Application of HEC-HMS Model on Event-Based Simulation in Kalu Ganga

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Rainfall-runoff modeling is a crucial tool for authorities dealing with flood risks, particularly for rivers like the Kalu Ganga in Sri Lanka, which is prone to frequent flooding. The Hydrologic Engineering Center's Hydrologic Modeling System (HEC-HMS- 4.10 version) proves invaluable for simulating and analyzing rainfall-runoff dynamics. Event-based hydrological modeling reveals how a basin responds to an individual rainfall event, which is very important in predicting a flood. This study assesses six combinations of rainfall-runoff models using various hydrological models to determine the most effective one for the Kalu Ganga Upper catchment up to Ellagawa. Criteria such as rainfall type (Event), spatial process (Semi-lumped), model type (Empirical), and relevant parameters (Fitted parameters) are considered based on the acquired data for the selection of model combinations. Event-based rainfall of four gauging stations in Rathnapura district and discharge at Ellagawa gauging station corresponding to the period of 2018-2021 is used in the Calibration and Validation process in this study. The initial parameters are optimized, and it's observed that each model combination performs differently for each event. Among the selected combinations, the Initial Constant method paired with the Clark Unit hydrograph, the Recession base flow method with Lag, and the Muskingum method exhibit superior performance. The model evaluation shows Nash Sutcliff value as 0.98, RMSE as 0.1, and Percent bias as 0.16. Visual assessments and statistical indicators from the study demonstrate that the developed model reasonably predicts floods in the basin. As a result, it can serve as a valuable tool for flood prediction, offering forecasts for flood peaks and their timing with a reasonable degree of accuracy.
Keywords: HEC-HMS, Rainfall-runoff model, Event-based rainfall, Calibration and Validation

Introduction

Rainfall is essential to the hydrological cycle, allowing water to circulate continuously between the Earth's surface and the atmosphere. The hydrological cycle is complicated, with runoff connecting precipitation to stream flow. Surface runoff occurs when there is excess precipitation that does not soak into the soil and instead flows across the land surface forming streams. A rainfall-runoff model is a mathematical representation or simulation of the hydrological processes that convert precipitation into runoff. These models attempt to estimate how rainfall and other factors influence the excess water to be transported through a watershed or catchment. Rainfall-runoff models aid in flood forecasting, water resource management, and estimating the effects of land use changes or climatic variability on runoff patterns by precisely simulating the hydrological processes. The number of hydrological models has evolved to simulate runoff from the rainfall data in the last 10 years. Hydrologic Engineering Center - Hydrologic Modeling System (HEC - HMS) is one of the hydrological models that has the capability of transforming rainfall into runoff which was created by USACE and was first released by the Hydrologic Engineering Center (HEC) in 1992. (Salil Sahu, et al., 2020). It has been used successfully to assess water resources in numerous basins, including river basins in Sri Lanka. This research describes a case study of developing event rainfall-runoff modeling using HEC-HMS to Kalu Ganga basin up to Ellagawa which is a located in wet zone of Sri Lanka with high flood frequency and the goal is to employ six alternative model combinations available in HEC-HMS software to identify the best model for the Kalu Ganga Ellagawa basin for event-based.

Materials and Methods

Data collection and processing

The methodology of this research has been followed to develop and identify a Suitable rainfall-runoff model for the Ellagawa sub-basin and the summarized workflow shown in Figure 1.

