

**INCORPORATION OF THE OPTIMUM RAINFALL
SPATIAL VARIABILITY IN A MONTHLY RAINFALL
RUNOFF MODEL**

Ankit Bhatt

(179232A)

Degree of Master of Science

Department of Civil Engineering

University of Moratuwa

Sri Lanka

April 2020

**INCORPORATION OF THE OPTIMUM RAINFALL
SPATIAL VARIABILITY IN A MONTHLY RAINFALL
RUNOFF MODEL**

Ankit Bhatt

(179232A)

Supervised by
Professor N.T.S Wijesekera

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

UNESCO Madanjeet Singh Centre for
South Asia Water Management (UMCSAWM)

Department of Civil Engineering

University of Moratuwa

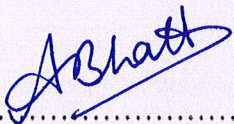
Sri Lanka

April 2020

DECLARATION

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

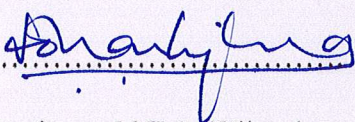
Also, I hereby grant to University of Moratuwa the non-exclusive right to reproduce and distribute my thesis, in whole or in part in print, electronic or other medium. I retain the right to use this content in whole or part in future works (such as articles or books).


.....

Date: 2020 . 04 . 20

Ankit Bhatt

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


.....

Date: 2020 . 04 . 27

Professor N.T.S. Wijesekera

Incorporation of the Optimum Rainfall Spatial Variability in a Monthly Rainfall Runoff Model

ABSTRACT

Most common method of accounting spatial variability of rainfall in hydrologic modelling is with the use of Thiessen Weights whereas some authors consider it illogical as it can result in biased distribution of rainfall. Mathematical rainfall-runoff models need a representative rainfall input and adequacy of a geometric method of rainfall accounting requires an investigation. Lack of sufficient information about spatial distribution of rainfall had always been one of the most important sources of errors in runoff estimations. Water resources planning is mostly done at a monthly time scale and hence a simple watershed model with the capability of moisture accounting is a desirable tool for practicing engineers. In 1990, a study of Mahaweli and Kalu Ganga watersheds had demonstrated an application of optimising rainfall station weights. Present study focusing on optimizing rainfall gauging station weights using the two-parameter monthly water balance model Xiong & Guo (1999), used daily rainfall from 2006-2017 of five rainfall gauging stations, evaporation and streamflow of Attanagalu Oya Basin at Dunamale to evaluate the spatial variability to contribute towards efficient water resources applications. Accordingly, the objective of the present study is to estimate streamflow using the 2P monthly water balance model by incorporating optimised rainfall spatial variability for water management, planning and design. First the model was developed, and the two model parameters c and SC were optimized using Thiessen average rainfall. Then in a stepwise manner, the station weights, parameter c and Sc were treated as parameters for optimisation. MRAE was used as the objective function for evaluation while observing the High, Medium and Low flow behaviour during optimisation. Water balance, soil moisture level, evaporation and the NSE model efficiencies were observed for comparison. Initial soil water content was found to be 186.13mm using a warmup period of 5 repetitions. The optimum model parameter (SC and C) values and optimized rainfall weights achieved during first and second optimization stages are 782.47 mm, 1.87 and 0.387, 0.325, 0.145, 135, & 0.008 for Vinctit, Pasyala, Nittambuwa, Karasnagala, & Chesterford respectively. The values achieved while simultaneously optimizing both rainfall & model parameters are 846.42 mm, 1.95, and 0.528, 0.199, 0.12, 0.144, 0.009. The mean MRAE value for calibration period is 0.43 and verification period 0.41. The 2P monthly water balance model with Thiessen rainfall station weights when compared with the optimised station weights indicated a difference of 8-9% in MRAE with an average MRAE value of 0.42 and a difference of 67 and 53 mm in average annual water balance error during calibration and verification respectively. On a monthly scale even a small change in rainfall station weight aggregates and gets reflected in the model estimates especially for stations receiving high intensity rainfall. Therefore, using a method of areal averaging that predetermines rainfall station weights and disregards the spatial mobility of a rainfall event will lead to erroneous results.

Keywords: two-parameter model; rainfall weight optimization; monthly water balance

ACKNOWLEDGEMENT

I would like to express my sincere gratitude to my research supervisor, Professor N.T.S Wijesekera for the continuous support of my study, for his patience, motivation and immense knowledge. Without his dedicated supervision and continued guidance, this thesis would not be in success. I am grateful to him for spending his valuable time with me in materializing this research work in time. He consistently allowed this research to be my own work but steered me in the right direction whenever he thought I needed it.

