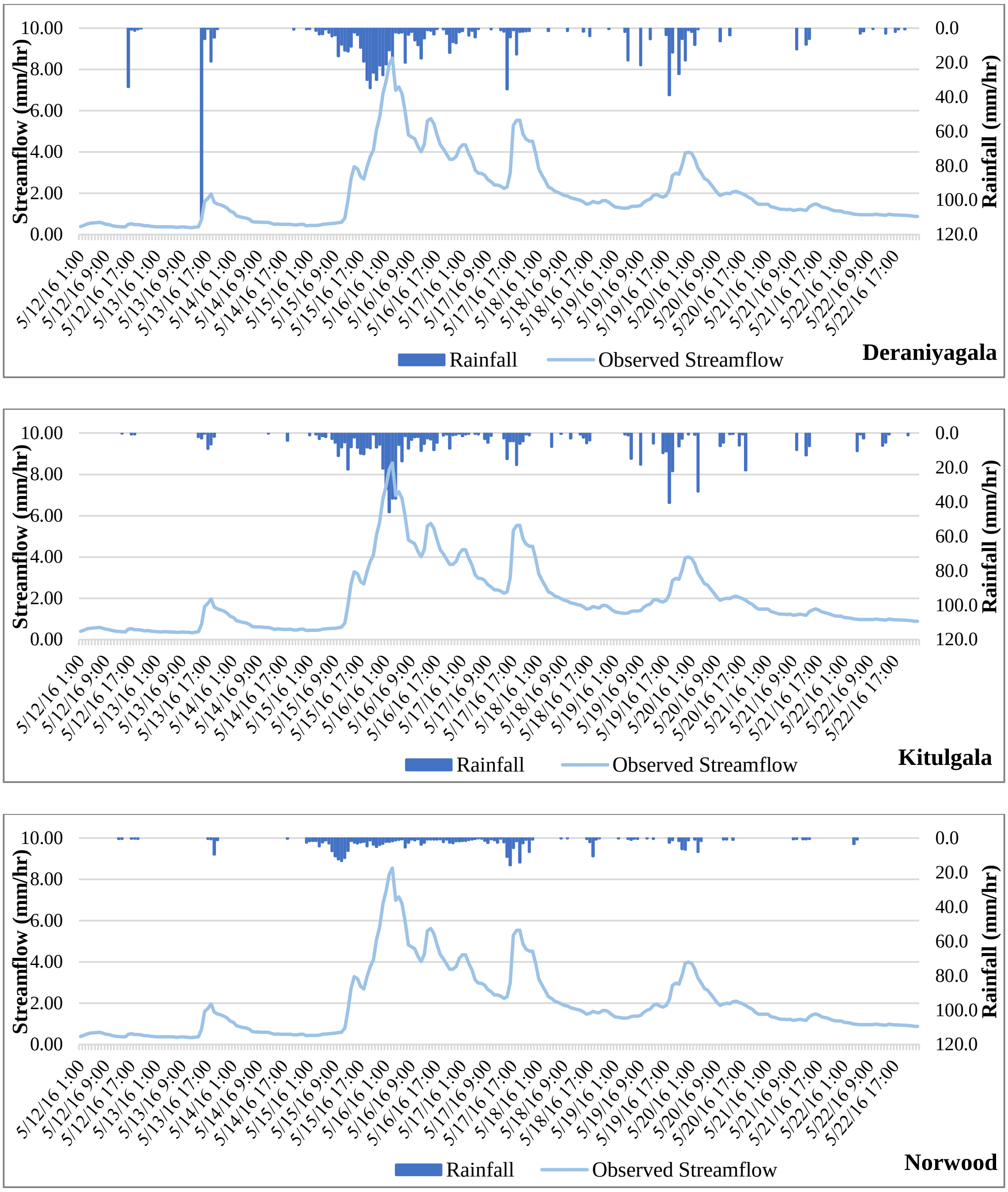

Figure A2- 2: Streamflow Vs Rainfall of Three Stations for 2016 Flood event

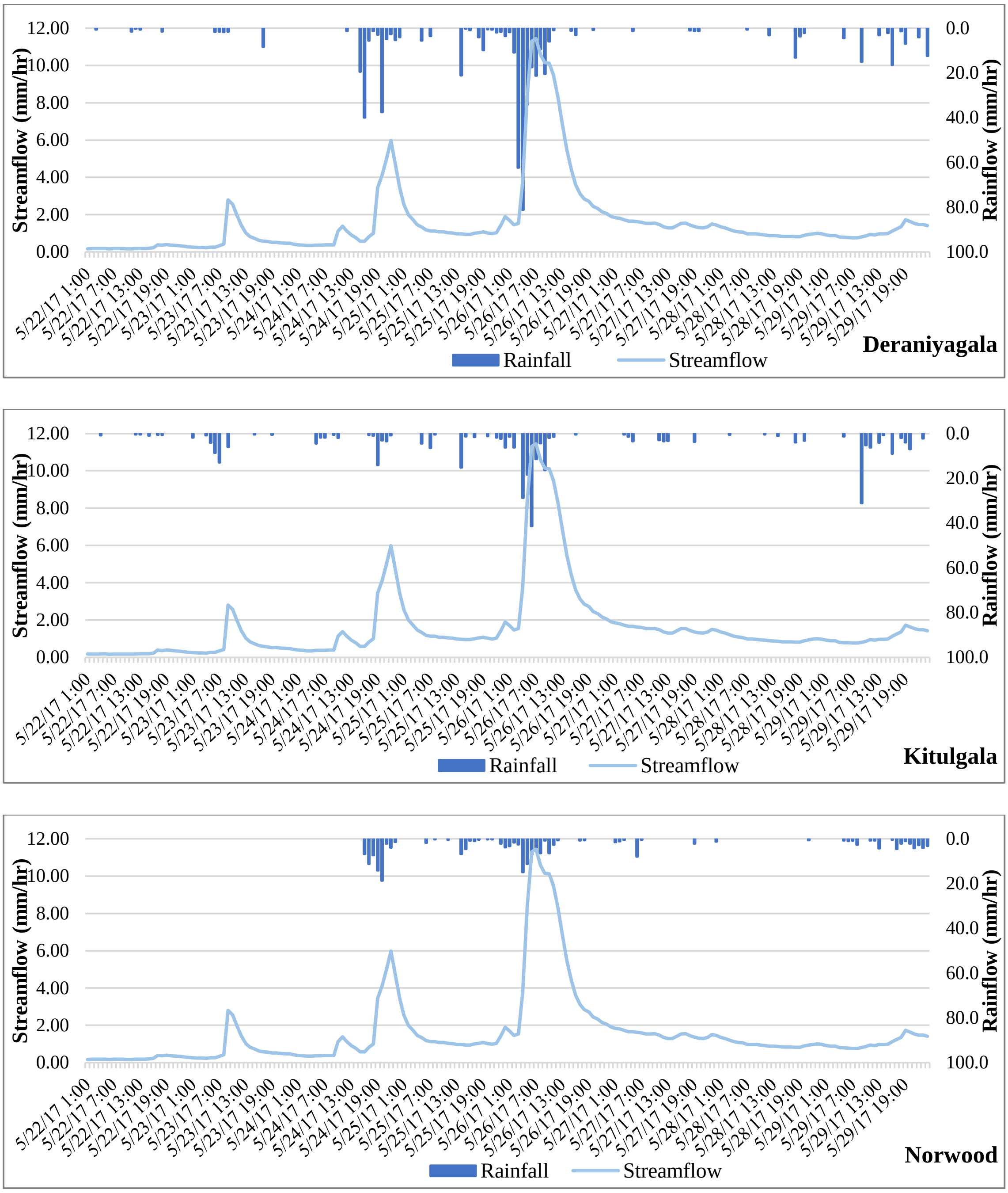

Figure A2- 3: Streamflow Vs Rainfall of Three Stations for 2017 Flood event

ANNEXURE 3

ANNEXURE 03 : CALIBRATION AND VALIDATION RESULTS

OUTFLOW HYDROGRAPHS

Figure A3-1 to Figure A3-8 show the observed and simulated hydrographs for Combination 03 to Combination 06 during the calibration period.

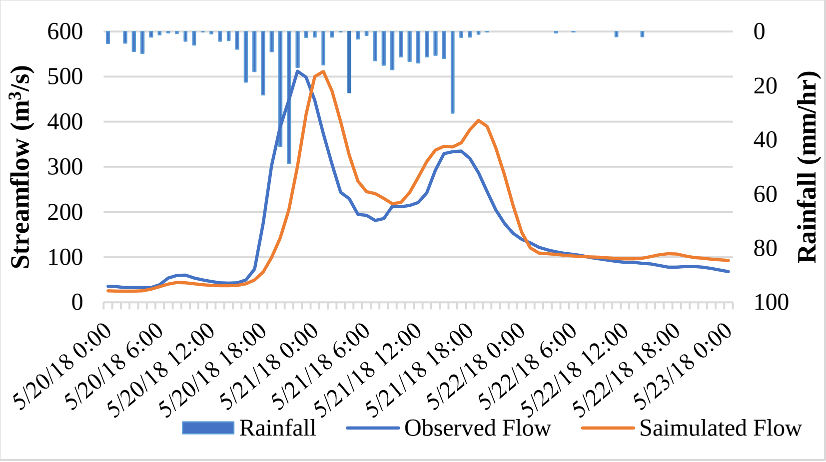

Figure A3- 1: Observed and Simulated Hydrographs for Combination 03 during calibration w.r.t. PEP

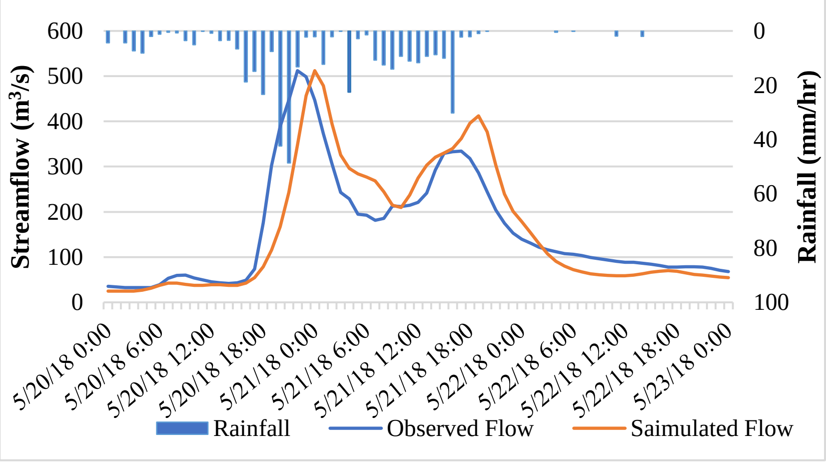

Figure A3- 2: Observed and Simulated Hydrographs for Combination 03 during calibration w.r.t. PEV

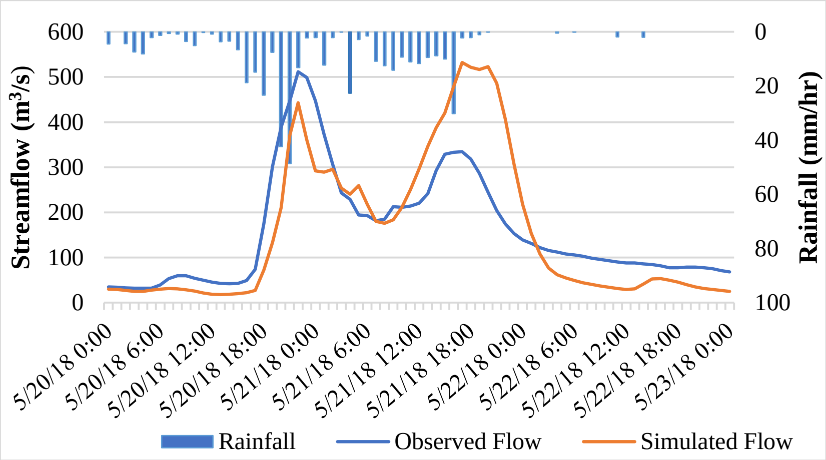

Figure A3- 3: Observed and Simulated Hydrographs for Combination 04 during calibration w.r.t. PEP

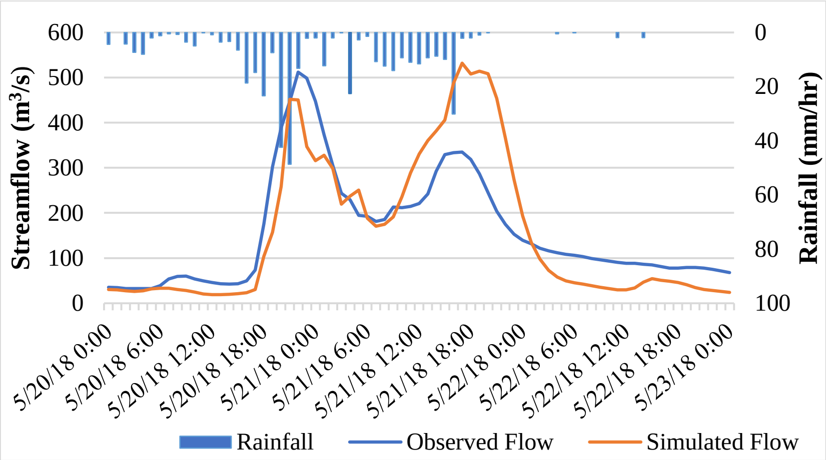

Figure A3- 4: Observed and Simulated Hydrographs for Combination 04 during calibration w.r.t. PEV

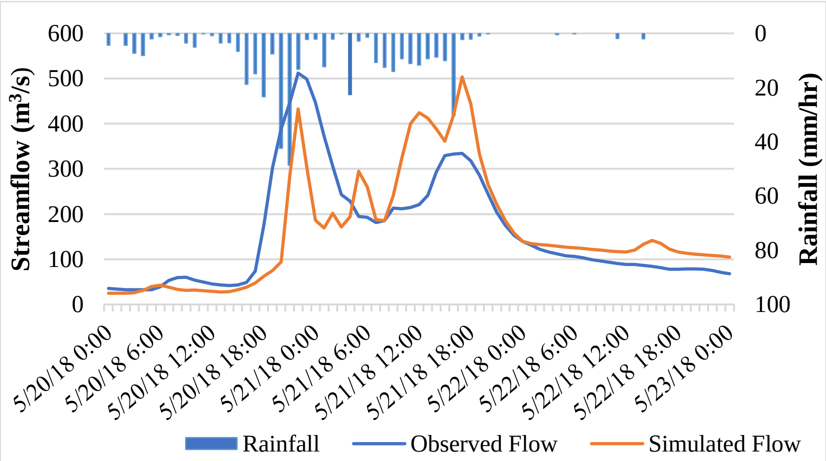

Figure A3- 5: Observed and Simulated Hydrographs for Combination 05 during calibration w.r.t. PEP

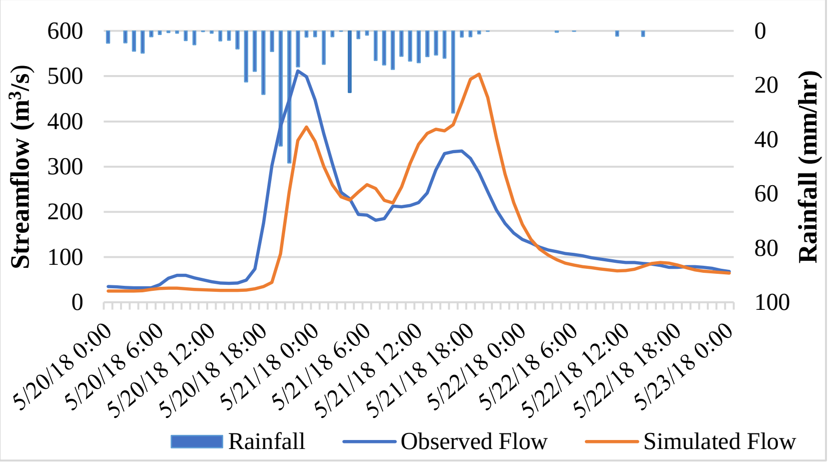

Figure A3- 6: Observed and Simulated Hydrographs for Combination 05 during calibration w.r.t. PEV

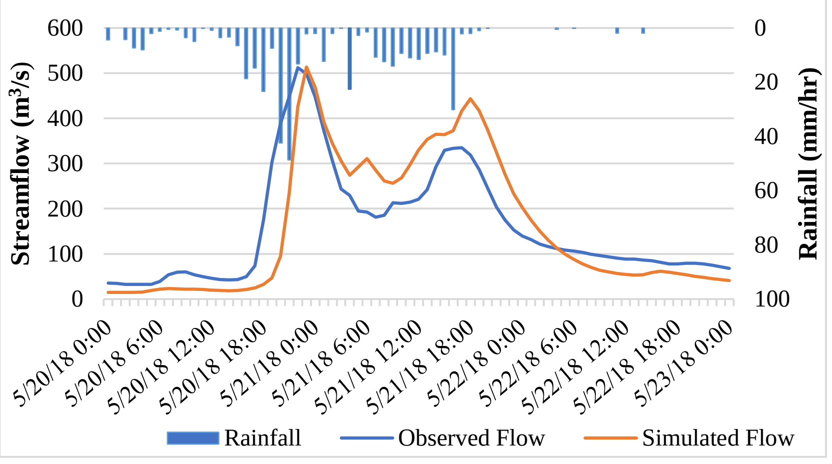

Figure A3- 7: Observed and Simulated Hydrographs for Combination 06 during calibration w.r.t. PEP

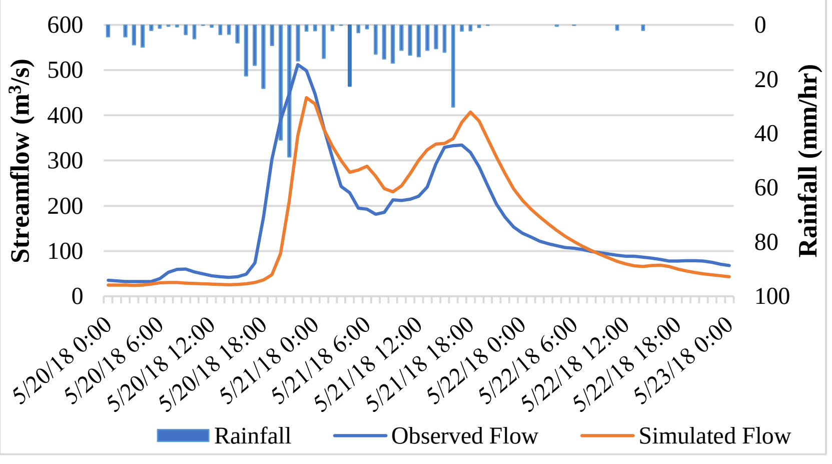

Figure A3- 8: Observed and Simulated Hydrographs for Combination 06 during calibration w.r.t. PEV

Figure A3 - 9 to Figure A3 - 18 show the observed and simulated hydrographs for Combination 02 to Combination 06 w.r.t. PEP and PEV objective functions during validation process using 2017 storm event.

