

**SUITABILITY OF A SELECTED HYDROLOGICAL
MODEL AND OBJECTIVE FUNCTION FOR RURAL
WATERSHED MANAGEMENT IN SRI LANKA**

Pratik Singh Thakuri

(158569 K)

Degree of Master of Science

Department of Civil Engineering

University of Moratuwa

Sri Lanka

May 2018

**SUITABILITY OF A SELECTED HYDROLOGICAL MODEL AND
OBJECTIVE FUNCTION FOR RURAL WATERSHED
MANAGEMENT IN SRI LANKA**

Pratik Singh Thakuri
(158569 K)

Supervised by
Professor N.T.S Wijesekera

Thesis submitted in partial fulfillment of the requirements for the degree Master of
Science

UNESCO Madanjeet Singh Centre for
South Asia Water Management (UMCSAWM)
Department of Civil Engineering

University of Moratuwa
Sri Lanka

May 2018

DECLARATION

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

Also, I hereby grant to University of Moratuwa the non-exclusive right to reproduce and distribute my thesis, in whole or in part in print, electronic or other medium. I retain the right to use this content in whole or part in future works (Such as articles or books).

.....
Pratik Singh Thakuri

.....
Date

The above candidate has carried out research for the Master's thesis under my supervision.

.....
Prof. NTS Wijsekera

.....
Date

ABSTRACT

In a period where water resources are becoming scarce due to increased population and human activities, it is very important to have appropriate models and objective functions for water resources management especially in rural contexts. Therefore, the selection of appropriate model and objective function and to ascertain their suitability on a rural watershed is necessary. Preliminary screening of hydrological models was carried out based on the application availabilities and modelling purpose. Five models namely HEC-HMS, SWAT, TOPMODEL, MIKE SHE and SWMM were shortlisted. The shortlisted models were reviewed under several criteria such temporal scale, spatial scale, hydrological processes, documentation, resources requirement, user interface and model acquisition cost. Similarly, objective functions recommended on 'Guide for hydro-meteorological practices' by WMO namely NSE, RMSE, RAEM and MRAE were reviewed. Review of the objective functions was based on criteria such as mathematical implications, flow regimes and modelling purpose. The review of hydrological models and objective function suggested the Storm Water Management Model (SWMM) and Mean Ratio of Absolute Error (MRAE) as an appropriate model and objective function respectively for water resources modelling in rural watersheds. Accordingly, the SWMM was applied to the Ellagawa (1342 km²) and Ratnapura (653 km²) watersheds in the Kalu river basin of Sri Lanka using observed rainfall and streamflow from 2006-2014. In the present work, the SWMM model was calibrated and validated while investigating the effect of layout modifications to carry out continuous simulation of streamflow. Initially, two lumped models were developed for Ellagawa and Ratnapura watershed. Then a semi-distributed model with three sub-watersheds was developed for Ellagawa watershed. Model calibration was done for 2006-2010, and verification was carried out for the period 2011-2014. High, medium and low flow in the flow duration curve and the annual water balance were also observed during the calibration and validation. Ellagawa and Ratnapura lumped were calibrated with MRAE 0.3634 and 0.4531 respectively and validated with MRAE 0.5865 and 0.7843 respectively. Annual water balance errors of Ellagawa and Ratnapura lumped model

were 38% and 31% respectively during calibration and 10.25% and 11% respectively during validation. Ellagawa and Ratnapura lumped models calibrated intermediate flow with MRAE 0.40 and 0.37 respectively. Manning's roughness coefficient for pervious layer, depression storage for pervious layer, saturated hydraulic conductivity and initial defect, lateral discharge coefficient and deep percolation coefficient were the main parameters to be calibrated. Manning's roughness coefficient of pervious layer (n_{pervious}) was optimized in the range (0.02-0.028), depression storage of pervious layer ($d_{\text{store pervious}}$) was optimized in the range of (1.2mm-2.5mm). Similarly, saturated hydraulic conductivity (K_{sat}) was optimized in the range of (0.3mm/hr.-0.67mm/hr.). Furthermore, the initial moisture deficit (Θ) was optimized in the range of (0.2-0.5). Ellagawa semi-distributed model showed some improvement in overall and intermediate flow compared to Ellagawa lumped model. MRAE for overall hydrograph was reduced by 19% and MRAE for intermediate flow was reduced by 24%. However, Ellagawa semi-distributed model showed a poor estimation of annual, seasonal and monthly streamflow compared to Ellagawa lumped model. Hence, the semi-distributed model with single gauging cannot be considered as a better and meaningful modelling option in SWMM with certainty. This study recommends more application of SWMM for continuous modelling of streamflow in monsoon regions and more research on automatic optimization, objective function and groundwater.