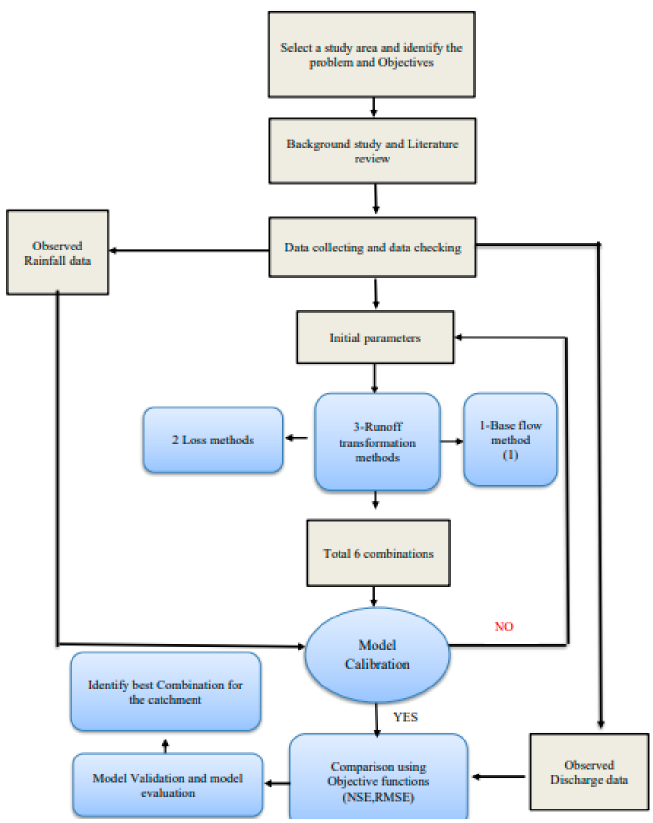

Figure 1: Summarized Methodology

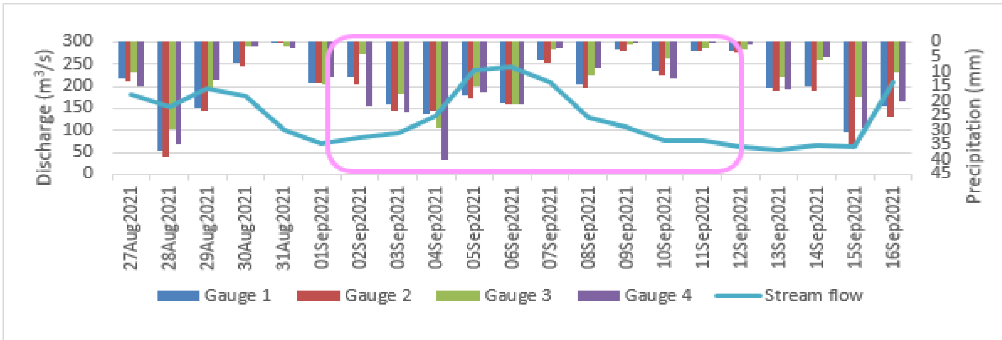

Figure 2: Calibration event (01/09/2021 – 12/09/2021)

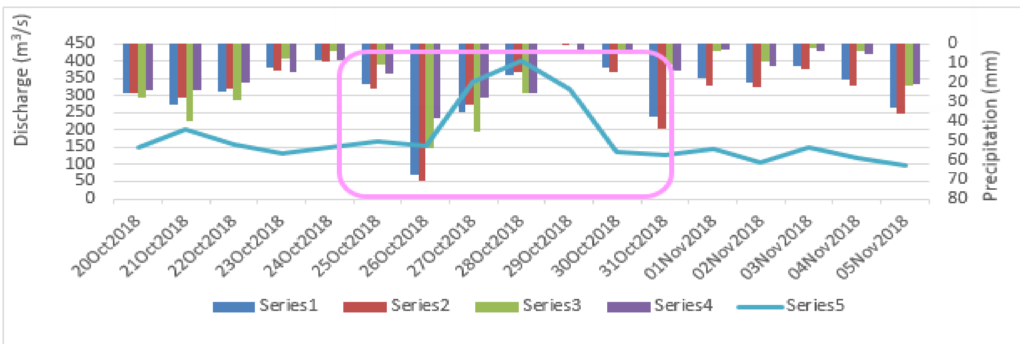

Figure 3: Validation event 2 (24/01/2018 – 31/10/2018)

Daily rainfall data from 2017 to 2022 were purchased from the Department of Meteorology for specific rain gauges located at Ratnapura, Halwatura, Wellandura, and Allupola. Similarly, stream flow data for the same period was gathered from the Department of Irrigation, focusing on river gauging stations at Ratnapura and Ellagawa. Additionally, we obtained digital elevation model (DEM) and land use data from the Department of Survey. Using the HEC-HMS model, calibration and validation were performed by analyzing events where discharge peaks occurred after rainfall peaks as shown in Figures 2 & 3, excluding any missing data spans. Following this, Thiessen polygons were generated using ArcGIS to accurately estimate the catchment average rainfall in the Ellagawa sub-basin calibration and validation. Table 1 shows the durations of the events chosen for calibration and validation.