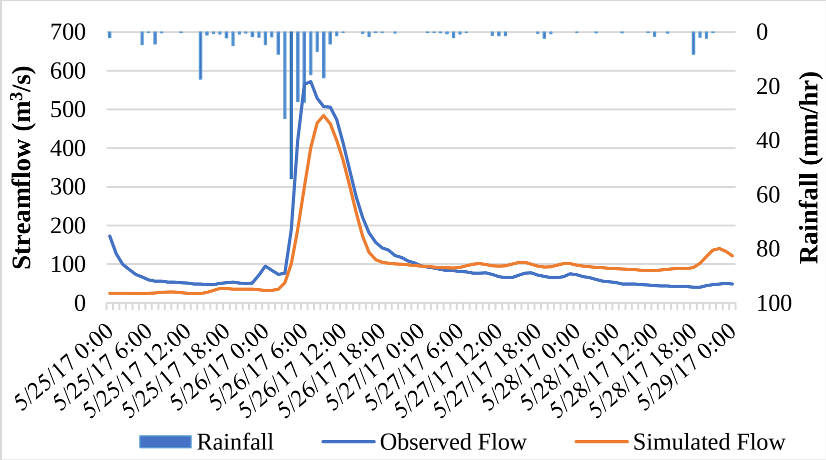

Figure A3- 9: Observed and Simulated Hydrographs for Combination 02 during Validation using 2017 event w.r.t. PEP

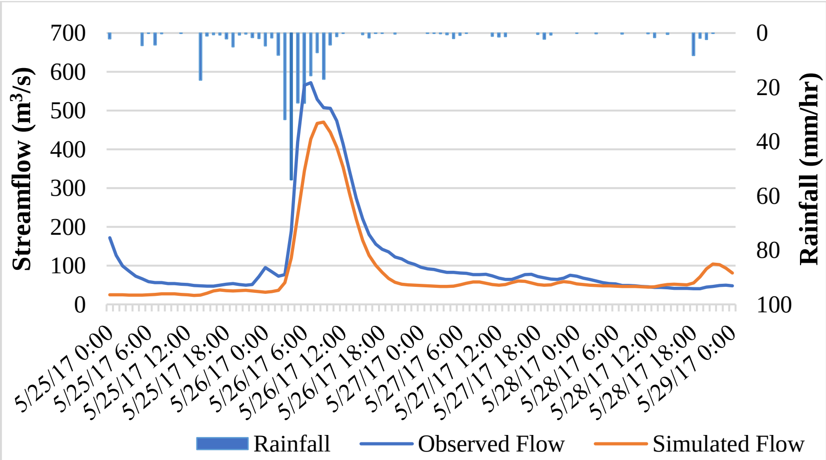

Figure A3- 10: Observed and Simulated Hydrographs for Combination 02 during Validation using 2017 event w.r.t. PEV

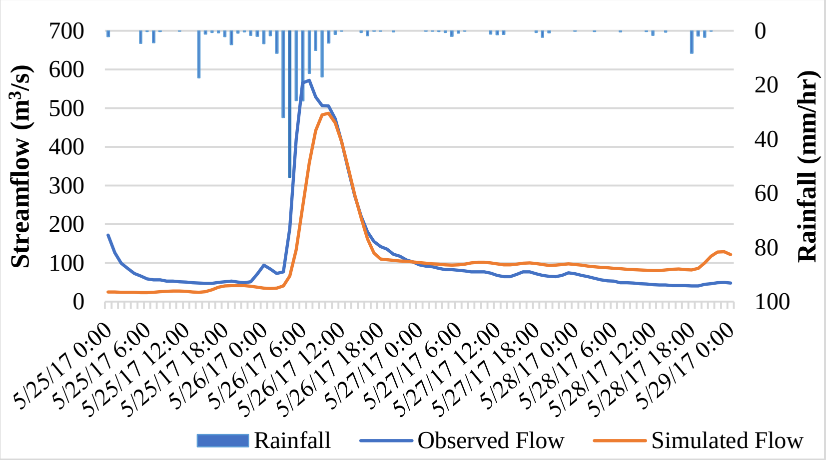

Figure A3- 11: Observed and Simulated Hydrographs for Combination 03 during Validation using 2017 event w.r.t. PEP

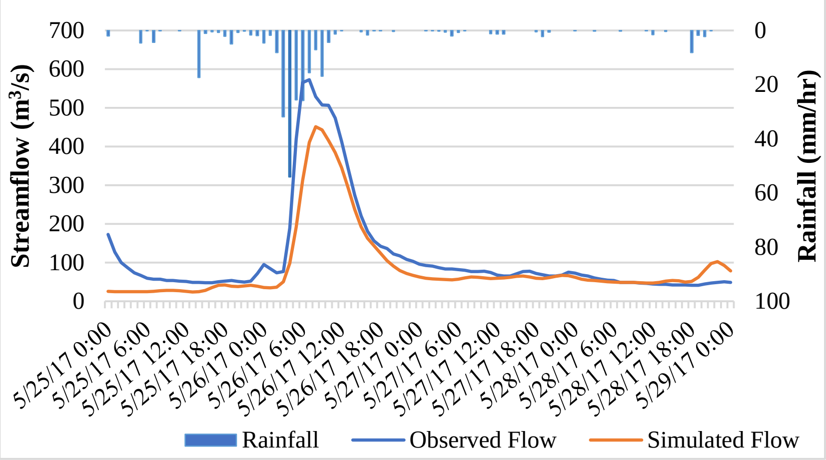

Figure A3- 12: Observed and Simulated Hydrographs for Combination 03 during Validation using 2017 event w.r.t. PEV

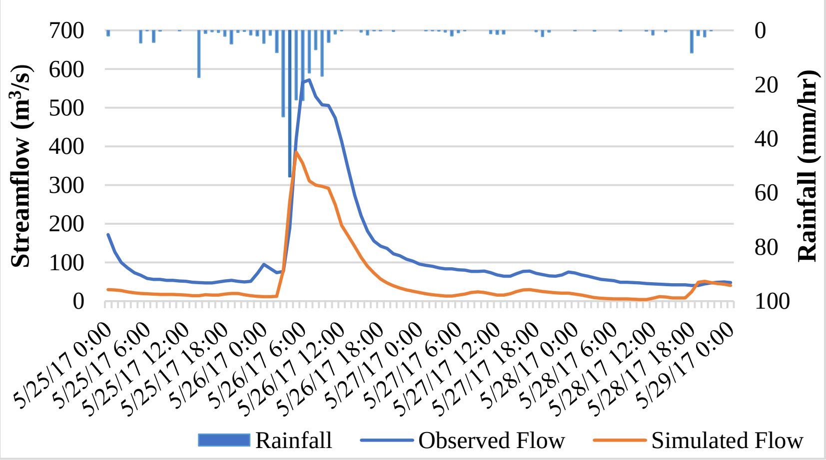

Figure A3- 13: Observed and Simulated Hydrographs for Combination 04 during Validation using 2017 event w.r.t. PEP

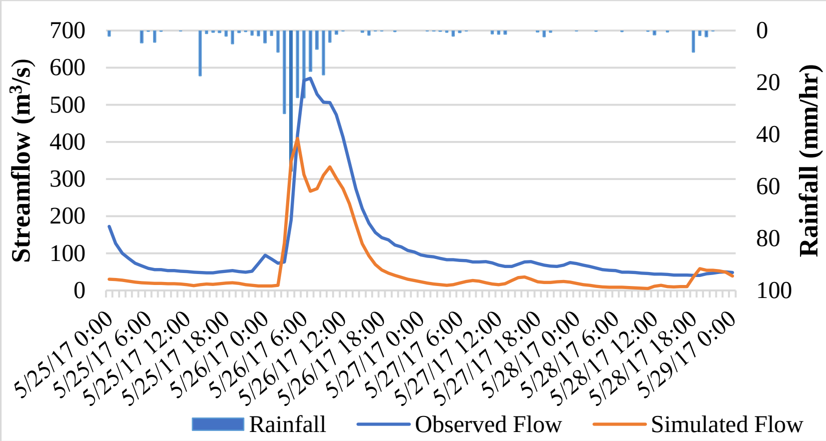

Figure A3- 14: Observed and Simulated Hydrographs for Combination 04 during Validation using 2017 event w.r.t. PEV

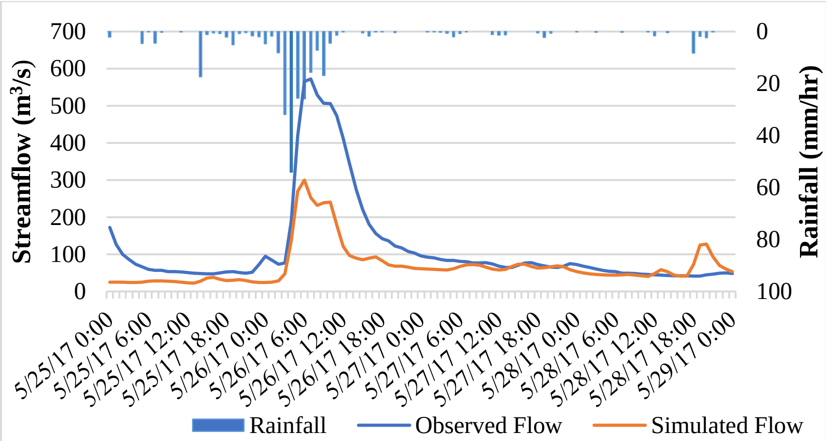

Figure A3- 15: Observed and Simulated Hydrographs for Combination 05 during Validation using 2017 event w.r.t. PEP

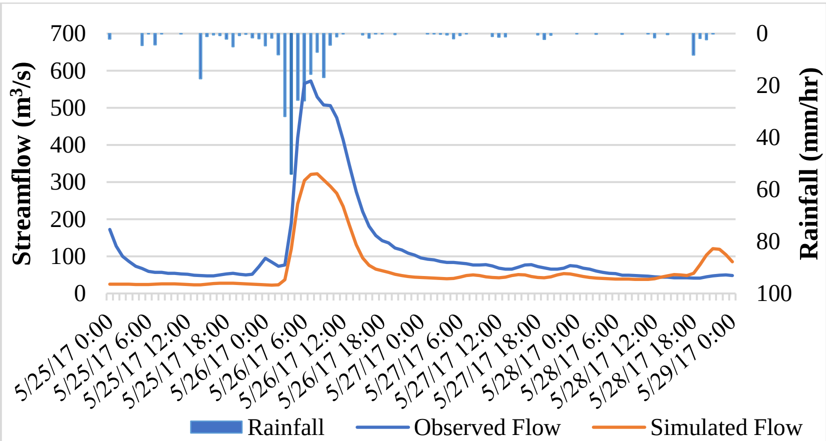

Figure A3- 16: Observed and Simulated Hydrographs for Combination 05 during Validation using 2017 event w.r.t. PEV

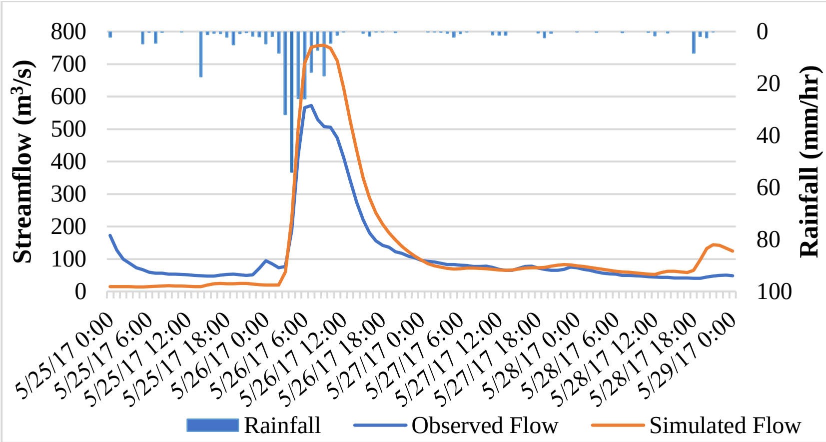

Figure A3- 17: Observed and Simulated Hydrographs for Combination 06 during Validation using 2017 event w.r.t. PEP

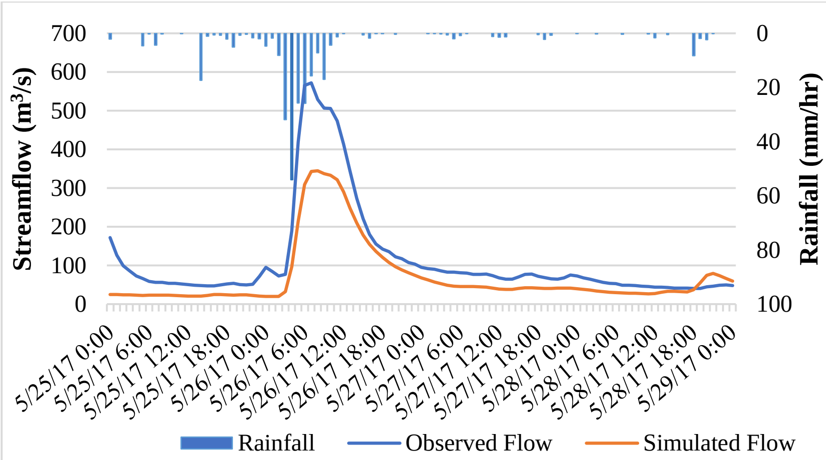

Figure A3- 18: Observed and Simulated Hydrographs for Combination 06 during Validation using 2017 event w.r.t. PEV

Figure A3 - 19 to Figure A3 -28 show the observed and simulated hydrographs for Combination 02 to Combination 06 w.r.t. PEP and PEV objective functions during the validation process using the 2016 storm event.

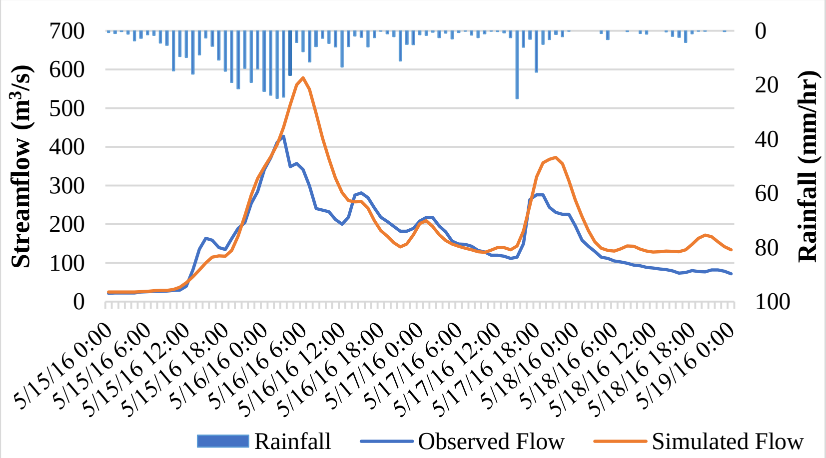

Figure A3- 19: Observed and Simulated Hydrographs for Combination 02 during Validation using 2016 event w.r.t. PEP

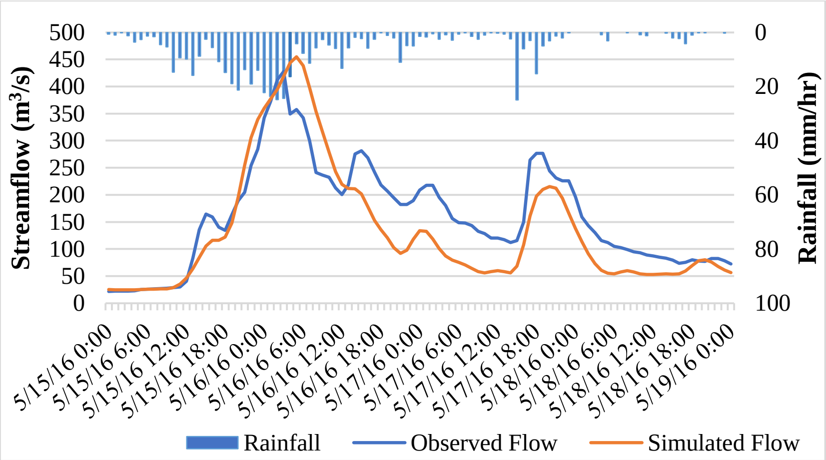

Figure A3- 20: Observed and Simulated Hydrographs for Combination 02 during Validation using 2016 event w.r.t. PEV

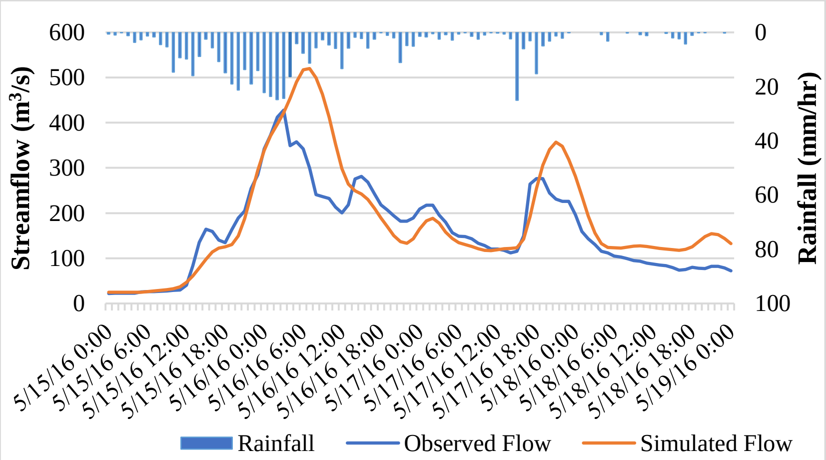

Figure A3- 21: Observed and Simulated Hydrographs for Combination 03 during Validation using 2016 event w.r.t. PEP

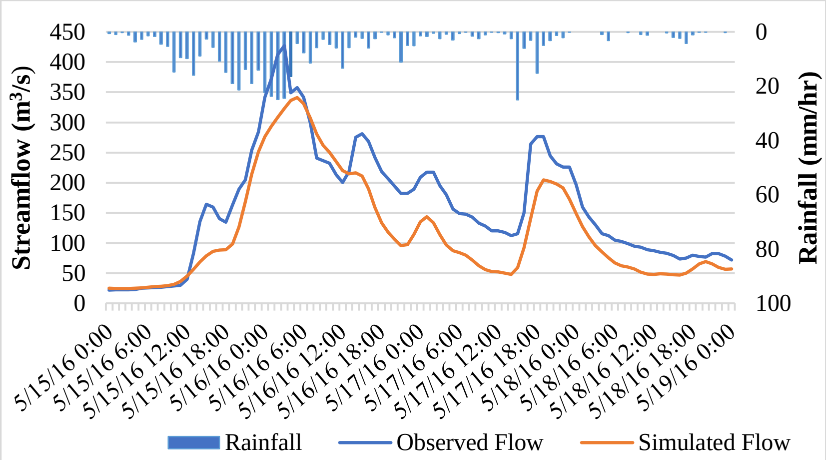

Figure A3- 22: Observed and Simulated Hydrographs for Combination 03 during Validation using 2016 event w.r.t. PEV

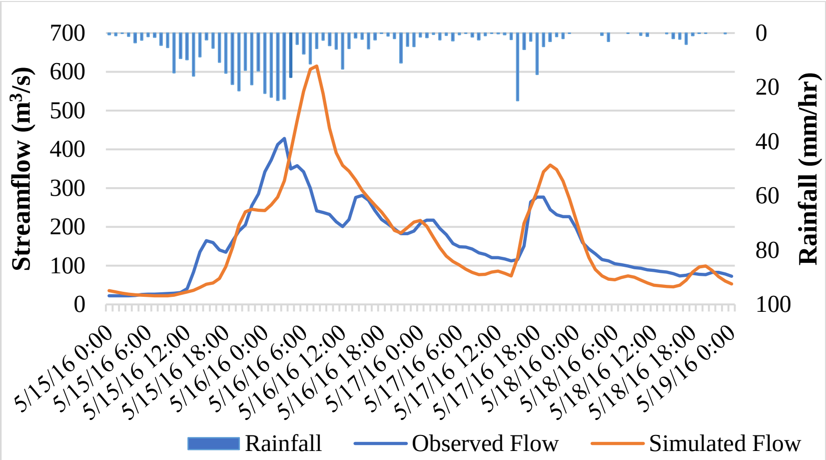

Figure A3- 23: Observed and Simulated Hydrographs for Combination 04 during Validation using 2016 event w.r.t. PEP