ACKNOWLEDGEMENT

With boundless appreciation and respect, I would like to extend my heartfelt gratitude to the people who helped me to bring this study into reality. I would like extend my profound gratitude to Professor N.T.S. Wijesekera for his continuous guidance, support, encouragement and valuable advice throughout the study. The outcome of this report and development of my research caliber was due to his strong commitment and conviction. He has been a true guardian.

I would like to sincerely thank Dr. R.L.H.L Rajapakse for his support and guidance. His sincere and consistent encouragement is greatly appreciated. He has been a source of inspiration.

I would also like to thank Mr. Wajira Kumarasinghe, for his support, care and hospitality that he have shown and all the staff of UNESCO Madanjeet Singh Centre for South Asia Water Management (UMSCSAWM), University of Moratuwa.

Finally, I would like to extend my gratitude to Late Shri Madanjeet Singh for his vision of seeking regional cooperation, peace and solidarity through education and South Asia Foundation (SAF) for giving me this opportunity.

TABLE OF CONTENT

DECLARATION	ii
ABSTRACT	ii
ACKNOWLEDGEMENT	iv
1. INTRODUCTION	1
1.1. General	1
1.2. Study Area	3
1.3. Objective of the Study	4
1.3.1. Overall Objective:	4
1.3.2. Specific Objectives.....	4
2. LITRATURE REVIEW.....	5
2.1. Hydrological Modelling Practice	5
2.2. Preliminary Screening of Hydrological model.....	5
2.3. Review of Hydrological Model	8
2.3.1. Hydrological Modelling System (HEC-HMS).....	8
2.3.2. Soil and Water Analysis Tool (SWAT)	9
2.3.3. MIKE SHE	10
2.3.4. TOPMODEL.....	10
2.3.5. Storm Water Management Model (SWMM)	11
2.4. Criteria for the Selection of Model.....	12
2.4.1. Temporal Scale.....	12
2.4.2. Spatial Scale	13
2.4.3. Modelling Process	15

2.4.4.	Resources Requirement.....	18
2.4.5.	Documentation Support	19
2.4.6.	User Interface	19
2.4.7.	Model Acquisition Cost	20
2.5.	Criteria Evaluation for Model Selection.....	21
2.6.	Storm Water Management Model (SWMM)	25
2.6.1.	General Description	25
2.7.	Review on SWMM Parameters	27
2.7.1.	Depression Storages	27
2.7.2.	Manning’s Roughness Coefficients	27
2.7.3.	Infiltration Parameters.....	28
2.8	Sensitivity Analysis	30
2.9.	Model Calibration and Validation	31
2.10.	Objective Function	31
2.10.1.	Nash-Sutcliffe Efficiency (NSE).....	32
2.10.2.	Root Mean Square Error (RMSE).....	33
2.10.3.	Ratio of Absolute Error to Mean (RAEM).....	34
2.6.4.	Mean Ratio of Absolute Error (MRAE)	34
2.11.	Criteria for the Selection of Objective Function	35
2.11.1.	Mathematical Implication.....	36
2.11.2.	Flow Regimes.....	36
2.11.3.	Modelling Purpose	36
2.12.	Criteria Evaluation for the Selection Objective Function	37
3.	METHODOLOGY	39

4.	DATA AND DATA CHECKING.....	41
4.1.	Study Area.....	41
4.2.	Data Collection Summary	43
4.3.	Data Screening	44
4.4.	Annual Water Balance.....	45
4.5.	Streamflow Response to Rainfall (Seasonal).....	49
4.6.	Streamflow Response to Rainfall (Monthly).....	51
4.7.	Thiessen Average Rainfall	53
5.	ANALYSIS.....	60
5.1.	Selection of Watersheds	60
5.2.	Model Compartments	60
5.2.1.	Surface Runoff.....	60
5.2.2.	Surface Runoff Parameter Estimation	60
5.2.3.	Infiltration	62
5.2.4.	Groundwater	62
5.3.	Parameter Sensitivity and Optimization.....	63
5.4.	Development of Watershed Model.....	64
5.5.	Delineation of Subwatersheds	64
5.6.	Development of Precipitation Model	66
5.7.	Development of Lumped model.....	66
5.8.	Development of Semi-distributed Model	66
5.9.	Selection of Routing Method	68
5.10.	Selection of Routing Time Steps.....	69
5.11.	Model Calibration.....	69