Table 1: Summary of the selected events

Event	**Duration**
Calibration Event 1	01/09/2021 – 12/09/2021
Validation Event 1	31/05/2018 – 07/06/2018
Validation Event 2	24/10/2018 – 31/10/2018
Validation Event 3	22/09/2021 – 30/09/2021

B. HEC HMS model development

After plotting the basin using Arc GIS, the map was imported to the HEC-HMS software to create watershed modeling components. The rainfall-runoff model in HEC HMS involves creating a basin model to convert atmospheric conditions into stream flow at specific locations in the Ellagawa watershed. The model is divided into sub-basins as shown in Figure 4 using GIS tools in HEC HMS software. Three Hydrologic elements, Sub-basins (Convert rainfall hydrograph to runoff), Reach (Transport runoff hydrographs from one place to another), and Sink (Watershed outlets) are connected in a dendritic network to represent the stream system in HEC HMS software as shown in Figure 5.

Table 2 presents the combinations of HEC-HMS used in this study, here, the base flow method and the routine method remain as same for all selected combinations as the Recession method and Lag and Muskingum method respectively. The lag method is used in steep slope areas, and the Muskingum method is used in mild slope areas in the Kalu Ganga. Model combinations are selected based on criteria such as rainfall type (Event), spatial process (Semi-lumped), model type (Empirical), and relevant parameters (Fitted parameters), comparing the specific model criteria as mentioned and utilizing acquired data for informed decision-making.

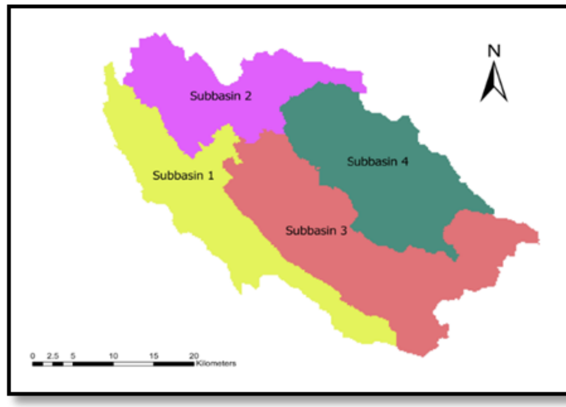

Figure 4: Sub-basins of Ellagawa watershed

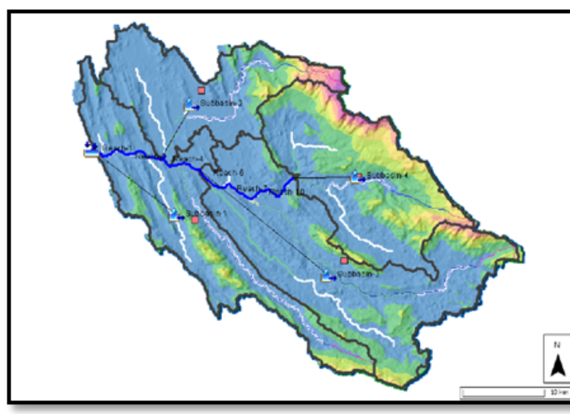

Figure 5: Hydrological elements represented in HEC HMS

Results & Discussion

Model Calibration

Model calibration is a process that involves changing the parameters of each model to find the best runoff hydrograph. Two methods are available in the HEC-HMS simulation run and optimization run. Both observed and simulated hydrographs are compared in the simulation run, but the simulated hydrograph may not fit with the observed one. Parameters are optimized in an optimization run to achieve more similar outputs. Figure 6 shows the parameters of each method. To compare these hydrographs program computes the index of

Table 2: Different combinations adopted to simulate floods in the study

Combination	**Direct runoff method**	**Loss method**	**Baseflow method**	**Routing method**
C1	Clark UH	Initial and constant method		
C2	Snyders UH	Initial and constant method		
C3	SCS UH	Initial and constant method	Recession method	Lag and Muskingum
C4	Clark UH	SCS curve No		
C5	Snyders UH	SCS curve No		
C6	SCS UH	SCS curve No		