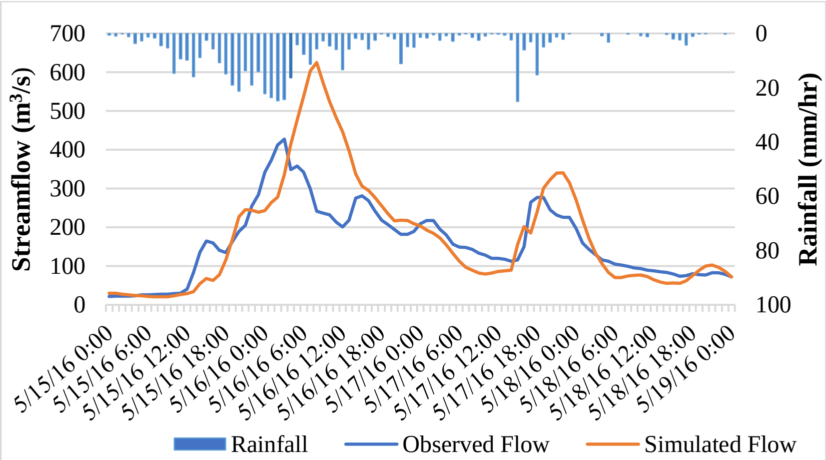

Figure A3- 24: Observed and Simulated Hydrographs for Combination 04 during Validation using 2016 event w.r.t. PEV

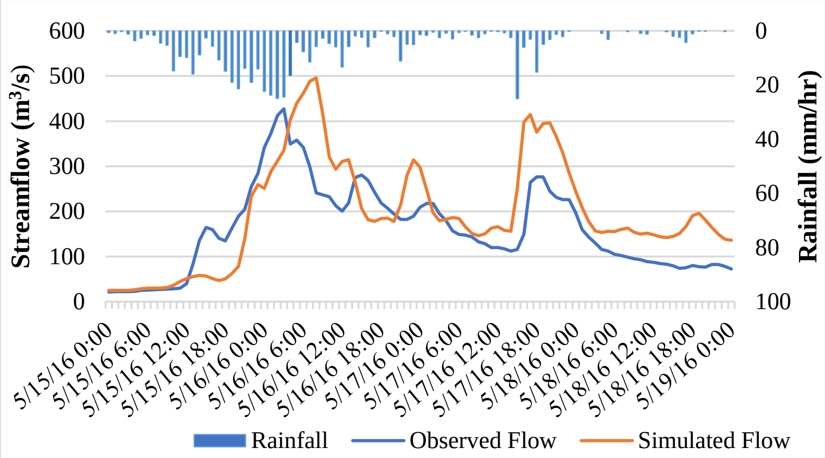

Figure A3- 25: Observed and Simulated Hydrographs for Combination 05 during Validation using 2016 event w.r.t. PEP

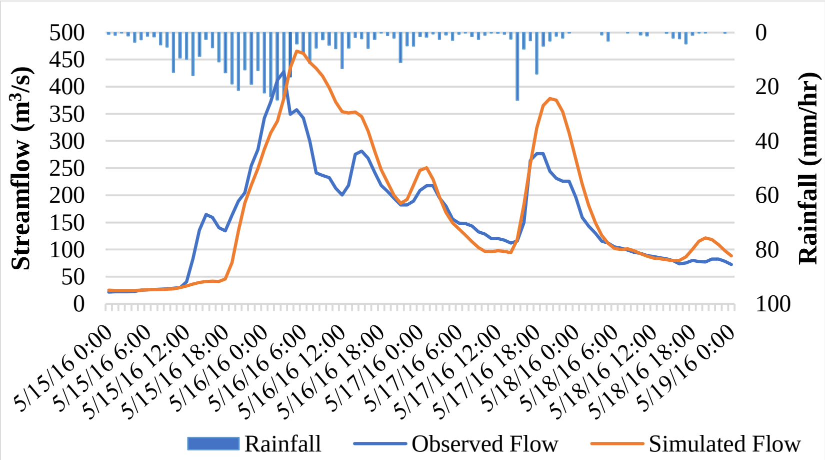

Figure A3- 26: Observed and Simulated Hydrographs for Combination 05 during Validation using 2016 event w.r.t. PEV

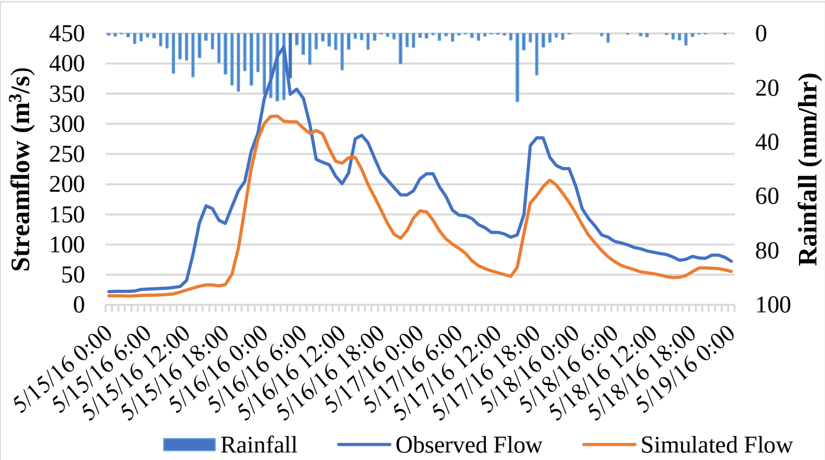

Figure A3- 27: Observed and Simulated Hydrographs for Combination 06 during Validation using 2016 event w.r.t. PEP

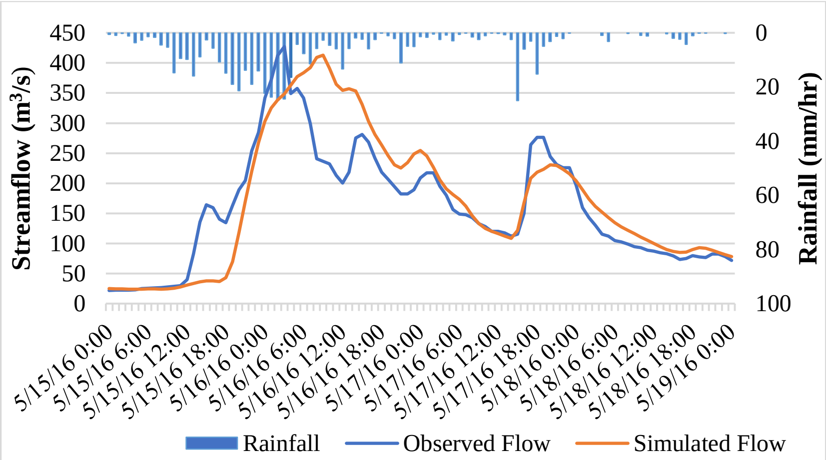

Figure A3-28: Observed and Simulated Hydrographs for Combination 06 during Validation using 2016 event w.r.t. PEV

Figure A3 - 29 to Figure A3 – 38 show the observed and simulated hydrographs for Combination 02 to Combination 06 w.r.t. PEP and PEV objective functions during the validation process using the 2014 storm event.

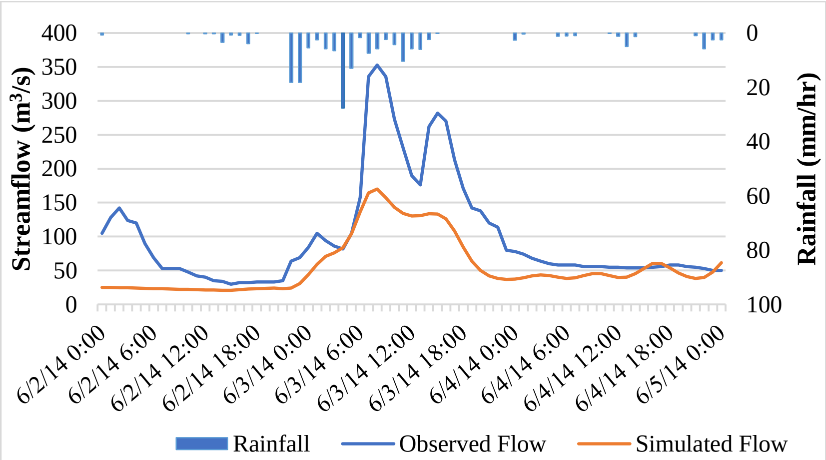

Figure A3-29: Observed and Simulated Hydrographs for Combination 02 during Validation using 2014 event w.r.t. PEP

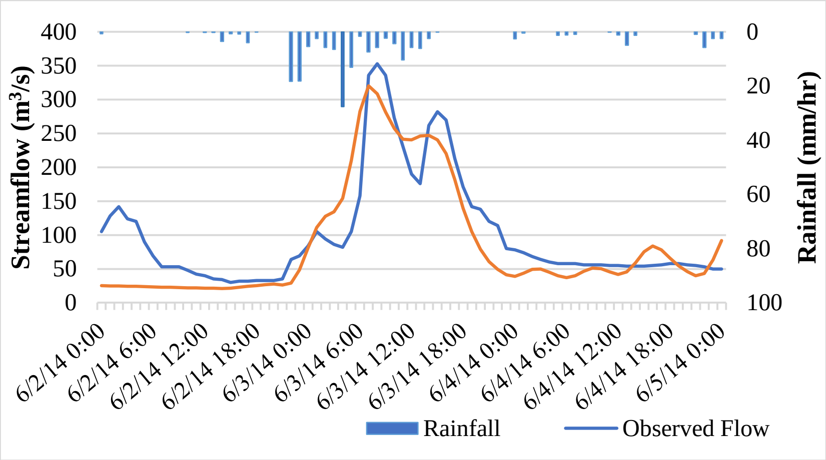

Figure A3-30: Observed and Simulated Hydrographs for Combination 02 during Validation using 2014 event w.r.t. PEV

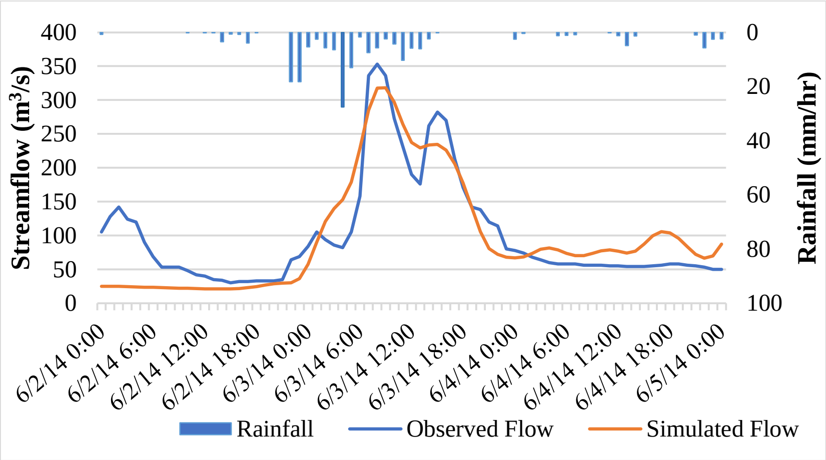

Figure A3-31: Observed and Simulated Hydrographs for Combination 03 during Validation using 2014 event w.r.t. PEP

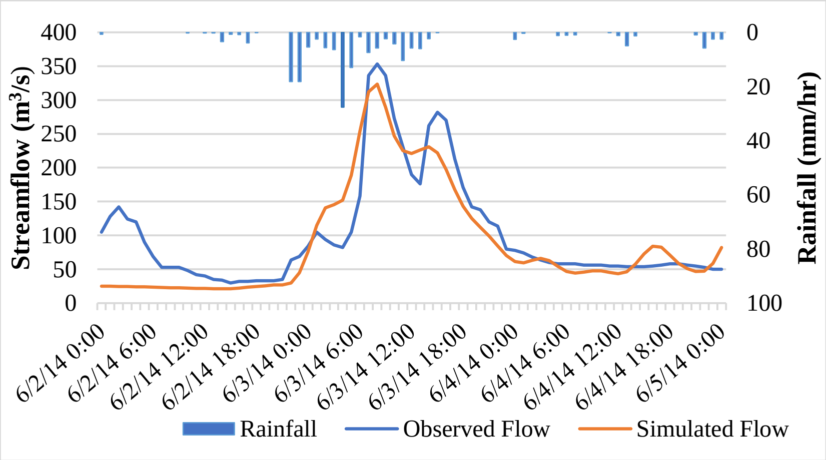

Figure A3-32: Observed and Simulated Hydrographs for Combination 03 during Validation using 2014 event w.r.t. PEV

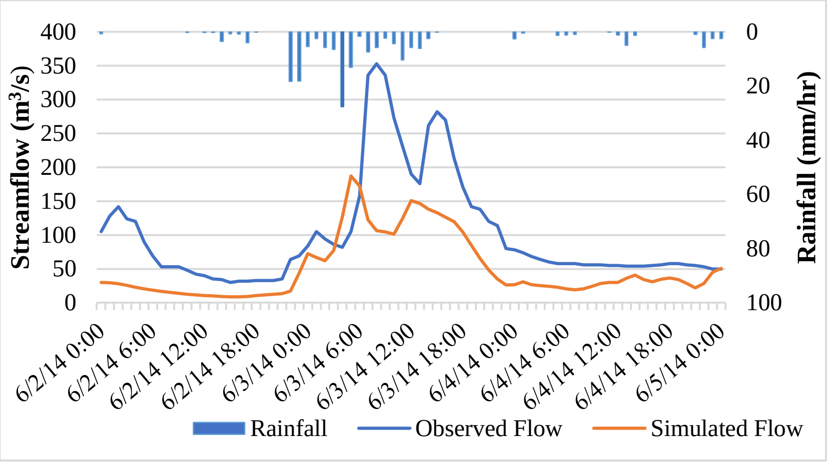

Figure A3-33: Observed and Simulated Hydrographs for Combination 04 during Validation using 2014 event w.r.t. PEP

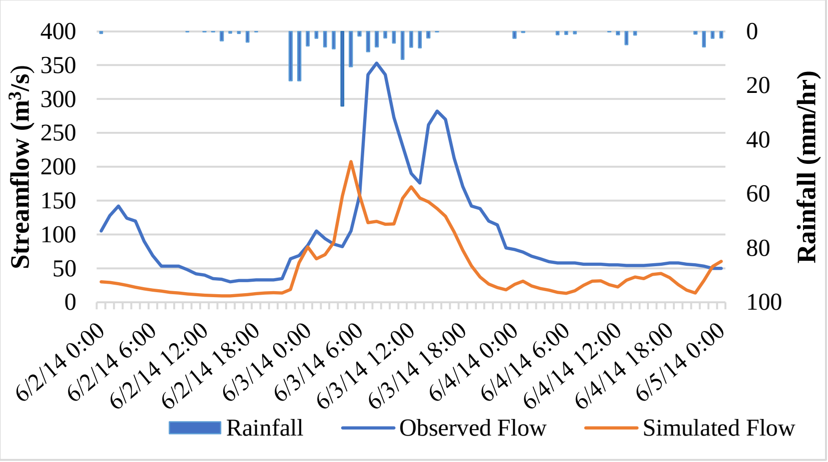

Figure A3-34: Observed and Simulated Hydrographs for the Combination 04 during Validation using 2014 event w.r.t. PEV

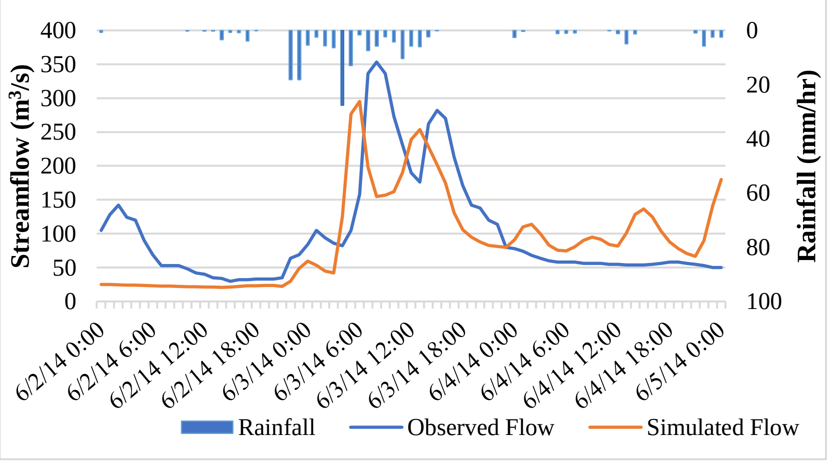

Figure A3-35: Observed and Simulated Hydrographs for the Combination 05 during Validation using 2014 event w.r.t. PEP

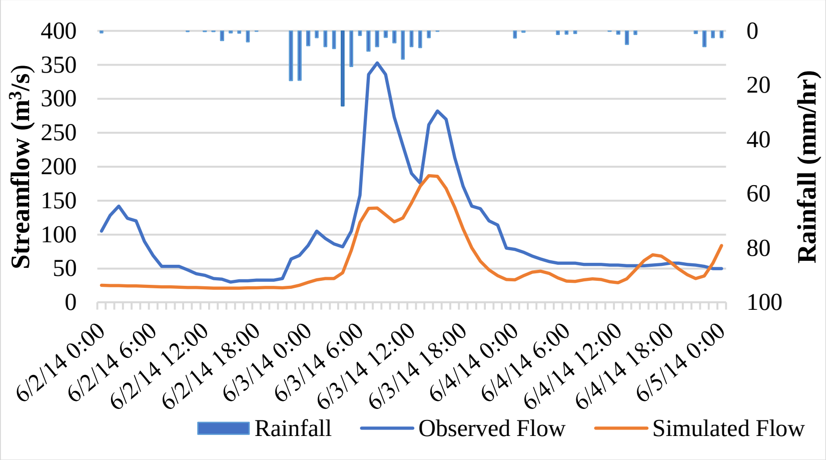

Figure A3-36: Observed and Simulated Hydrographs for the Combination 05 during Validation using 2014 event w.r.t. PEV

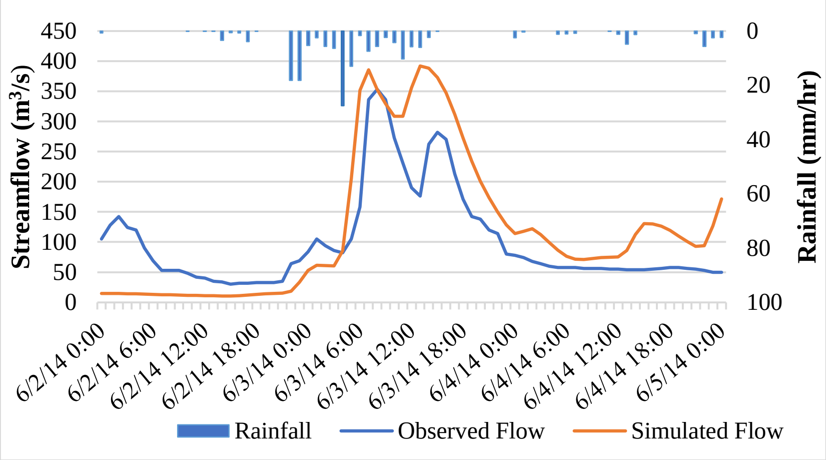

Figure A3-37: Observed and Simulated Hydrographs for the Combination 06 during Validation using 2014 event w.r.t. PEP

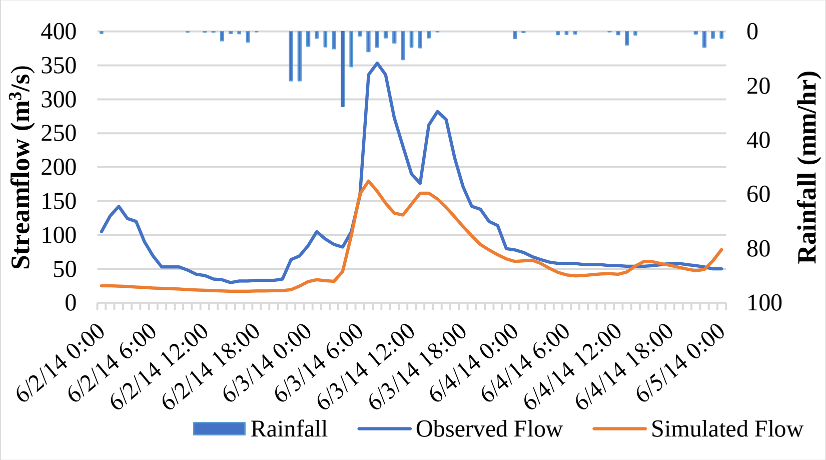

Figure A3- 38: Observed and Simulated Hydrographs for the Combination 06 during Validation using 2014 event w.r.t. PEV

FLOW DURATION CURVES – CALIBRATION PERIOD

Figure A3-39 to Figure A3-58 show the flow duration curves for calibration of each combination w.r.t. PEP and PEV objective functions using the 2018 storm event.