I will never hesitate to convey my thanks to the course coordinator Dr R.L.H Rajapakse by extending all necessary help. He was kind enough to provide help and support with his busy schedule. His sincere and consistent encouragement is greatly appreciated.

I am grateful to Mr. Wajira Kumarasinghe who looked after day to day needs during research period, would thank him for his help and support all the way during this research work.

My thanking list also includes the late Shri Madanjeet Singh and the University of Moratuwa for furnishing this outstanding opportunity to study towards a Master's Degree of Water Resource Engineering and Management, at UNESCO Madanjeet Singh Center for South Asia Water Management, Department of Civil Engineering, University of Moratuwa, Sri Lanka.

CONTENTS

DECLARATION	i
ABSTRACT	ii
ACKNOWLEDGEMENT	iii
LIST OF FIGURES	vii
LIST OF TABLES	x
1 INTRODUCTION	1
1.1 Overview	1
1.2 Objective of the Study	5
1.2.1 Overall objective	5
1.2.2 Specific objective	5
2 LITERATURE REVIEW	6
2.1 Types of Water Balance Models	6
2.1.1 General	6
2.1.2 Monthly water balance models	7
2.1.3 Two-parameter monthly water balance models	8
2.2 Rainfall Spatial Variability	9
2.2.1 Methods of areal averaging rainfall	9
2.2.2 Importance spatial variability of rainfall	10
2.3 Model Evaluation and Parameter Optimization	11
2.3.1 Calibration and Verification data requirement	12
2.3.2 High, Medium, and Low flows	13
2.3.3 Objective function	14
2.3.4 Evaluation criteria	16
2.3.5 Initial parameter values	16
2.3.6 Warm-up period	17
2.3.7 Parameter threshold values	18
2.4 Data Checking Methods	18
2.4.1 Graphical	18
2.4.2 Statistical	18
2.4.3 Filling of missing data	19
3 METHODOLOGY	20
4 DATA AND DATA CHECKING	22

4.1	Attanagalu Oya Basin.....	22
4.2	Data Summary	24
4.2.1	Rainfall Stations and Missing Data.....	24
4.2.2	Stream Gauging Station and Missing Data	25
4.3	Annual Data Checking	26
4.3.1	Annual Data Statistics	26
4.3.2	Annual Water Balance	27
4.4	Monthly Data Checking	28
4.4.1	Rainfall Data Statistics.....	32
4.4.2	Streamflow Data Statistics	33
4.4.3	Evaporation Data Statistics	34
4.5	Daily Data Checking	34
5	ANALYSIS.....	36
5.1	Thiessen Averaged Rainfall	36
5.2	Identification of High, Medium and Low Flows.....	37
5.3	Selected Model Structure and Parameters.....	39
5.3.1	Model Development.....	40
5.4	Objective Function and Parameter Optimization	41
5.4.1	Selected objective function	41
5.4.2	Initial soil moisture	41
5.4.3	Search for Global minimum.....	42
5.5	Optimization of Model Parameters	45
5.5.1	Performance of model during Calibration period	45
5.5.2	Performance of model during Verification period.....	49
5.6	Optimization of Rainfall Station Weights	53
5.6.1	Performance of model during Calibration period	53
5.6.2	Performance of model during Verification period.....	57
5.7	Optimization of Model Parameters and Rainfall Station Weights	61
5.7.1	Performance of model during Calibration period	61
5.7.2	Performance of model during Verification period.....	65
6	RESULTS	69
6.1	Optimization of Model Parameters	69
6.2	Optimization of Rainfall Station Weights	71

6.3	Optimization of Model Parameters and Rainfall Station Weights	73
6.4	Comparison of various cases of Optimization	75
6.4.1	Comparison of Rainfall station weights.....	75
6.4.2	Comparison of model performance during Calibration period.....	75
6.4.3	Comparison of model performance during Verification period.....	76
7	DISCUSSION.....	78
7.1	Data Disparities	78
7.2	Data Filling Importance and Drawbacks.....	78
7.3	Areal Average Rainfall.....	78
7.4	Model Identification	79
7.5	Search for Global Minimum.....	79
7.6	Model Parameter Ranges.....	79
7.7	Model Conceptualization	79
7.8	Two-parameter Model Performance.....	79
7.9	Influence of Model Parameters	80
7.10	Influence of Rainfall Spatial Variability	80
7.11	Model Development and Modelling Difficulties	80
7.12	Improvements on Streamflow Estimates.....	81
8	CONCLUSIONS	82
9	RECOMMENDATIONS.....	83
	REFERENCES.....	84
	ANNEX A – Data	88
	ANNEX B – Data Checking	92
	ANNEX C – Methodology	134
	ANNEX D – Model Development.....	136
	ANNEX E – Analysis	138