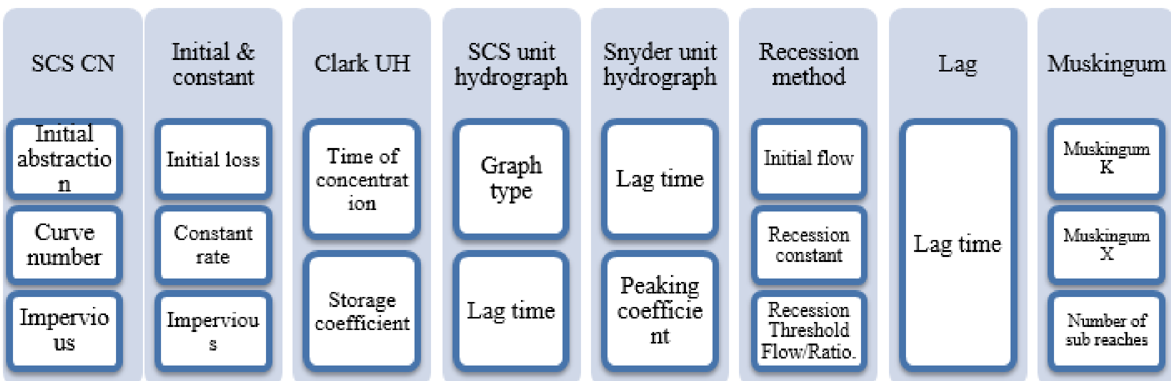

Figure 6: Initial Parameters

goodness of fit. Algorithms included in the program search for the model parameters that yield the best value of an index, also known as objective functions. There are four objective functions in HEC HMS and we used the Sum of squared residuals, Nash Sutcliff value, and Percent bias which is shown in Table 3. Figure 7 depicts the difference between observed and simulated hydrographs during the calibration event for combination 1. Variations for other combinations were discovered that were nearly identical to this variation.

Table 3: Nash Sutcliff value, RMSE value, and percent bias for the calibration event

Combination	**Nash-Sutcliff value**	**RMSE**	**Percent bias %**
1	0.981	0.1	0.05
2	0.978	0.1	-0.06
3	0.978	0.1	0.16
4	0.980	0.1	-0.58
5	0.981	0.1	-0.65
6	0.980	0.1	-0.36

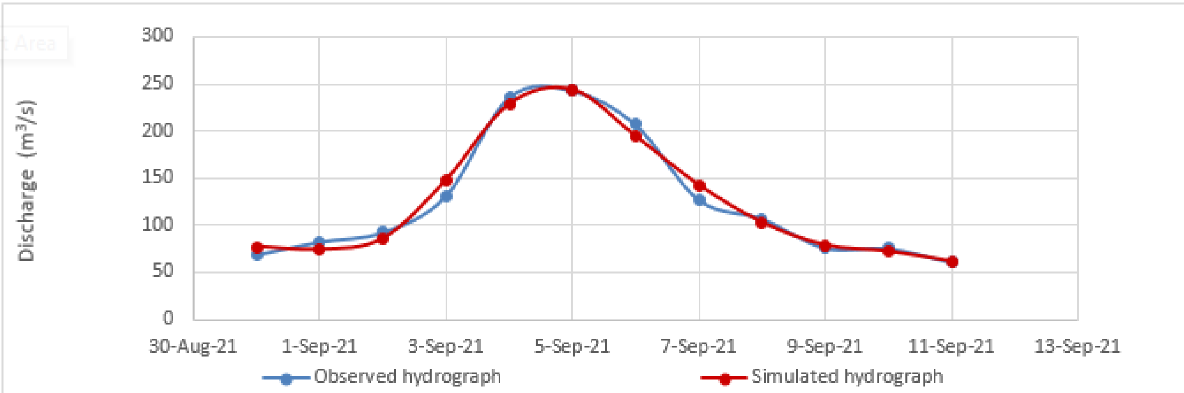

Figure 7: Combination of observed discharge and simulated discharge graph in Calibration

Table 4: Nash sutcliff value for validation events

Combination	Validation event 1	Validation event 2	Validation event 3
1	0.940	0.531	0.857
2	0.905	0.528	0.831
3	0.936	0.692	0.904
4	0.894	0.784	0.836
5	0.890	0.773	0.827
6	0.628	0.704	0.833

Model Validation

After completing the calibration procedure, the model is ready for validation, where it's evaluated for correctness using identical objective functions and three validation events for each combination. Table 4,5,6 shows the Nash Sutcliff, RMSE, and Percent bias values yielded for each event through each model combination.

Model evaluation

HEC-HMS provides several objective functions that can be used during the model calibration process. These objective functions can be used individually or in combination to assess the performance of the HEC-HMS model and guide the calibration process. Table 7 shows the ranges of the values used for the performance evaluation criteria. According to the performance evaluation criteria, the ranking of the model combinations took place. For all the validation events model performance criteria were satisfied.