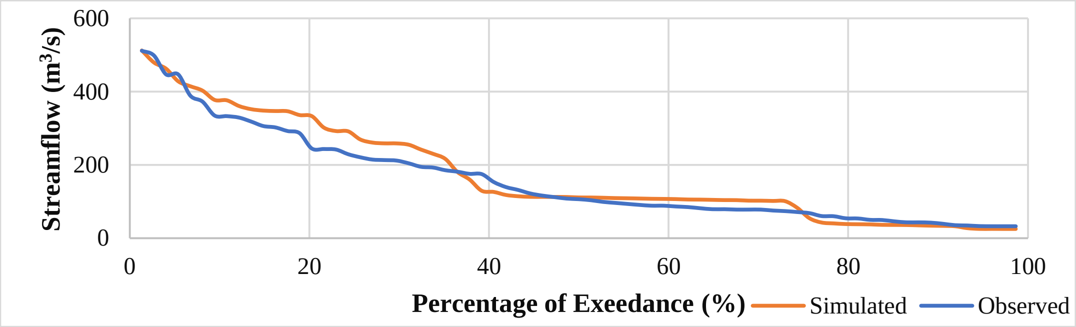

Figure A3-39: Flow Duration Curve for Combination 02 w.r.t. PEP (Normal Scale)

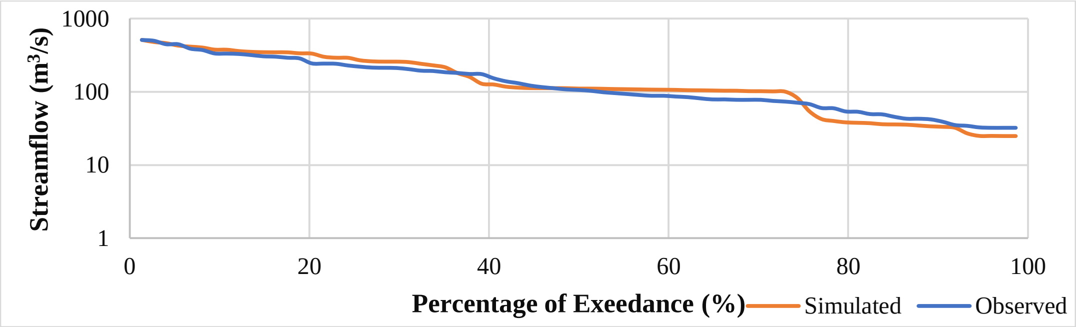

Figure A3-40: Flow Duration Curve for Combination 02 w.r.t. PEP (Log Scale)

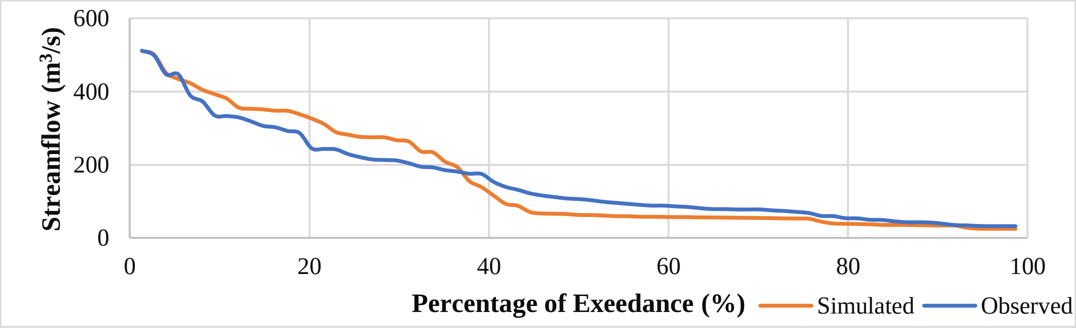

Figure A3-41: Flow Duration Curve for Combination 02 w.r.t. PEV (Normal Scale)

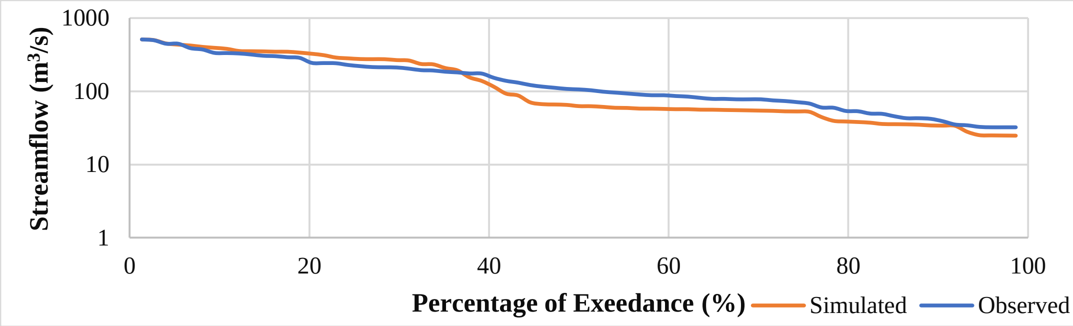

Figure A3-42: Flow Duration Curve for Combination 02 w.r.t. PEV (Log Scale)

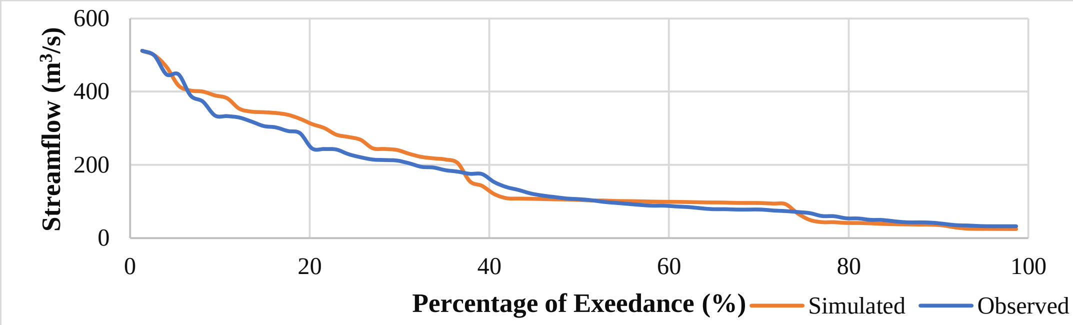

Figure A3-43: Flow Duration Curve for Combination 03 w.r.t. PEP (Normal Scale)

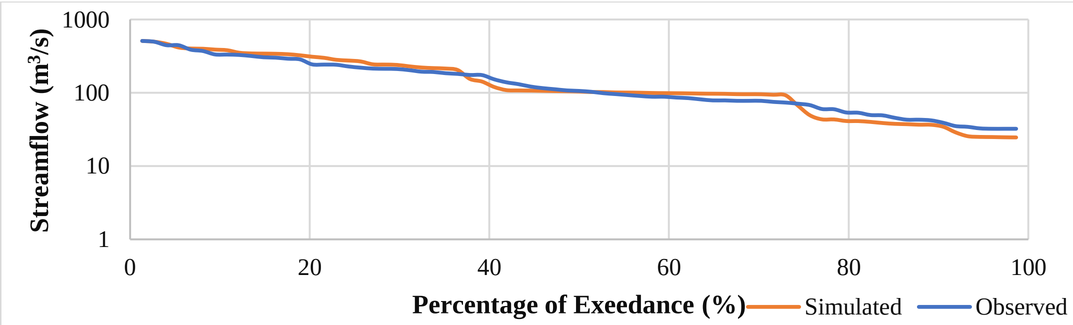

Figure A3-44: Flow Duration Curve for Combination 03 w.r.t. PEP (Log Scale)

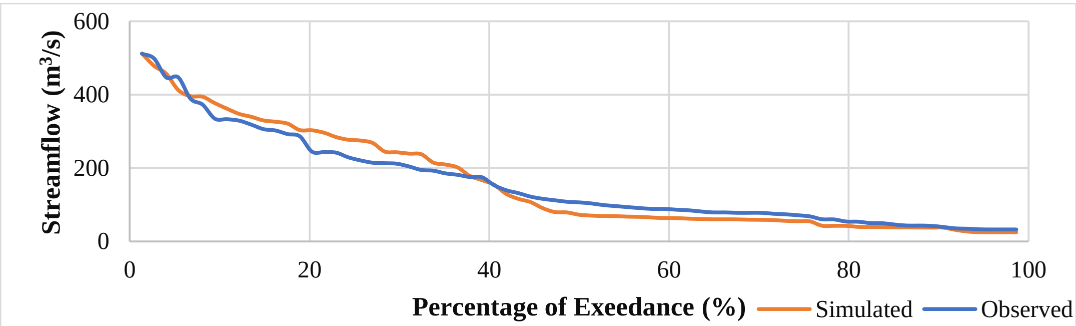

Figure A3-45: Flow Duration Curve for Combination 03 w.r.t. PEV (Normal Scale)

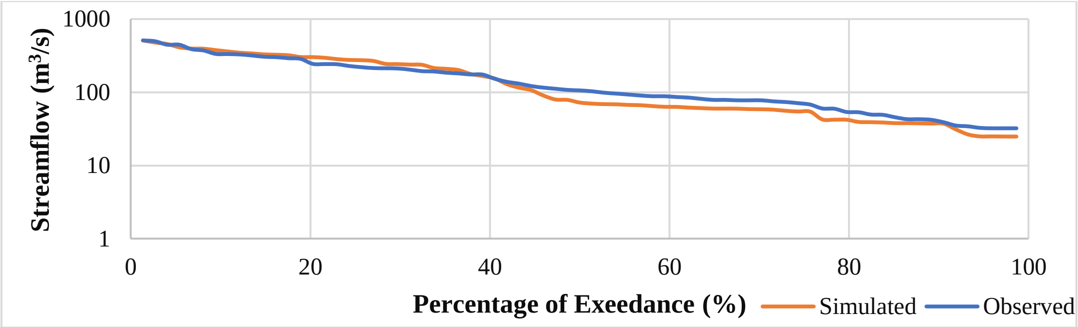

Figure A3-46: Flow Duration Curve for Combination 03 w.r.t. PEV (Log Scale)

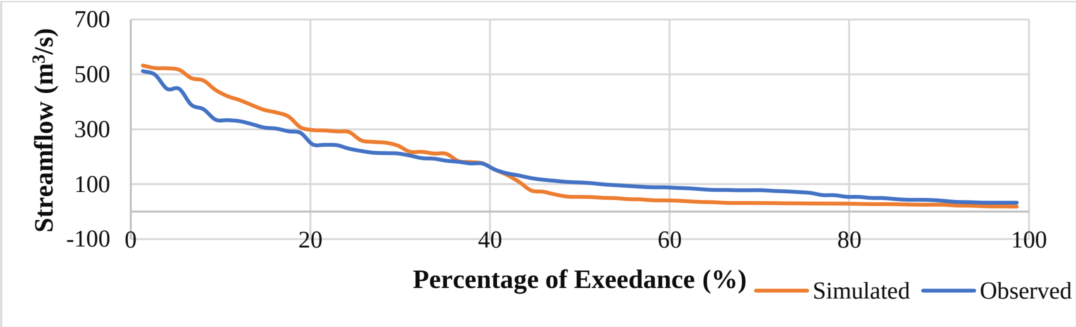

Figure A3-47: Flow Duration Curve for Combination 04 w.r.t. PEP (Normal Scale)

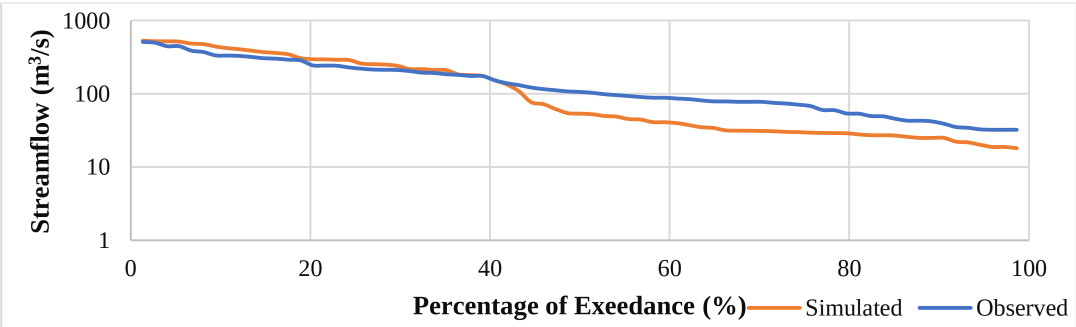

Figure A3-48: Flow Duration Curve for Combination 04 w.r.t. PEP (Log Scale)

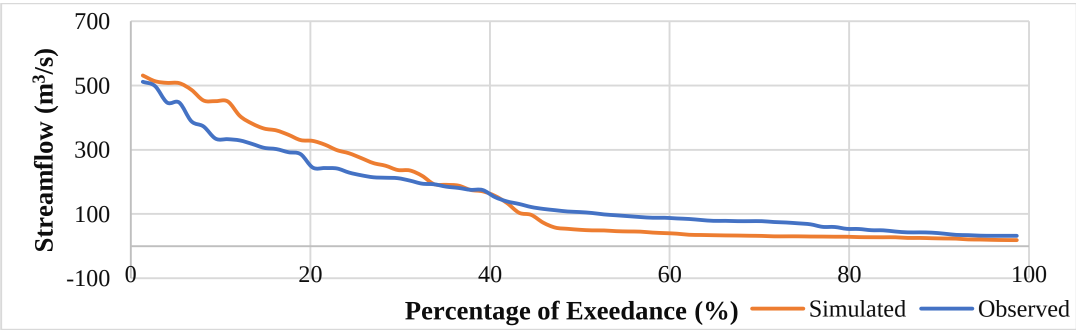

Figure A3-49: Flow Duration Curve for Combination 04 w.r.t. PEV (Normal Scale)

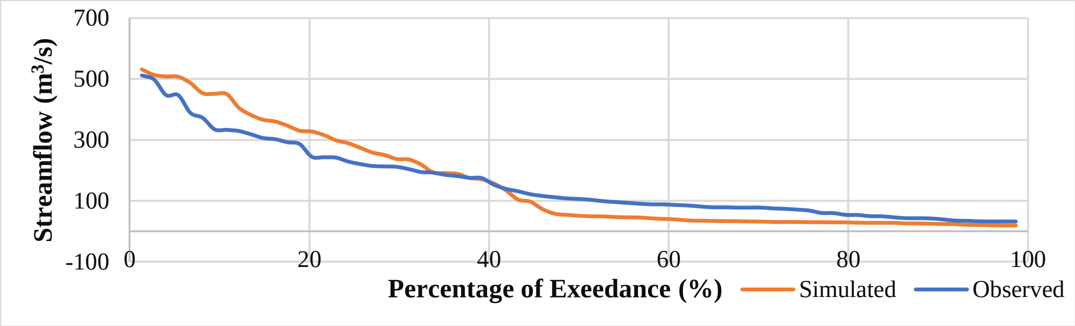

Figure A3-50: Flow Duration Curve for Combination 04 w.r.t. PEV (Log Scale)

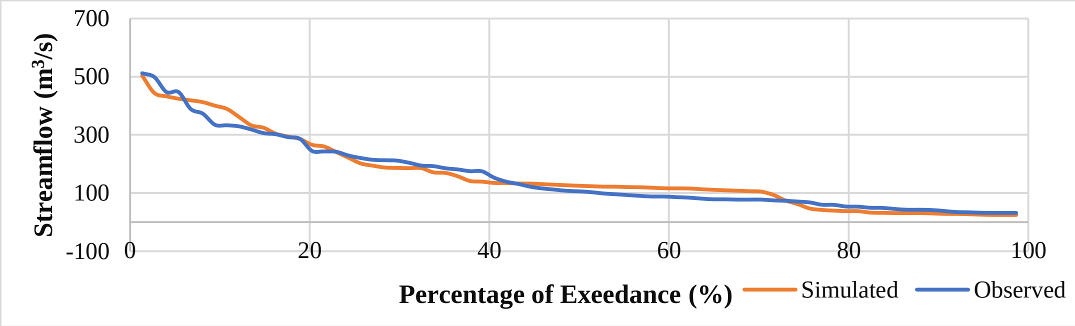

Figure A3-51: Flow Duration Curve for Combination 05 w.r.t. PEP (Normal Scale)

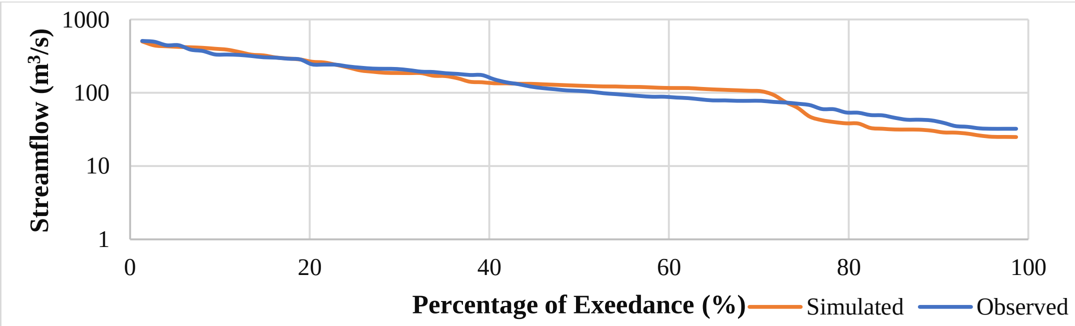

Figure A3-52: Flow Duration Curve for Combination 05 w.r.t. PEP (Log Scale)

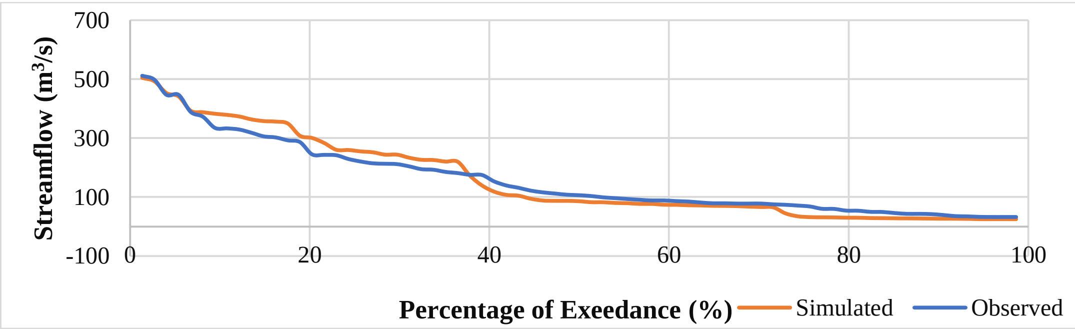

Figure A3-53: Flow Duration Curve for Combination 05 w.r.t. PEV (Normal Scale)

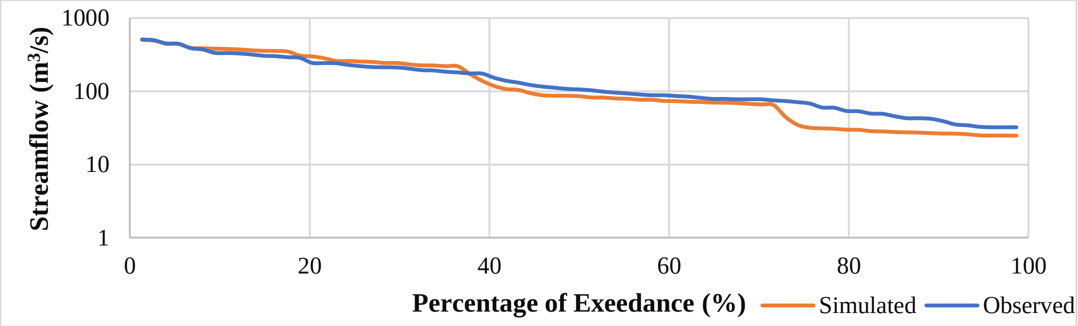

Figure A3-54: Flow Duration Curve for Combination 04 w.r.t. PEV (Log Scale)