6. RESULTS	70
6.1. Lumped Model Calibration	70
6.1.1. Ratnapura Lumped Model Calibration	70
6.1.2. Ellagawa Lumped Model Calibration	75
6.2. Lumped Model Validation	80
6.2.1. Ratnapura Lumped Model Validation	80
6.2.2. Ellagawa Lumped Model Validation	84
6.3. Ellagawa Semi-Distributed Model Calibration	88
6.3.1. Modelling Scenario	88
6.3.2. Model Calibration	89
6.4. Ellagawa Semi-Distributed Model Validation	93
7. DISCUSSION	98
7.1. Model Components	98
7.2. Optimization	100
7.3. Lumped Model	101
7.3.1. Comparison of Calibration Results	101
7.3.2. Comparison of Validation Results	102
7.4. Semi-Distributed Modeling	103
7.4.1. Semi-Distributed Modelling (SWMM)	103
7.4.2. Calibration Procedure	104
7.4.3. Improvement of model performance	105
7.5. Comparison of Parameters	106
7.5.1. Physical Parameters	106
7.5.2. Calibration Parameters	107

7.6. Comparison of Water Quantity Estimations	111
7.7. Hydro-Meteorological Data	112
7.7.1. Selection of Data Period	112
7.7.2. Data Error	112
7.8. Uncertainty in Groundwater Model.....	113
8. CONCLUSIONS	114
9. RECOMMENDATIONS.....	115
REFERENCES.....	116
APPENDIX A: Mass Curve Analysis	129
APPENDIX B: Streamflow Response with Rainfall	134
APPENDIX C: Parameter Sensitivity.....	139
APPENDIX D: Matching of Hydrograph in Normal Plot	142
APPENDIX E: Parameter Optimization.....	149

LIST OF FIGURES

Figure 1-1 Study Area	3
Figure 2-1 SWMM Schematic (Rossman & Huber, 2016).	26
Figure 3-1 Methodology flowchart.....	39
Figure 4-1 Study Area in Topographical Map.....	42
Figure 4-2 Landuse Map of Ellagawa Watershed	42
Figure 4-3 Annual Rainfall vs Observed Annual Streamflow on Ellagawa Watershed.....	45
Figure 4-4 Variation of Annual Losses and Runoff on Ellagawa Watershed	46
Figure 4-5 Variation of Annual Rainfall and Streamflow on Ratnapura Watershed.....	47
Figure 4-6 Variation of Annual Losses and Runoff at Ratnapura Watershed	48
Figure 4-7 Streamflow at Ellagawa corresponding to Maha Season (2006-2014).....	49
Figure 4-8 Streamflow at Ellagawa corresponding to Yala Season (2006-2014)	50
Figure 4-9 Ellagawa Monthly Rainfall in Response to Streamflow (2006-20014).....	51
Figure 4-10 Thiessen Polygons on Ellagawa Watershed	53
Figure 4-11 Thiessen Polygon on Ratnapura Watershed	54
Figure 4-12 Observed Streamflow with Thiessen Rainfall (Ratnapura Calibration)	55
Figure 4-13 Observed Streamflow with Thiessen Rainfall (Ratnapura Validation)	56
Figure 4-14 Observed Streamflow with Thiessen Rainfall (Ellagawa Calibration).....	57
Figure 4-15 Observed Streamflow with Thiessen Rainfall (Ellagawa Validation).....	58
Figure 5-1 DEM of the Study Area	64
Figure 5-2 Delineated Subwatersheds of Ellagawa watershed.....	65
Figure 5-3 Layout of Ellagawa Model with Subwatersheds in SWMM	67
Figure 6-1 Hydrographs of Ratnapura Lumped Model (Calibration)	71
Figure 6-2 Flow Duration Curves of Ratnapura Lumped Model (Calibration).....	72
Figure 6-3 Annual Water Balance of Ratnapura Lumped Model (Calibration).....	74
Figure 6-4 Hydrographs of Ellagawa Lumped Model (Calibration).....	76
Figure 6-5 Flow Duration Curves of Ellagawa Lumped Model (Calibration)	77
Figure 6-6 Annual Water Balance of Ellagawa Lumped Model (Calibration)	79
Figure 6-7 Hydrographs of Ratnapura Lumped Model (Validation).....	81
Figure 6-8 Flow Duration Curves of Ellagawa Lumped Model (Validation)	82

Figure 6-9 Annual Water Balance of Ratnapura Lumped Model (Validation)	83
Figure 6-10 Hydrographs of Ellagawa Lumped Model (Validation)	85
Figure 6-11 Flow Duration of Ellagawa Lumped Model (Validation).....	86
Figure 6-12 Annual water balance Ellagawa lumped model (Validation)	87
Figure 6-13 Hydrographs of Ellagawa Semi-distributed Model (Calibration).....	90
Figure 6-14 Flow duration curve of Ellagawa semi-distributed Model (Calibration).....	91
Figure 6-15 Annual Wter Balance of Ellagawa semi-distributed model (Calibration)	92
Figure 6-16 Hydrographs of Ellagawa semi-distributed model (Validation).....	94
Figure 6-17 Flow Duration Curves of Ellagawa semi-distributed Model (Validation).....	95
Figure 6-18 Annual Water Balance of Ellagawa semi-distributed Model (Validation).....	97