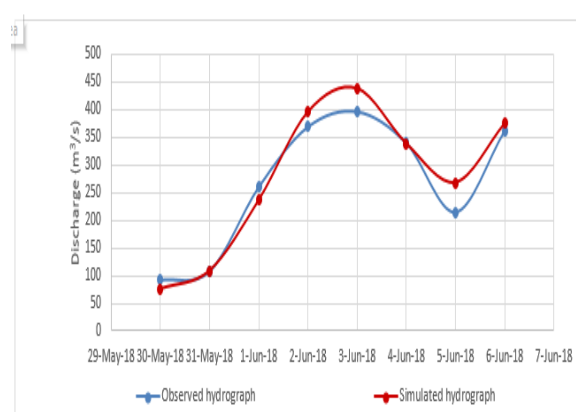

Figure 8: Observed and simulated hydrographs for Validation event 1- Combination 3

Table 5: RMSE value for validation events

Combination	Validation event 1	Validation event 2	Validation event 3
1	0.2	0.7	0.4
2	0.3	0.7	0.4
3	0.3	0.6	0.3
4	0.3	0.5	0.4
5	0.3	0.5	0.4
6	0.6	0.5	0.4

Table 6: Percent bias value for validation events

Combination	Validation event 1	Validation event 2	Validation event 3
1	-3.64	15.30	-15.04
2	-2.54	15.11	-10.83
3	4.51	3.23	-4.42
4	-7.75	-14.19	-19.14
5	-8.36	-16.05	-19.14
6	6.12	-6.33	-15.68

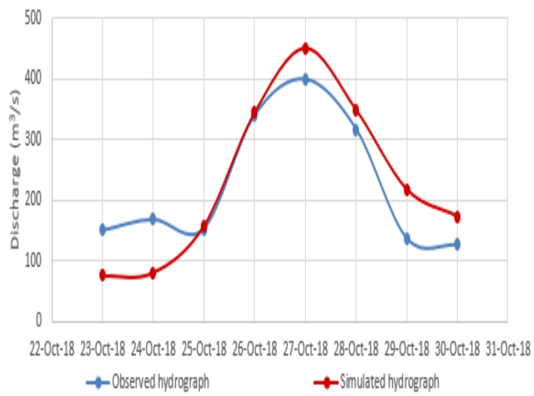

Figure 9: Observed and simulated hydrographs for Validation event 2- Combination 3

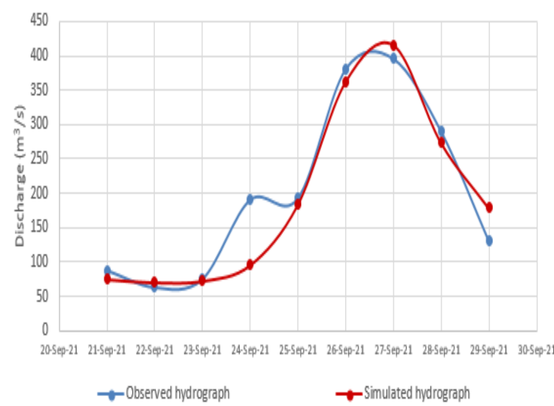

Figure 10: Observed and simulated hydrographs for Validation event 3- Combination 3

Conclusion & Recommendations

This study aimed to identify the optimal model combination for the Kalu Ganga basin up to Ellagawa, using the HEC-HMS 4.10 model and six different precipitation losses and runoff methods. Out of all the combinations performed combination 3 shows the best performance. Figures 8,9 and 10 show the validation results obtained for combination 3. Table 8 shows the final optimized values of the combination 3 parameters. The second validation event differs from the calibration event and the other two validation events in that it displays less rainfall for sub-basin 4 whereas the other events indicate maximum rainfall for sub-basin 4. The Initial constant technique performs well for validation events, but the SCS Curve

Table 7: Performance evaluation criteria

Performance rating	**Nash-Sutcliff**	**RMSE std div.**	**Percent bias**
Very good	0.75-1.00	0-0.5	<Âś10
Good	0.65-0.75	0.5-0.6	Âś10-Âś15
Satisfactory	0.50-0.65	0.6-0.7	Âś15-Âś25
Unsatisfactory	<0.50	≥0.7	>Âś25