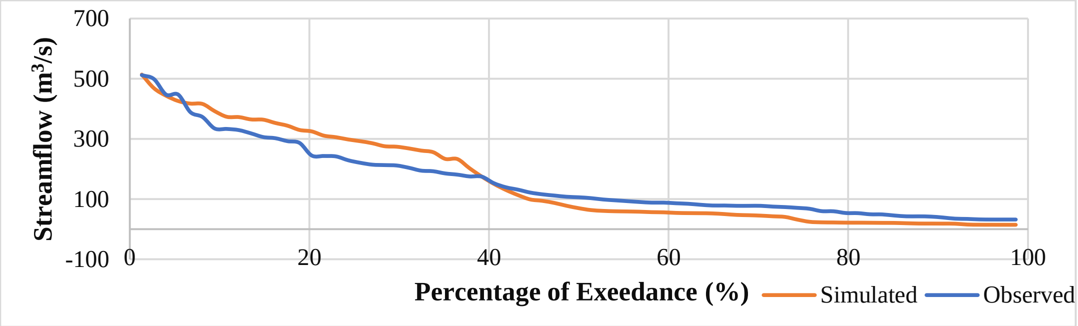

Figure A3-55: Flow Duration Curve for Combination 06 w.r.t. PEP (Normal Scale)

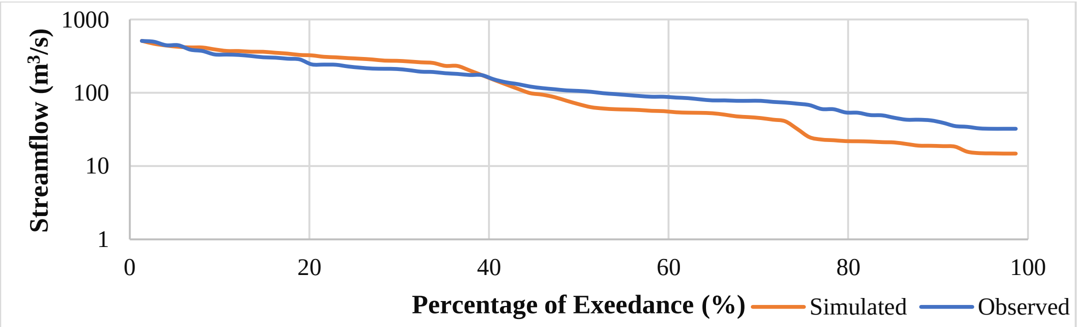

Figure A3-56: Flow Duration Curve for Combination 06 w.r.t. PEP (Log Scale)

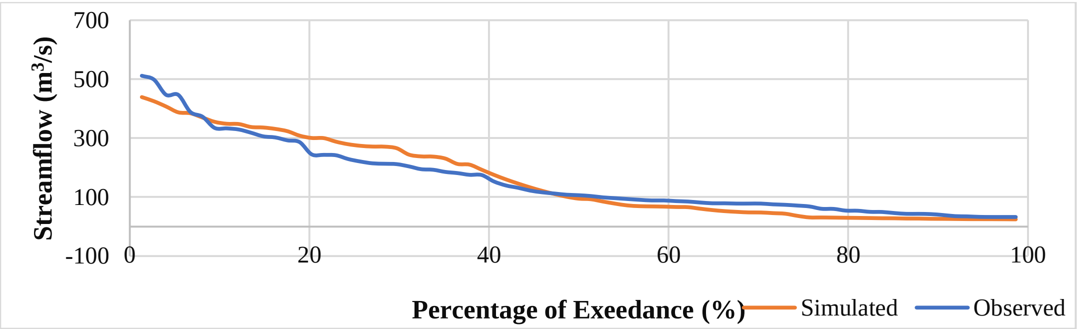

Figure A3-57: Flow Duration Curve for Combination 06 w.r.t. PEV (Normal Scale)

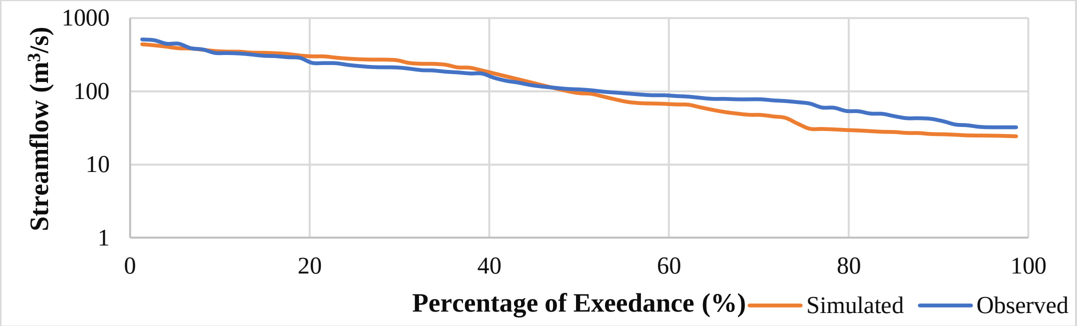

Figure A3-58: Flow Duration Curve for Combination 06 w.r.t. PEV (Log Scale)

FLOW DURATION CURVES – VALIDATION PERIOD

Figure A3-59 to Figure A3-78 shows the flow duration curves for validation of each combination w.r.t. PEP and PEV objective functions using 2017 storm event.

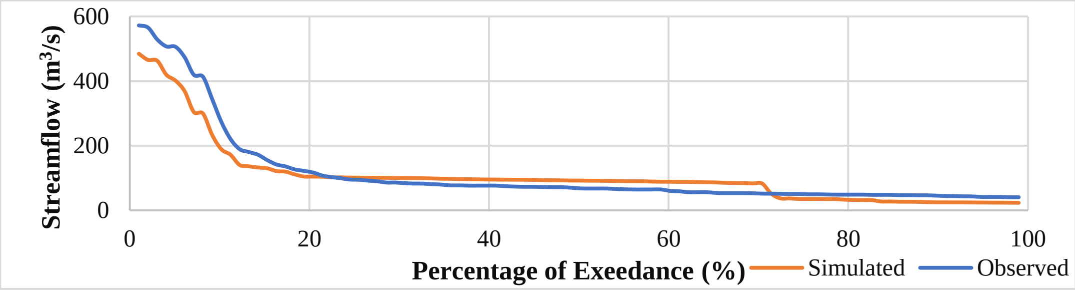

Figure A3-59: Flow Duration Curve for Combination 02 w.r.t. PEP (Normal Scale)

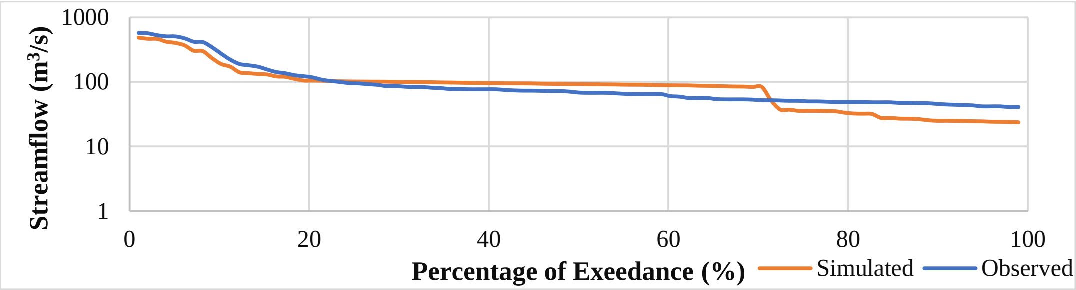

Figure A3-60: Flow Duration Curve for Combination 02 w.r.t. PEP (Log Scale)

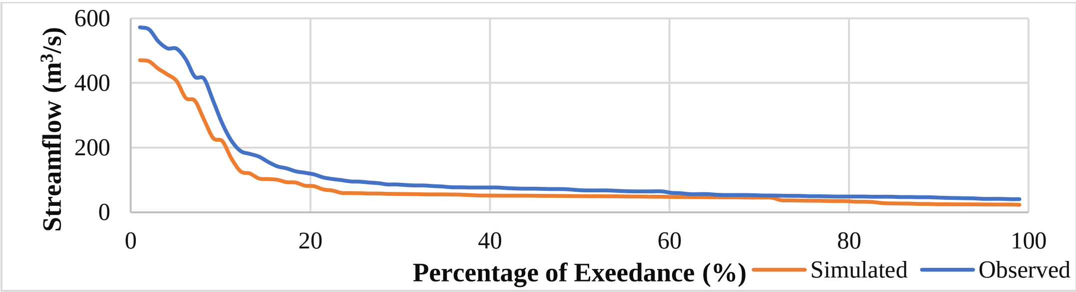

Figure A3-61: Flow Duration Curve for Combination 02 w.r.t. PEV (Normal Scale)

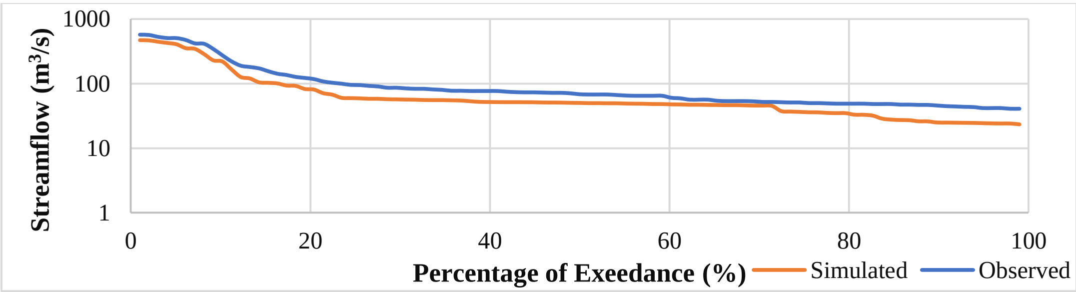

Figure A3-62: Flow Duration Curve for Combination 02 w.r.t. PEV (Log Scale)

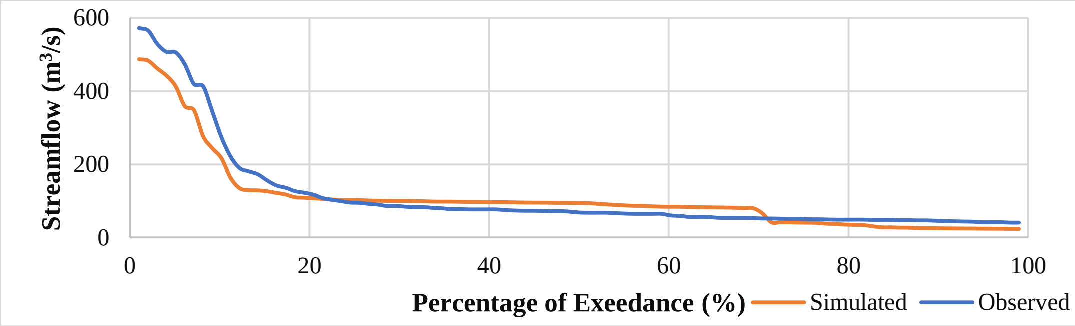

Figure A3-63: Flow Duration Curve for Combination 03 w.r.t. PEP (Normal Scale)

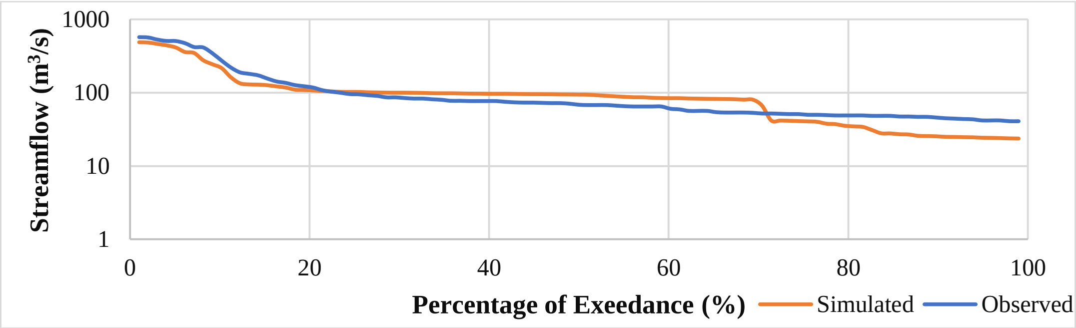

Figure A3-64: Flow Duration Curve for Combination 03 w.r.t. PEP (Log Scale)

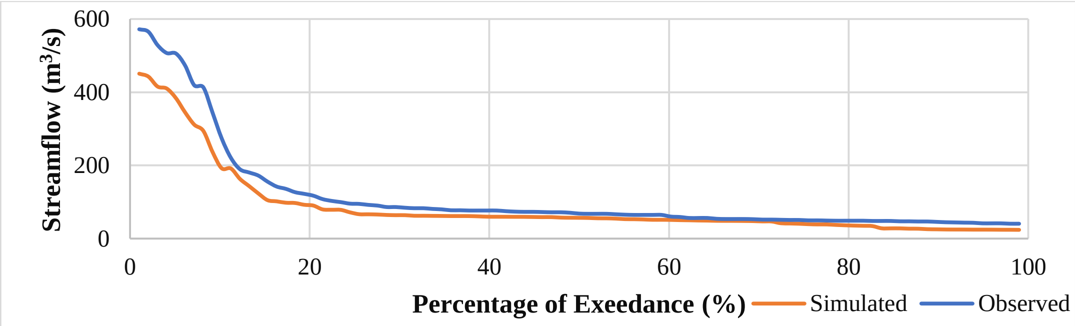

Figure A3-65: Flow Duration Curve for Combination 03 w.r.t. PEV (Normal Scale)

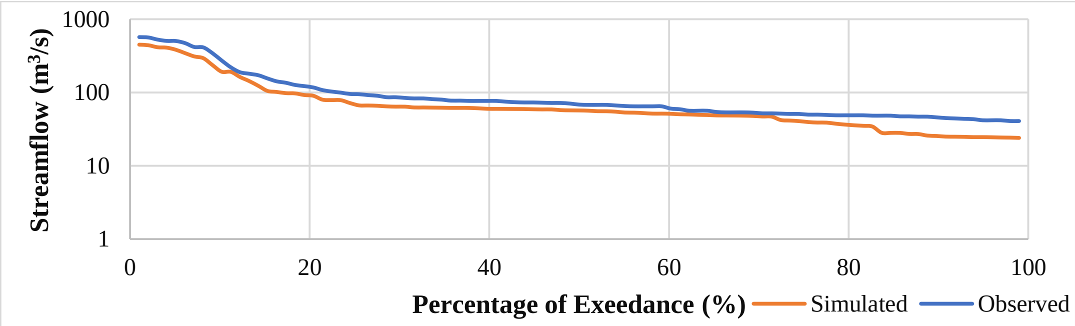

Figure A3-66: Flow Duration Curve for Combination 03 w.r.t. PEV (Log Scale)

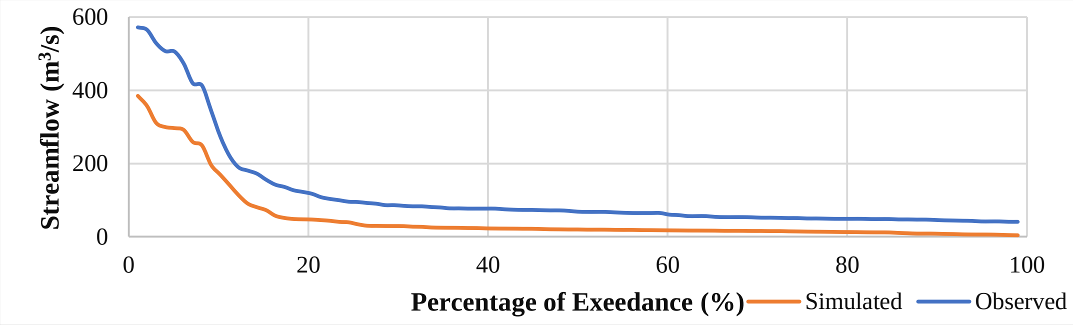

Figure A3-67: Flow Duration Curve for Combination 04 w.r.t. PEP (Normal Scale)

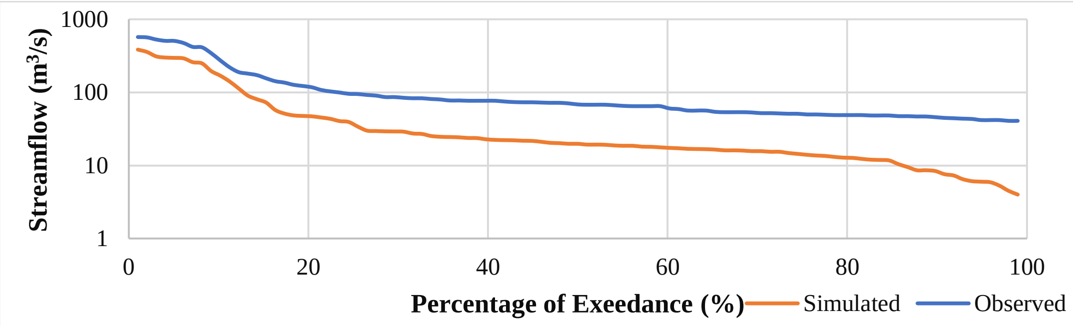

Figure A3-68: Flow Duration Curve for Combination 04 w.r.t. PEP (Log Scale)

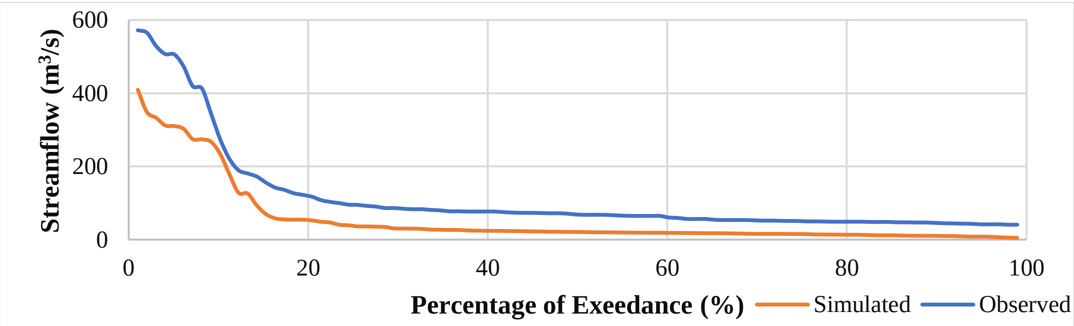

Figure A3-69: Flow Duration Curve for Combination 04 w.r.t. PEV (Normal Scale)

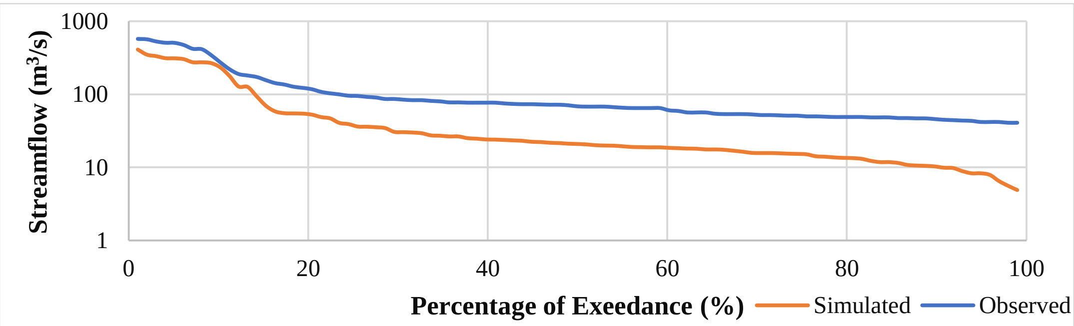

Figure A3-70: Flow Duration Curve for Combination 04 w.r.t. PEV (Log Scale)