LIST OF TABLES

Table 2-1 Literature Survey for Preliminary Screening of Hydrological Models	6
Table 2-2 Criteria, Factors, Ranks and Scores for the Selection of the Model	22
Table 2-3 Criteria Evaluation for the Selection of the Model	23
Table 2-4 Literature summary of CN method	29
Table 2-5 Comparison of Horton's and Green Ampt Method.....	29
Table 2-6 Merits and Demerits of the Selected Objective Function	35
Table 2-7 Criteria, Factors, Ranks and Scores for the Selection of Objective Function	37
Table 2-8 Criteria Evaluation for the Selection of Objective Function.....	38
Table 4-1 Coordinates of Rainfall Stations	41
Table 4-2 Coordinates of Streamflow gauging Stations.....	41
Table 4-3 Landuse Coverage on Ellagawa Watershed	43
Table 4-4 Data Summary.....	44
Table 4-5 Variation of Annual Rainfall and Streamflow on Ellagawa Watershed	45
Table 4-6 Variation of Annual Rainfall and Streamflow at Ratnapura Watershed	47
Table 4-7 Streamflow corresponding to Seasonal Rainfall (2006-2014)	49
Table 4-8 Thiessen Weight for Rainfall Station for Ellagawa watershed	53
Table 4-9. Thiessen Weight of Rainfall for Ratnapura Stations.....	54
Table 5-1 Parameter Estimation of the Surface Runoff Compartment.....	61
Table 5-2 Initial Estimation of the Parameter.....	61
Table 5-3 Initial Estimation of Green-Ampt Infiltration Model Parameter	62
Table 5-4 Thiessen Weights of Subwatersheds	66
Table 5-5 Description of Junctions and Outlets of Ellagawa Semi-Distributed Model	68
Table 5-6 Description of Nodes of Ellagawa Semi-Distributed Model	68
Table 6-1 Calibration Results of Ratnapura Lumped Model.....	70
Table 6-2 Calibrated Parameters of Ratnapura Lumped Model.....	70
Table 6-3 Annual Water Balance of Ratnapura Lumped Model Calibration	73
Table 6-4 Annual Mass Balance of Ratnapura Lumped Model Calibration	73
Table 6-5 Calibration Results of Ellagawa Lumped Calibration.....	75
Table 6-6 Calibrated Parameter of Ellagawa Lumped Model	75

Table 6-7 Annual Water Balance of Ellagawa Lumped Model Calibration	78
Table 6-8 Annual Mass Balance of Ellagawa Lumped Model Calibration	78
Table 6-9 Validation Results of Ratnapura Lumped Model.....	80
Table 6-10 Annual Water balance of Ratnapura Lumped Model Validation.....	83
Table 6-11 Annual Mass Balance of Ratnapura Lumped Model Validation	83
Table 6-12 Validation Results of Ellagawa Lumped Model	84
Table 6-13 Annual Water Balance of Ellagawa Lumped Model Validation.....	87
Table 6-14 Annual Mass Balance of Ellagawa Lumped Model Validation	87
Table 6-15 Calibrated Parameter of Ellagawa Semi-Distributed Model.....	88
Table 6-16 Calibration Results of Ellagawa Semi-Distributed Model.....	89
Table 6-17 Annual Water Balance of Ellagawa Semi-Distributed Model Calibration	92
Table 6-18 Annual Mass Balance of Ellagawa Semi-Distributed Model Calibration.....	92
Table 6-19 Validation Results of Ellagawa Semi-Distributed Model	93
Table 6-20 Annual Water Balance of Ellagawa Semi-Distributed Model Validation	96
Table 6-21 Annual Mass Balance of Ellagawa semi-Distributed Model Validation	96
Table 7-1 Available Models within the various Components of SWMM.....	98
Table 7-2 Parameters Subjected to Optimization	100
Table 7-3 Comparison of Results of Lumped Models (Calibration).....	101
Table 7-4 Comparison of Runoff coefficients of Lumped Models (Calibration).....	102
Table 7-5 Comparison of Results of Lumped Models (Validation).....	102
Table 7-6 Comparison of Runoff Coefficients of Lumped Model (Validation).....	103
Table 7-7 Comparison of Ellagawa Lumped and Semi-Distributed Model (Calibration) ..	105
Table 7-8 Comparison of Ellagawa Lumped and Semi-Distributed Model (Validation)....	105
Table 7-9 Comparison of Physical Parameters of the Models	107
Table 7-10 Comparison of Calibration Parameters	108
Table 7-11 Comparison of Water Quantity Estimation.....	111