Number method is better for the second validation event. The Curve Number approach, established for temperate conditions, may be inaccurate in tropical watersheds like the Kalu Ganga catchment, where rubber plantations and forests make up nearly half of the land use [3]. Direct runoff techniques SCS UH, Cleark UH, and Snyder UH show little variation. Based on the results, the Initial Constant technique was chosen as the loss method, the SCS Unit Hydrograph method as the transformation method, and the Recession method as the base flow method shows the best performance for the Kalu Ganga upper catchment area. As for the modification, this model can be developed with different methods like the Green Ampt method, Mod Clark and soil moisture accounting, etc. These methods need several initial parameters, some needing to be collected in the field. Also, as further improvement, we can add the canopy, surface method, and Loss-gain method to HEC HMS software. Using those methods, we can get a more accurate rainfall-runoff model. Also, using more rainfall gauging stations and more rainfall events in calibration can get more precise parameter values. This model can be used in flood forecasting but using continuous rainfall data can further develop into water resource planning and management. In most studies, HEC-HMS rainfall-runoff modeling was found efficient and reliable in different river basins to simulate runoff with accuracy. Thus, the model could be used for runoff simulation in an ungauged basin for water resources planning, development, management, and decision-making. Kalu Ganga is a frequently flooded river, so it is good to develop a model related to flood forecasting. Improving a rainfall-runoff model is an iterative process, and it may take several cycles of data collection, calibration, and validation to achieve a high level of accuracy. Regularly updating the model with new data and adapting to changing conditions will help maintain its relevance and effectiveness over time.

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Table 8: Initial parameter values combination

Element	Parameter	Units	Optimized value
Subbasin-1	Recession - Ratio to Peak		0.6585
Subbasin-2	Recession - Ratio to Peak		0.8943
Subbasin-2	Recession - Ratio to Peak		0.8943
Subbasin-3	Recession - Ratio to Peak		0.8624
Subbasin-4	Recession - Ratio to Peak		0.99906
Subbasin-1	Recession - Recession Constant		0.93756
Subbasin-2	Recession - Recession Constant		0.64405
Subbasin-3	Recession - Recession Constant		0.58915
Subbasin-4	Recession - Recession Constant		0.66622
Subbasin-1	Initial and Constant - Constant Rate	mm/hr	14.607
Subbasin-2	Initial and Constant - Constant Rate	mm/hr	15.828
Subbasin-3	Initial and Constant - Constant Rate	mm/hr	12.251
Subbasin-4	Initial and Constant - Constant Rate	mm/hr	54.264
Subbasin-1	Initial and Constant - Initial Loss	mm	114.9
Subbasin-2	Initial and Constant - Initial Loss	mm	48.788
Subbasin-3	Initial and Constant - Initial Loss	mm	70.33
Subbasin-4	Initial and Constant - Initial Loss	mm	53.211
Subbasin-1	SCS Unit Hydrograph - Lag Time	mm	2977.7
Subbasin-2	SCS Unit Hydrograph - Lag Time	min	2138.1
Subbasin-3	SCS Unit Hydrograph - Lag Time	min	1302.2
Subbasin-4	SCS Unit Hydrograph - Lag Time	min	535.73
Subbasin-1	Recession - Initial Discharge	m^3/s	27.405
Subbasin-2	Recession - Initial Discharge	m^3/s	19.707
Subbasin-3	Recession - Initial Discharge	m^3/s	15.644
Subbasin-4	Recession - Initial Discharge	m^3/s	12.392
Reach-10	Lag - Lag	min	4.9585
Reach-7	Lag - Lag	min	5.8691
Reach-6	Lag - Lag	min	7.1955
All Subbasins	Initial and Constant - Initial Loss Scale Factor		0.0183423
All Subbasins	Initial and Constant - Constant Rate Scale Factor		0.0183423
Reach-5	Muskingnam-Muskingnam K	hr	4
Reach-4	Muskingnam-Muskingnam K	hr	4
Reach-8	Muskingnam-Muskingnam K	hr	4
Reach-3	Muskingnam-Muskingnam K	hr	4
Reach-2	Muskingnam-Muskingnam K	hr	4
Reach-1	Muskingnam-Muskingnam K	hr	4
Reach-5	Muskingnam-Muskingnam X		0.2
Reach-4	Muskingnam-Muskingnam X		0.2
Reach-8	Muskingnam-Muskingnam X		0.2
Reach-3	Muskingnam-Muskingnam X		0.2
Reach-2	Muskingnam-Muskingnam X		0.2
Reach-1	Muskingnam-Muskingnam X		0.2

Element	Parameter	Units	Optimized value
Reach-5	Muskingnam-Number of Subreaches		1
Reach-4	Muskingnam-Number of Subreaches		1
Reach-8	Muskingnam-Number of Subreaches		1
Reach-3	Muskingnam-Number of Subreaches		1
Reach-2	Muskingnam-Number of Subreaches		1
Reach-1	Muskingnam-Number of Subreaches		1
Subbasin 1	Initial and Constant - Impervious	%	25
Subbasin 2	Initial and Constant - Impervious	%	20
Subbasin 3	Initial and Constant - Impervious	%	15
Subbasin 4	Initial and Constant - Impervious	%	15

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