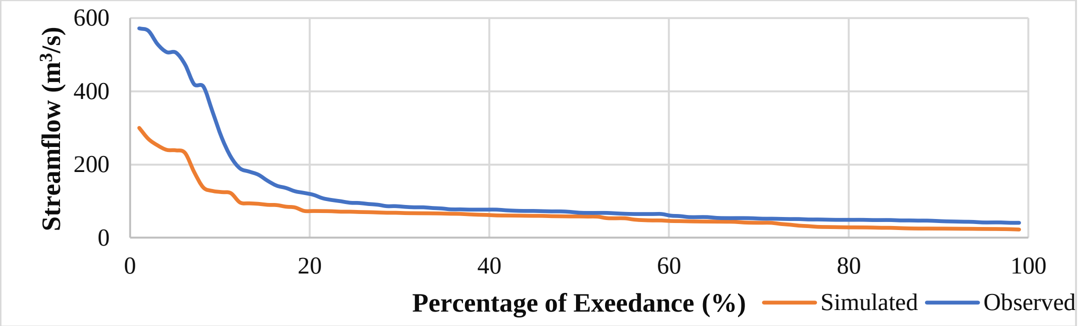

Figure A3-71: Flow Duration Curve for Combination 05 w.r.t. PEP (Normal Scale)

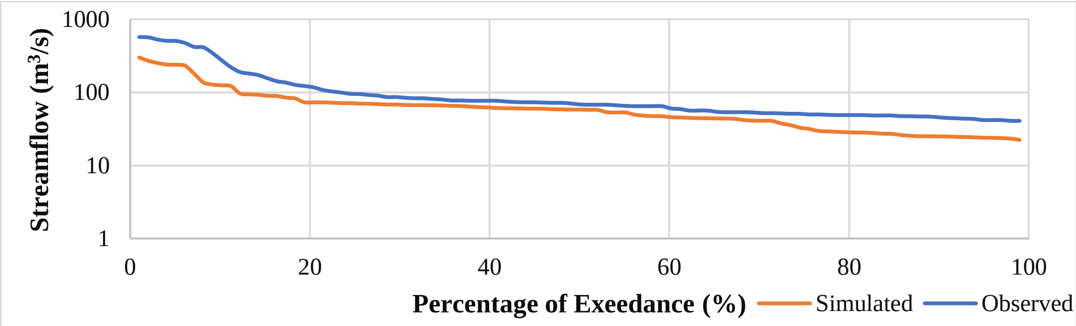

Figure A3-72: Flow Duration Curve for Combination 05 w.r.t. PEP (Log Scale)

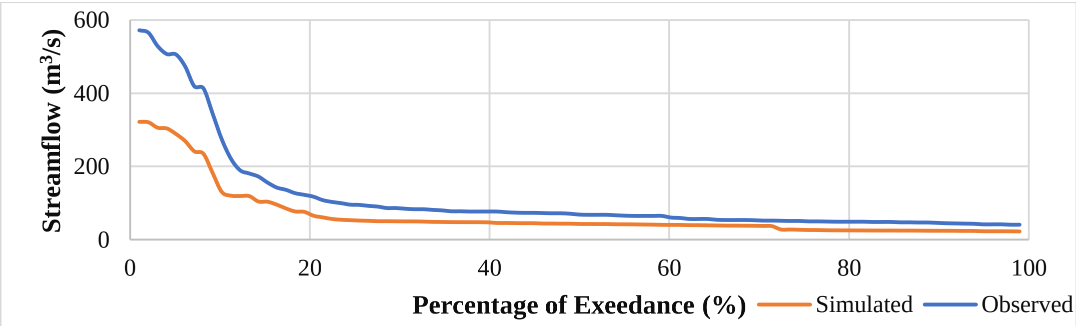

Figure A3-73: Flow Duration Curve for Combination 05 w.r.t. PEV (Normal Scale)

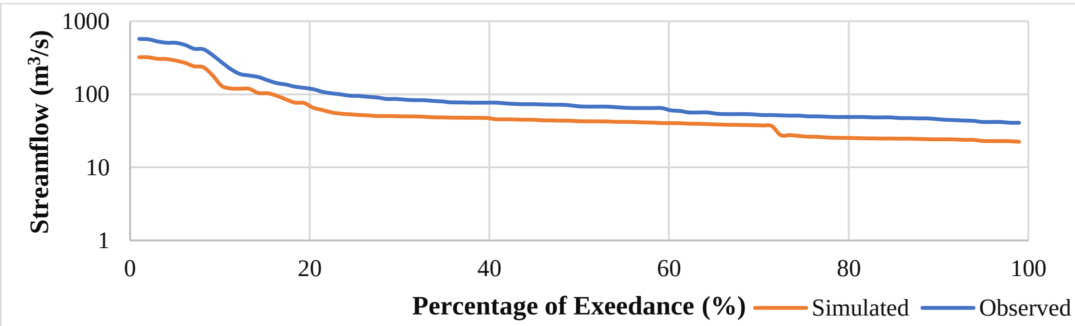

Figure A3-74: Flow Duration Curve for Combination 05 w.r.t. PEV (Log Scale)

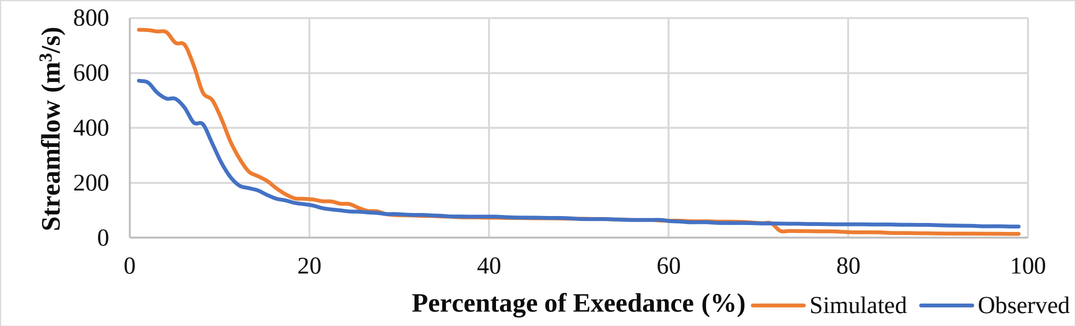

Figure A3-75: Flow Duration Curve for Combination 06 w.r.t. PEP (Normal Scale)

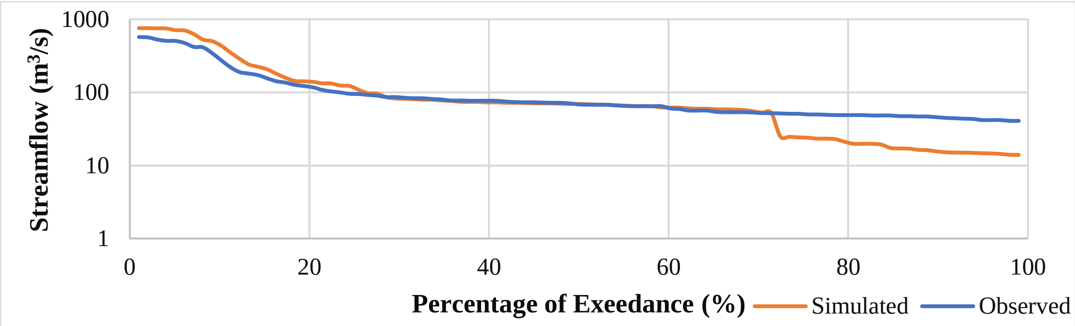

Figure A3-76: Flow Duration Curve for Combination 06 w.r.t. PEP (Log Scale)

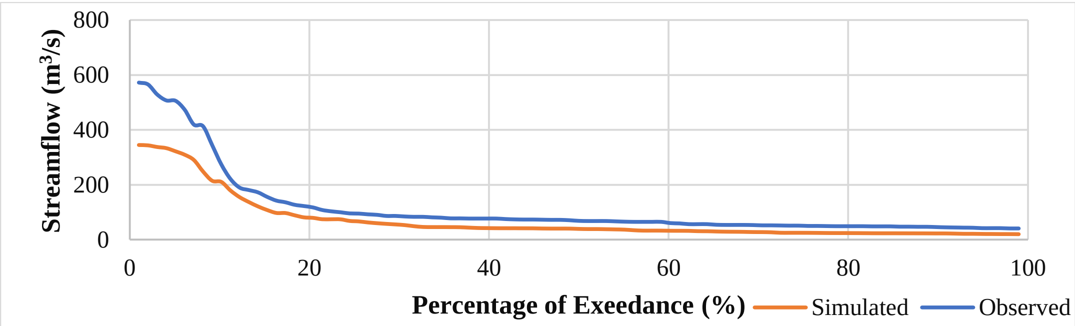

Figure A3-77: Flow Duration Curve for Combination 06 w.r.t. PEV (Normal Scale)

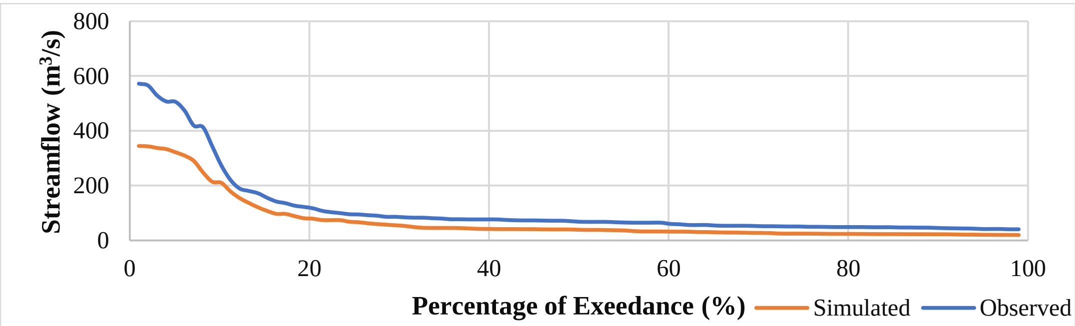

Figure A3-78: Flow Duration Curve for Combination 06 w.r.t. PEV (Log Scale)

Figure A3-79 to Figure A3-98 shows the flow duration curves for validation of each combination w.r.t. PEP and PEV objective functions using 2016 storm event.

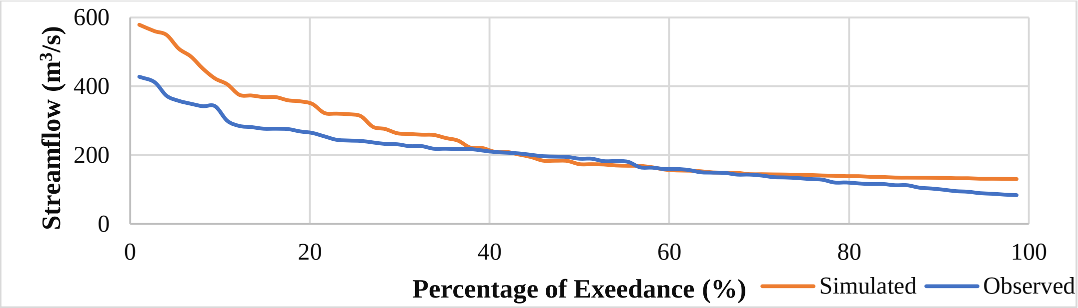

Figure A3-79: Flow Duration Curve for Combination 02 w.r.t. PEP (Normal Scale)

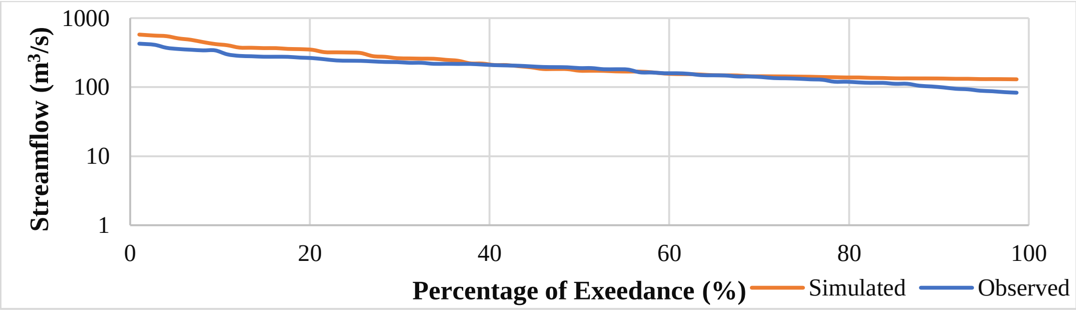

Figure A3-80: Flow Duration Curve for Combination 02 w.r.t. PEP (Log Scale)

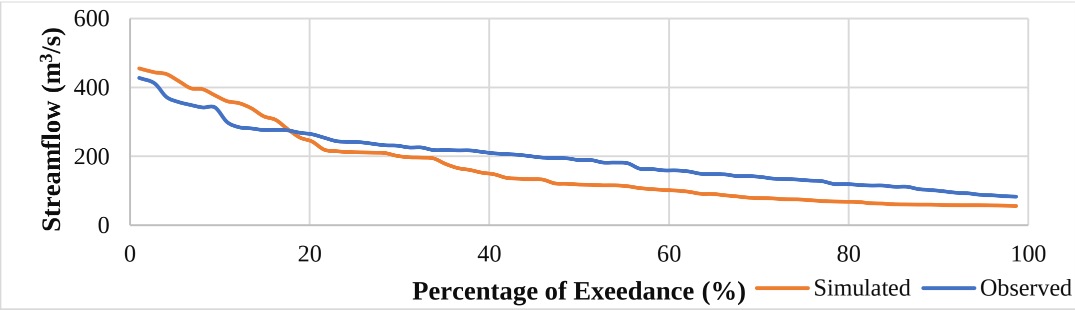

Figure A3-81: Flow Duration Curve for Combination 02 w.r.t. PEV (Normal Scale)

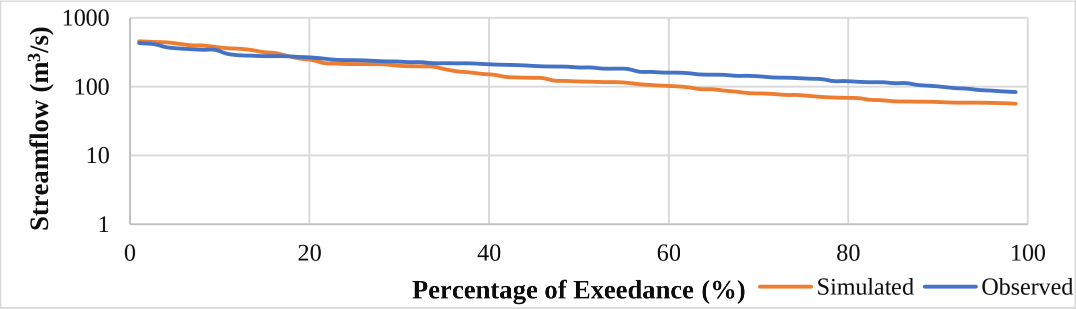

Figure A3-82: Flow Duration Curve for Combination 02 w.r.t. PEV (Log Scale)

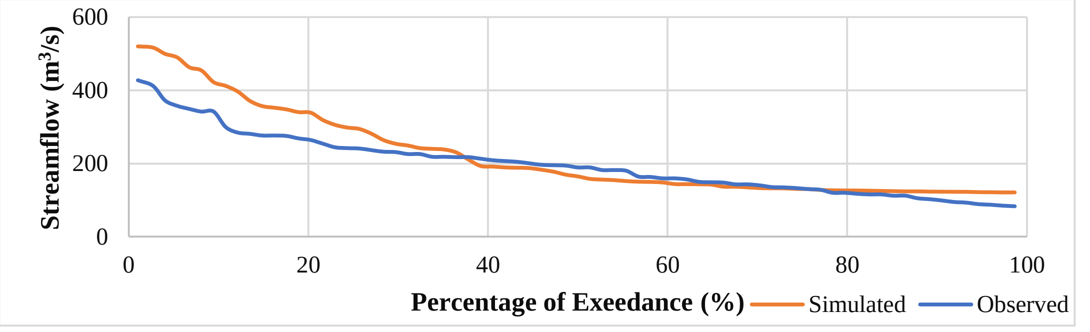

Figure A3-83: Flow Duration Curve for Combination 03 w.r.t. PEP (Normal Scale)

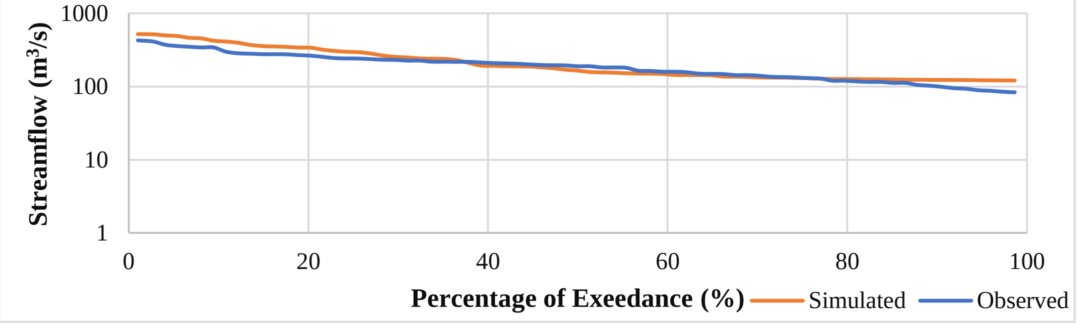

Figure A3-84: Flow Duration Curve for Combination 03 w.r.t. PEP (Log Scale)

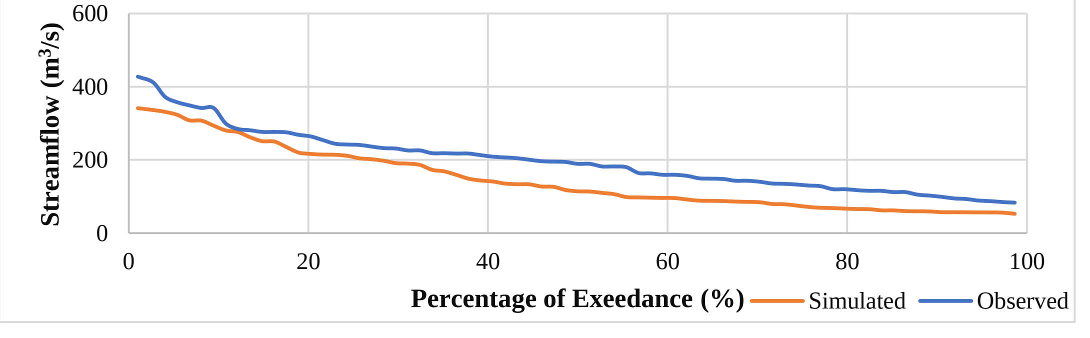

Figure A3-85: Flow Duration Curve for Combination 03 w.r.t. PEV (Normal Scale)

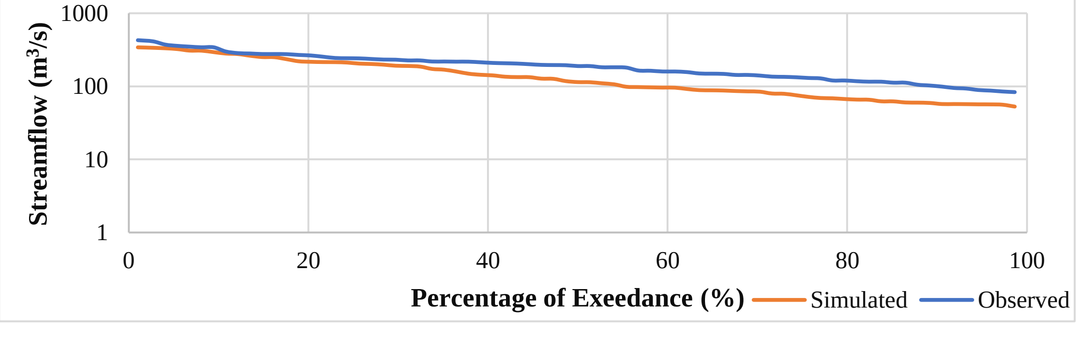

Figure A3-86: Flow Duration Curve for Combination 03 w.r.t. PEV (Log Scale)