LIST OF FIGURES

Figure 1-1 Catchment Area of Attanagalu Oya at Dunamale	4
Figure 3-1 Methodology Flow Chart	21
Figure 5-1 Thissen polygon for Dunamale Watershed	37
Figure 5-2 Flow Duration Curve for Calibration Dataset – 2006 to 2012.....	38
Figure 5-3 Flow Duration Curve for Verification Dataset – 2012 to 2017.....	38
Figure 5-2 Determination of Initial Soil Moisture using Warmup Period.....	42
Figure 5-2 Variation of Objective function with Parameter Values - Dunamale Watershed.....	43
Figure 5-3 Search for Global Minimum of MRAE - Dunamale Watershed.....	44
Figure 5-4 Flow Duration Curve of Two-parameter monthly water balance model for Dunamale Watershed of Calibration Period – Normal and Semi-Log Plot	46
Figure 5-5 Hydrographs of Two-parameter monthly water balance model for Dunamale Watershed of Calibration Period (2006-2011) – Normal Plot	47
Figure 5-6 Hydrographs of Two-parameter monthly water balance model for Dunamale Watershed of Calibration Period (2006-2011) – Semi-log Plot	47
Figure 5-7 Annual Water Balance of Two-parameter model for Dunamale Watershed of Calibration Period (2006-2011)	48
Figure 5-8 Flow Duration Curve of Two-parameter monthly water balance model for Dunamale Watershed of Verification Period – Normal and Semi- Log Plot.....	50
Figure 5-9 Hydrographs of Two-parameter monthly water balance model for Dunamale Watershed of Verification Period (2011-2017) – Normal Plot	51
Figure 5-10 Hydrographs of Two-parameter monthly water balance model for Dunamale Watershed of Verification Period (2011-2017) – Semi-log Plot	51
Figure 5-11 Annual Water Balance of Two-parameter model for Dunamale Watershed of Verification Period (2011-2017).....	52

Figure 5-12 Flow Duration Curve of Two-parameter monthly water balance model for Dunamale Watershed of Calibration Period – Normal and Semi-Log Plot	54
Figure 5-13 Hydrographs of Two-parameter monthly water balance model for Dunamale Watershed of Calibration Period (2006-2011) – Normal Plot	55
Figure 5-14 Hydrographs of Two-parameter monthly water balance model for Dunamale Watershed of Calibration Period (2006-2011) – Semi-Log Plot	55
Figure 5-15 Annual Water Balance of Two-parameter model for Dunamale Watershed of Calibration Period (2006-2011)	56
Figure 5-16 Flow Duration Curve of Two-parameter monthly water balance model for Dunamale Watershed of Verification Period – Normal and Semi- Log Plot	58
Figure 5-17 Hydrographs of Two-parameter monthly water balance model for Dunamale Watershed of Verification Period (2011-2017) – Normal Plot	59
Figure 5-18 Hydrographs of Two-parameter monthly water balance model for Dunamale Watershed of Verification Period (2011-2017) – Semi-log Plot	59
Figure 5-19 Annual Water Balance of Two-parameter model for Dunamale Watershed of Verification Period (2011-2017)	60
Figure 5-20 Flow Duration Curve of Two-parameter monthly water balance model for Dunamale Watershed of Calibration Period – Normal and Semi-Log Plot	62
Figure 5-21 Hydrographs of Two-parameter monthly water balance model for Dunamale Watershed of Calibration Period (2006-2011) – Normal Plot	63
Figure 5-22 Hydrographs of Two-parameter monthly water balance model for Dunamale Watershed of Calibration Period (2006-2011) – Semi-Log Plot	63
Figure 5-23 Annual Water Balance of Two-parameter model for Dunamale Watershed of Calibration Period (2006-2011)	64

Figure 5-24 Flow Duration Curve of Two-parameter monthly water balance model for Dunamale Watershed of Verification Period – Normal and Semi-Log Plot.....	66
Figure 5-25 Hydrographs of Two-parameter monthly water balance model for Dunamale Watershed of Verification Period (2011-2017) – Normal Plot	67
Figure 5-26 Hydrographs of Two-parameter monthly water balance model for Dunamale Watershed of Verification Period (2011-2017) – Semi-Log Plot	67
Figure 5-27 Annual Water Balance of Two-parameter model for Dunamale Watershed of Verification Period (2011-2017).....	68
Figure 6-1 Observed and Simulated Streamflow Comparison of Dunamale Watershed for Model Parameter Optimization - Calibration Period.....	70
Figure 6-2 Observed and Simulated Streamflow Comparison of Dunamale Watershed for Model Parameter Optimization - Verification Period	70
Figure 6-3 Observed and Simulated Streamflow Comparison of Dunamale Watershed for Rainfall Station Weights Optimization - Calibration Period	72
Figure 6-4 Observed and Simulated Streamflow Comparison of Dunamale Watershed for Rainfall Station Weights Optimization - Verification Period	72
Figure 6-5 Observed and Simulated Streamflow Comparison of Dunamale Watershed for Rainfall Station Weights and Model Parameter Optimization - Calibration Period.....	74
Figure 6-6 Observed and Simulated Streamflow Comparison of Dunamale Watershed for Rainfall Station Weights and Model Parameter Optimization - Verification Period.....	74