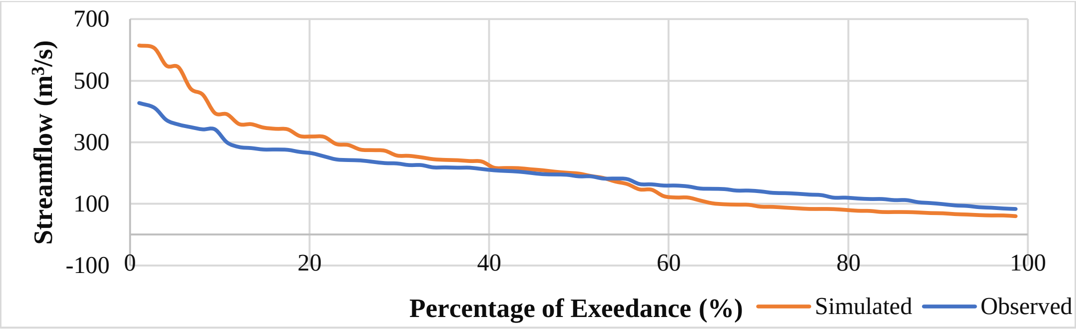

Figure A3-87: Flow Duration Curve for Combination 04 w.r.t. PEP (Normal Scale)

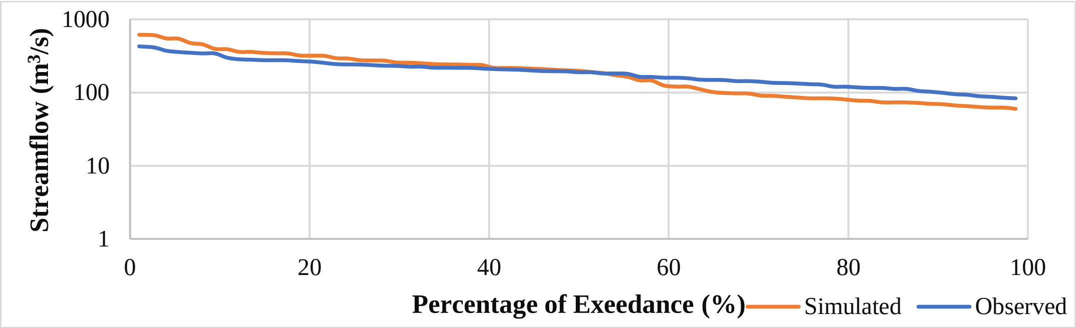

Figure A3-88: Flow Duration Curve for Combination 04 w.r.t. PEP (Log Scale)

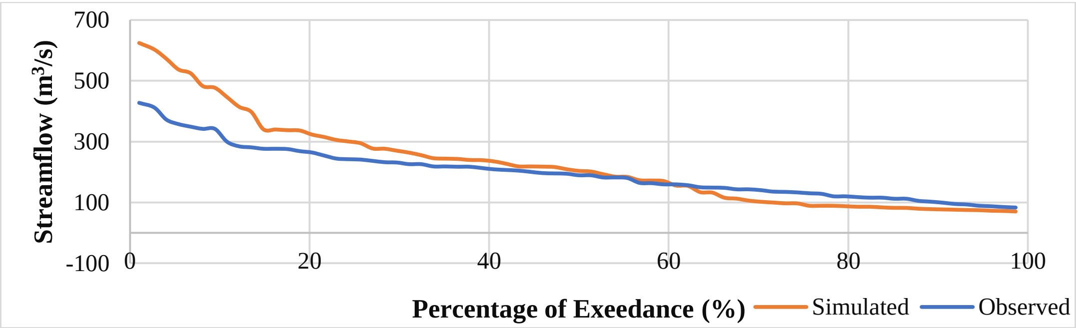

Figure A3-89: Flow Duration Curve for Combination 04 w.r.t. PEV (Normal Scale)

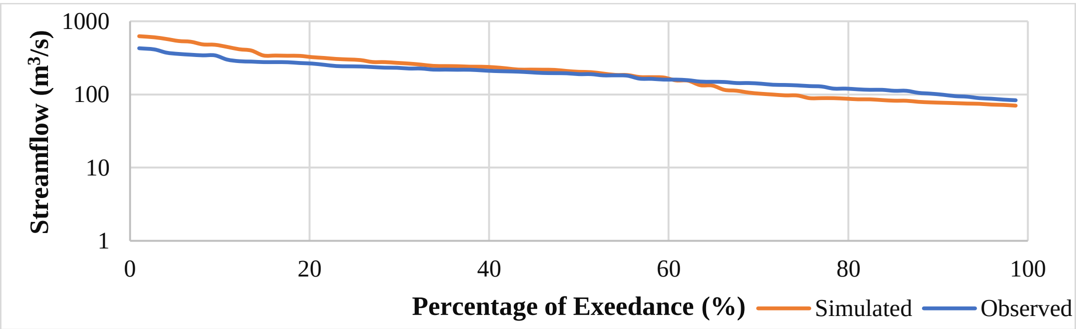

Figure A3-90: Flow Duration Curve for Combination 04 w.r.t. PEV (Log Scale)

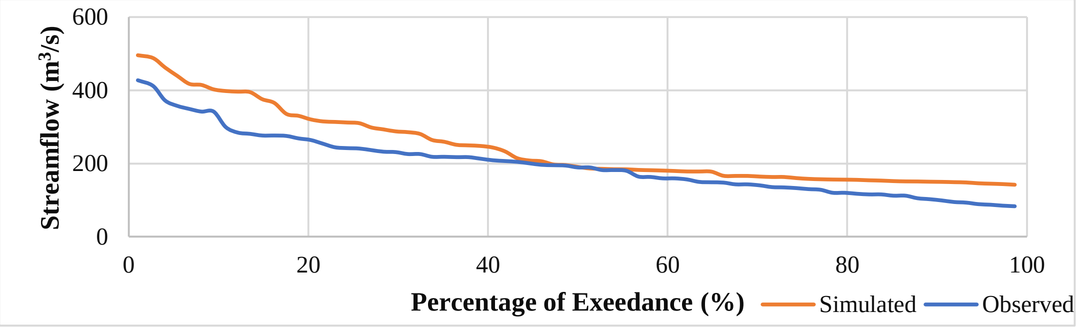

Figure A3-91: Flow Duration Curve for Combination 05 w.r.t. PEP (Normal Scale)

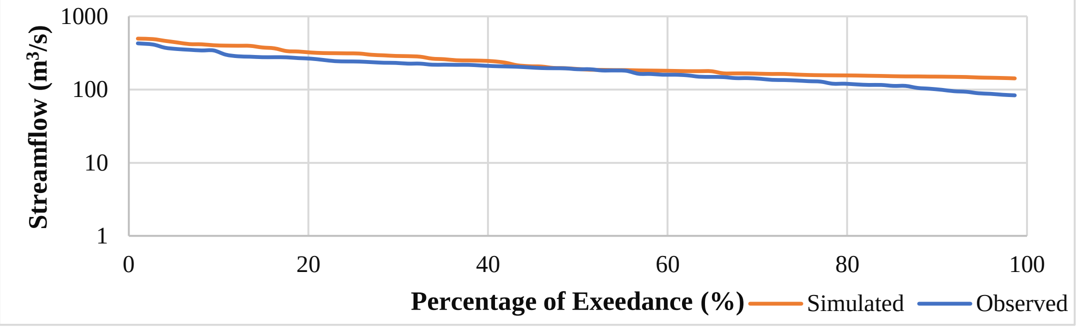

Figure A3-92: Flow Duration Curve for Combination 05 w.r.t. PEP (Log Scale)

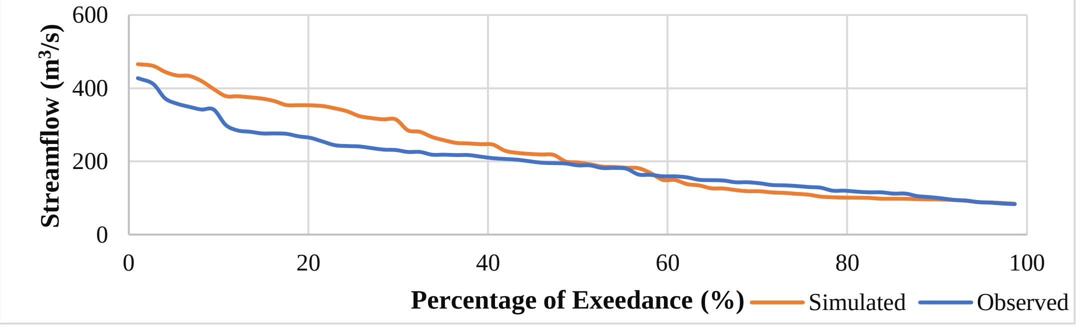

Figure A3-93: Flow Duration Curve for Combination 05 w.r.t. PEV (Normal Scale)

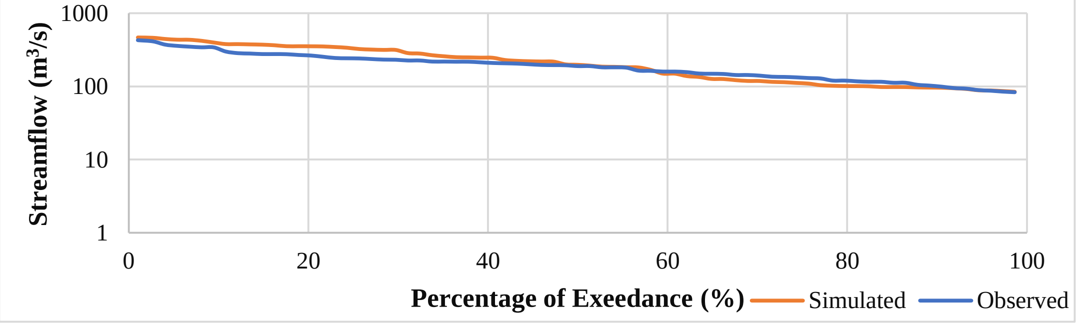

Figure A3-94: Flow Duration Curve for Combination 05 w.r.t. PEV (Log Scale)

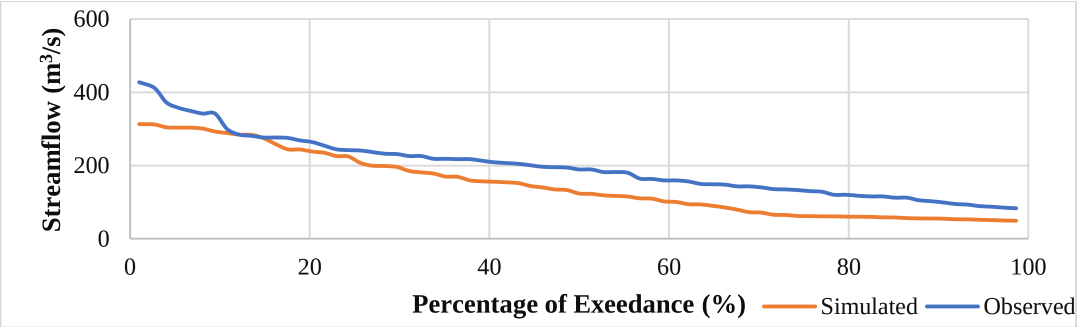

Figure A3-95: Flow Duration Curve for Combination 06 w.r.t. PEP (Normal Scale)

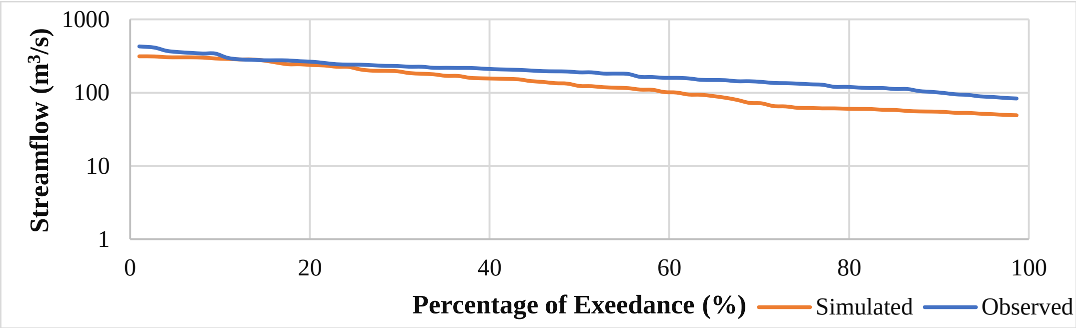

Figure A3-96: Flow Duration Curve for Combination 06 w.r.t. PEP (Log Scale)

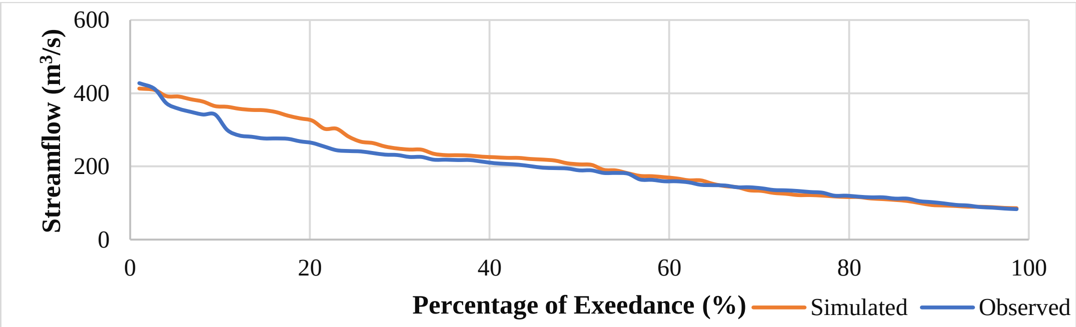

Figure A3-97: Flow Duration Curve for Combination 06 w.r.t. PEV (Normal Scale)

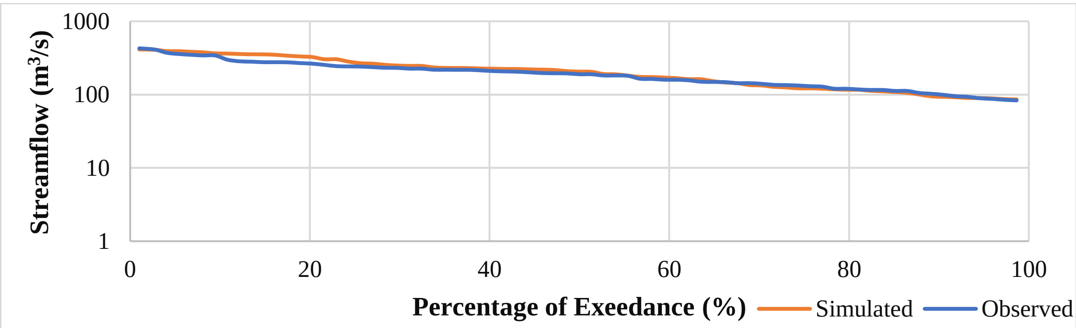

Figure A3-98: Flow Duration Curve for Combination 06 w.r.t. PEV (Log Scale)

Figure A3-99 to Figure A3-118 shows the flow duration curves for validation of each combination w.r.t. PEP and PEV objective functions using 2014 storm event.

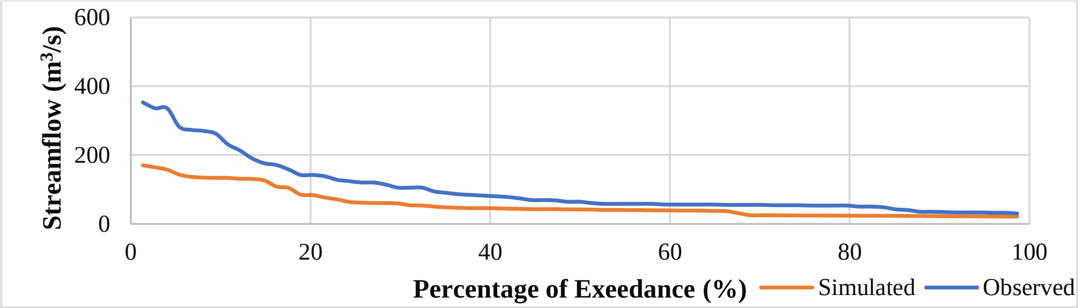

Figure A3-99: Flow Duration Curve for Combination 02 w.r.t. PEP (Normal Scale)

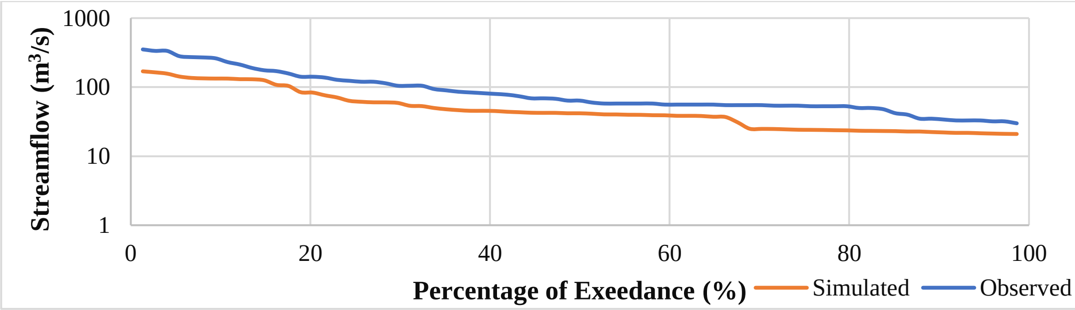

Figure A3-100: Flow Duration Curve for Combination 02 w.r.t. PEP (Log Scale)

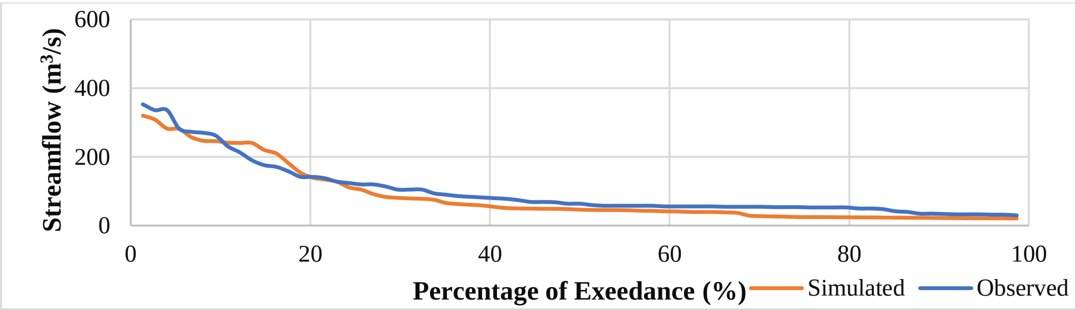

Figure A3-101: Flow Duration Curve for Combination 02 w.r.t. PEV (Normal Scale)

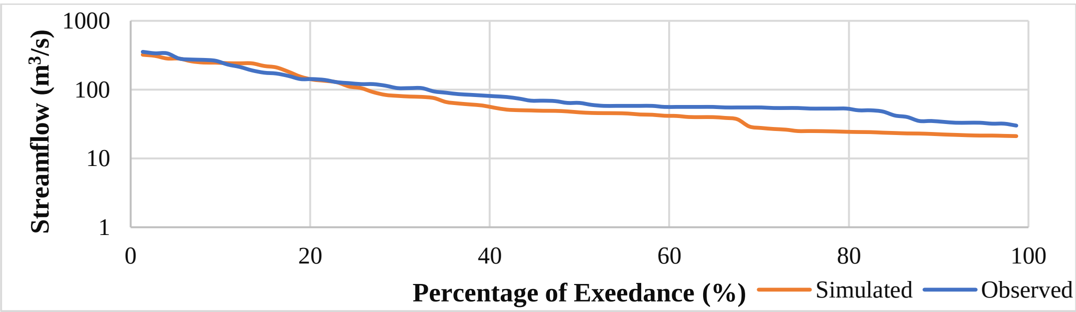

Figure A3-102: Flow Duration Curve for Combination 02 w.r.t. PEV (Log Scale)