LIST OF TABLES

Table 4.1 Distribution of Gauging Stations of Dunamale Watershed	22
Table 4.2 Data Details of Attanagalu Oya at Dunamale	24
Table 4.3 Rainfall Gauging Station Details of Attanagalu Oya at Dunamale	24
Table 4.4 Missing Rainfall Data of Attanagalu Oya at Dunamale	25
Table 4.5 Missing Streamflow Data of Attanagalu Oya at Dunamale.....	25
Table 4.6 Annual Data Statistics for each Water Year - Dunamale Watershed	26
Table 4.7 Annual Water Balance - Dunamale Watershed	28
Table 4.8 Statistics of Monthly Thiessen Rainfall Data (mm) for each Water Year (2006 to 2017) – Dunamale Watershed.....	33
Table 4.9 Statistics of Monthly Streamflow Data for Water Year (2006 to 2017) – Dunamale Station	33
Table 4.10 Statistics of Monthly Evaporation Data for Water Year (2006 to 2017) – Colombo Station.....	34
Table 5.1 Thiessen Areas and Weights of Rainfall Stations in Attanagalu Oya at Dunamale	36
Table 5.2 High, Medium & Low flow limits with Monthly Data for Calibration & Verification Datasets	38
Table 5.3 Model Performance during Optimization of Model Parameters for Calibration Period - Dunamale Watershed.....	45
Table 5.4 Annual Water Balance for Optimization of Model Parameters - Calibration Period	45
Table 5.5 Model Performance during Optimization of Model Parameters for Verification Period - Dunamale Watershed	49
Table 5.6 Annual Water Balance for Optimization of Model Parameters - Verification Period	49
Table 5.7 Model Performance during Optimization of Rainfall Station Weights for Calibration Period - Dunamale Watershed.....	53
Table 5.8 Annual Water Balance for Optimization of Rainfall Station Weights - Calibration Period	53

Table 5.9 Model Performance during Optimization of Rainfall Station Weights for Verification Period - Dunamale Watershed	57
Table 5.10 Annual Water Balance for Optimization of Rainfall Station Weights - Verification Period	57
Table 5.11 Model Performance during Optimization of Model Parameters and Rainfall Station Weights for Calibration Period - Dunamale Watershed	61
Table 5.12 Annual Water Balance for Optimization of Model Parameters and Rainfall Station Weights - Calibration Period.....	61
Table 5.13 Model Performance during Optimization of Model Parameters and Rainfall Station Weights for Verification Period - Dunamale Watershed.....	65
Table 5.14 Annual Water Balance for Optimization of Model Parameters and Rainfall Station Weights - Verification Period	65
Table 6.1 Rainfall Station Weights used for calculating Areal Average Rainfall	69
Table 6.2 Optimized Model Parameters.....	69
Table 6.3 Comparison of results during calibration and verification of optimized model parameters	69
Table 6.4 Selected Model Parameters	71
Table 6.5 Optimized Rainfall Station Weights used for calculating Areal Average Rainfall	71
Table 6.6 Comparison of results during calibration and verification of optimized rainfall station weights	71
Table 6.7 Optimized Model Parameters.....	73
Table 6.8 Optimized Rainfall Station Weights used for calculating Areal Average Rainfall	73
Table 6.9 Comparison of results during calibration and verification of optimized model parameters and rainfall station weights.....	73
Table 6.10 Comparison of Rainfall Station Weights for each Optimization case	75
Table 6.11 Comparison of model performance for Optimization stage I and II during Calibration (2006-2012)	75
Table 6.12 Comparison of model performance for Optimization stage I and III during Calibration (2006-2012)	76

Table 6.13 Comparison of model performance for Optimization stage II and III during Calibration (2006-2012)	76
Table 6.14 Comparison of model performance for Optimization stage I and II during Verification (2012-2017)	76
Table 6.15 Comparison of model performance for Optimization stage I and III during Verification (2012-2017)	77
Table 6.16 Comparison of model performance for Optimization stage II and III during Verification (2012-2017)	77