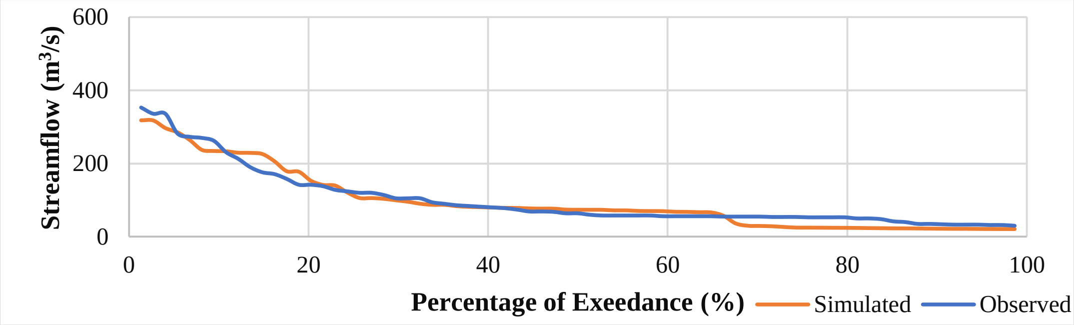

Figure A3-103: Flow Duration Curve for Combination 03 w.r.t. PEP (Normal Scale)

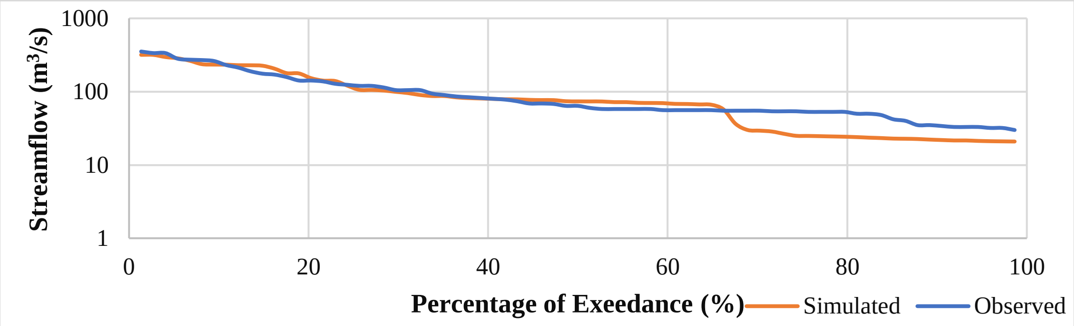

Figure A3-104: Flow Duration Curve for Combination 03 w.r.t. PEP (Log Scale)

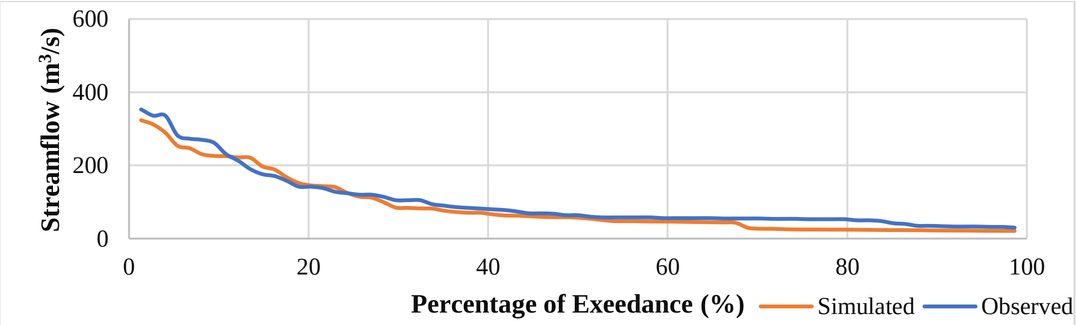

Figure A3-105: Flow Duration Curve for Combination 03 w.r.t. PEV (Normal Scale)

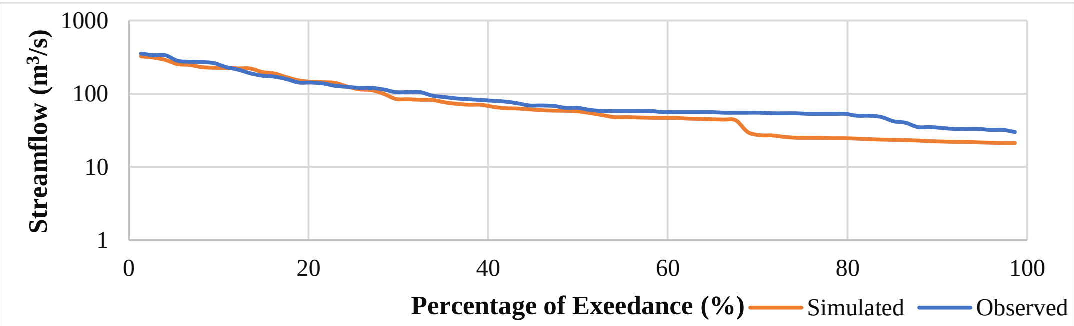

Figure A3-106: Flow Duration Curve for Combination 03 w.r.t. PEV (Log Scale)

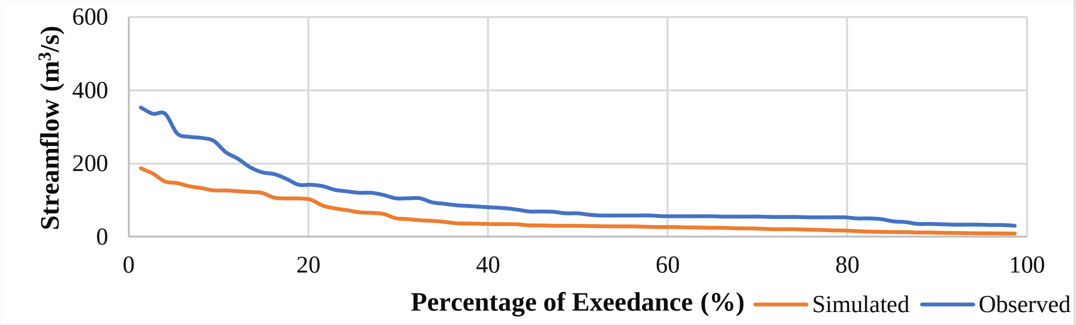

Figure A3-107: Flow Duration Curve for Combination 04 w.r.t. PEP (Normal Scale)

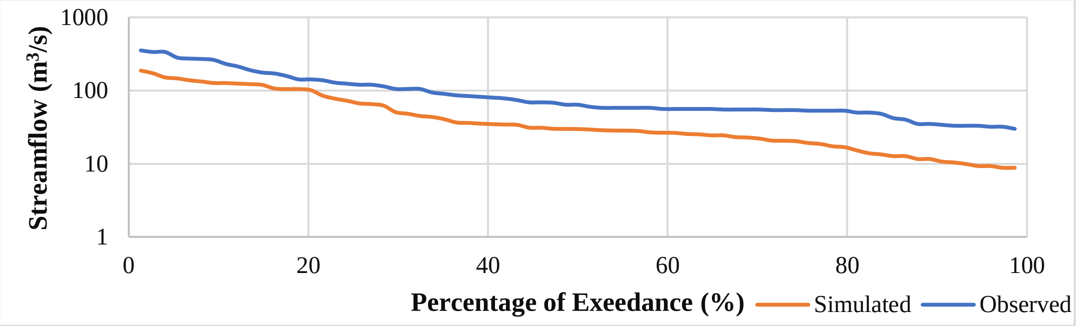

Figure A3-108: Flow Duration Curve for Combination 04 w.r.t. PEP (Log Scale)

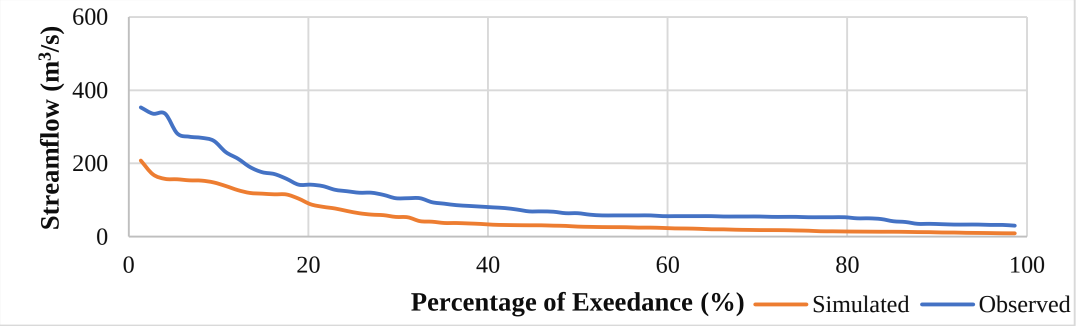

Figure A3-109: Flow Duration Curve for Combination 04 w.r.t. PEV (Normal Scale)

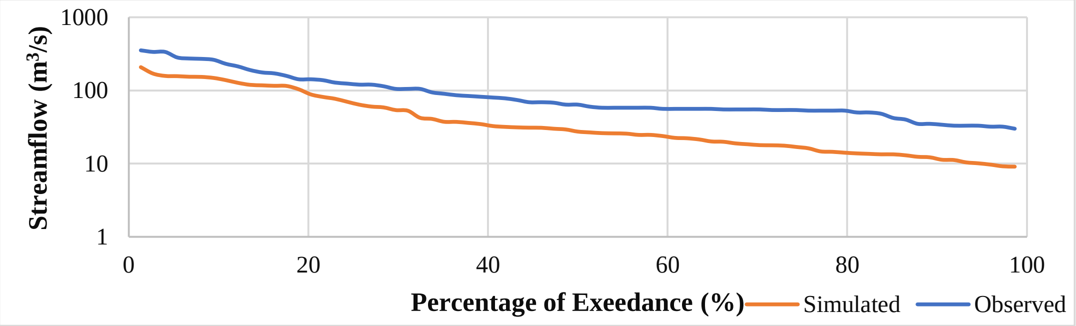

Figure A3-110: Flow Duration Curve for Combination 04 w.r.t. PEV (Log Scale)

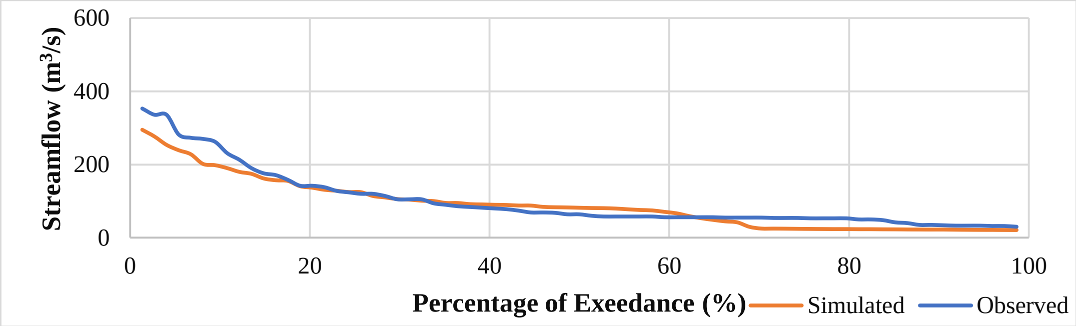

Figure A3-111: Flow Duration Curve for Combination 05 w.r.t. PEP (Normal Scale)

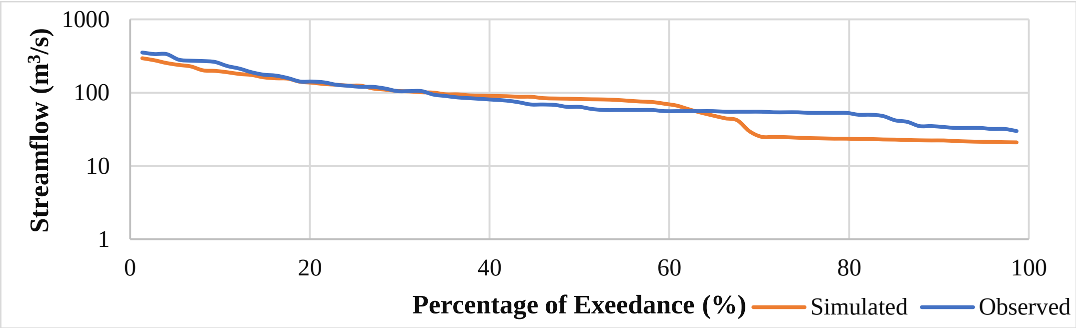

Figure A3-112: Flow Duration Curve for Combination 05 w.r.t. PEP (Log Scale)

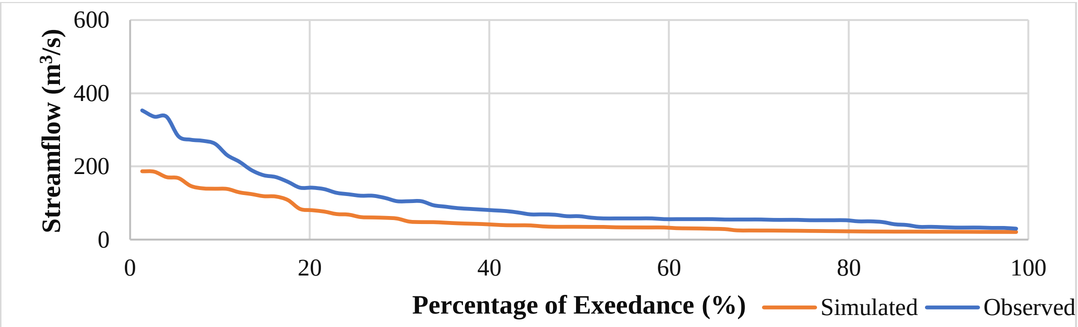

Figure A3-113: Flow Duration Curve for Combination 05 w.r.t. PEV (Normal Scale)

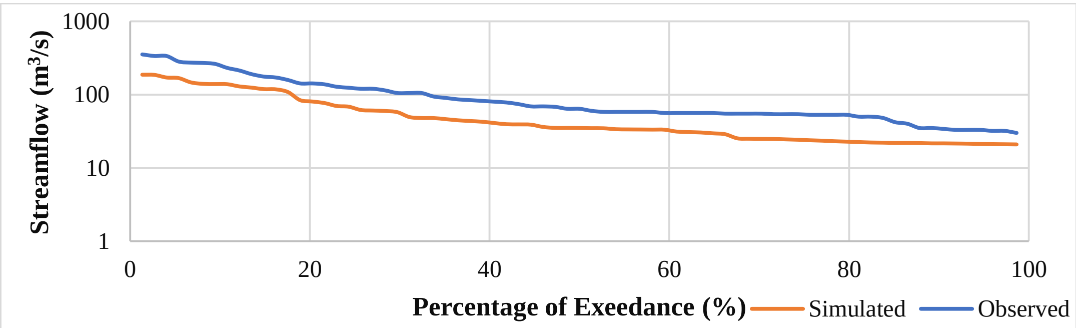

Figure A3-114: Flow Duration Curve for Combination 05 w.r.t. PEV (Log Scale)

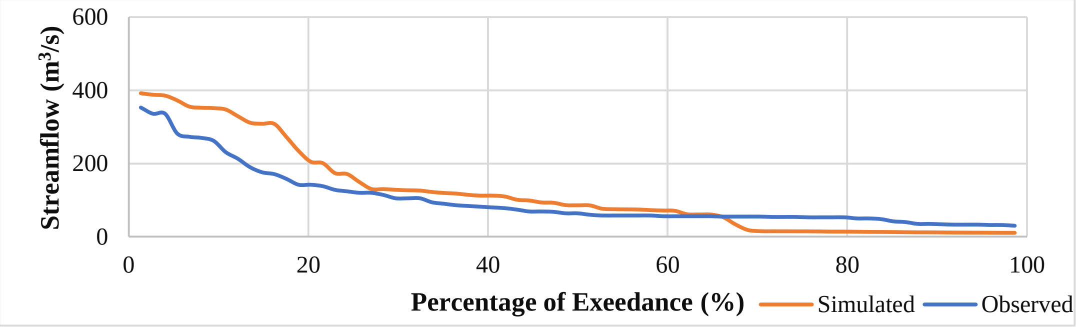

Figure A3-115: Flow Duration Curve for Combination 06 w.r.t. PEP (Normal Scale)

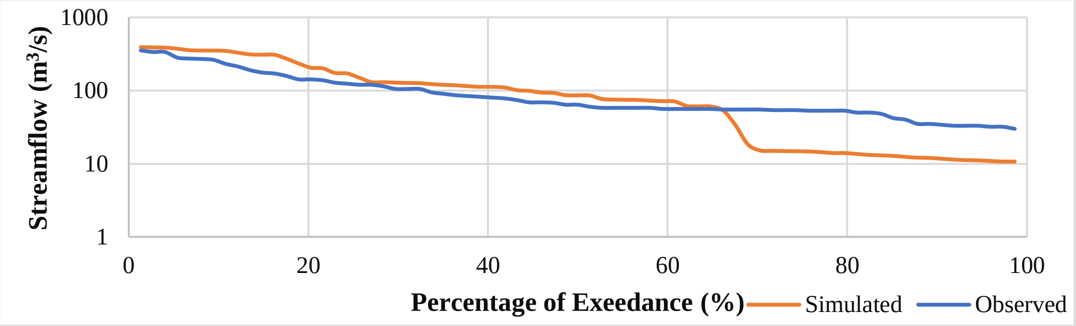

Figure A3-116: Flow Duration Curve for Combination 06 w.r.t. PEP (Log Scale)

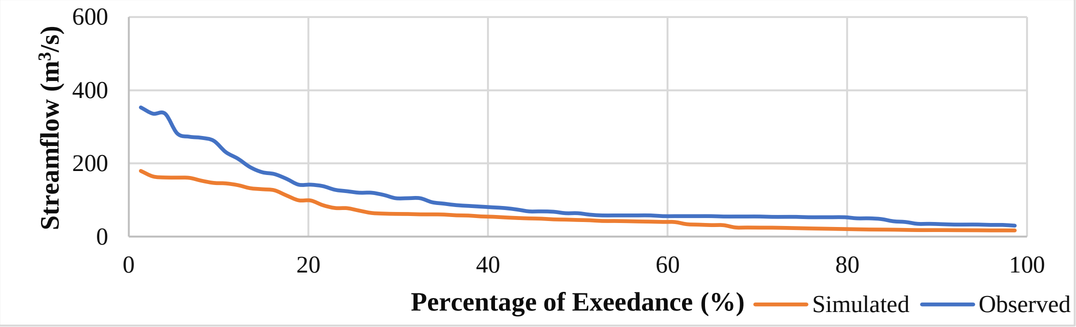

Figure A3-117: Flow Duration Curve for Combination 06 w.r.t. PEV (Normal Scale)

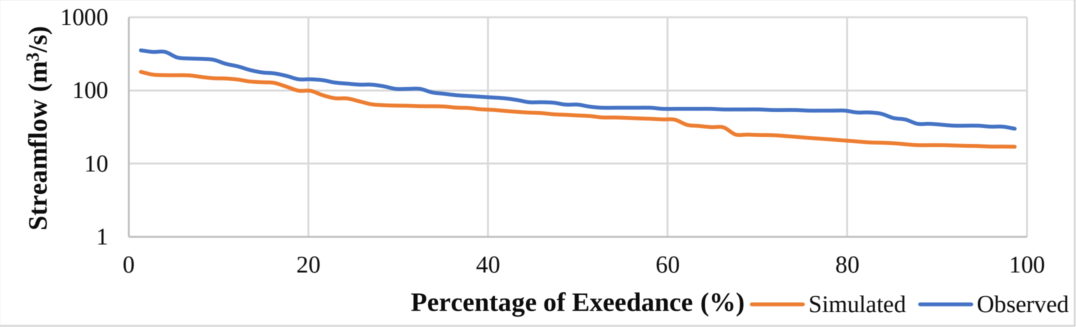

Figure A3-118: Flow Duration Curve for Combination 06 w.r.t. PEV (Log Scale)