

**A MONTHLY WATER BALANCE MODEL FOR
EVALUATION OF CLIMATE CHANGE IMPACTS ON
THE STREAMFLOW OF GINGANGA AND KELANI
GANGA BASINS, SRI LANKA**

Dorji Khandu

148658A

Master of Engineering in Water Resources Engineering and
Management

Department of Civil Engineering

University of Moratuwa

Sri Lanka

October 2015

**A MONTHLY WATER BALANCE MODEL FOR
EVALUATION OF CLIMATE CHANGE IMPACTS ON
THE STREAMFLOW OF GINGANGA AND KELANI
GANGA BASINS, SRI LANKA**

Dorji Khandu

148658A

Thesis submitted in partial fulfillment of the requirements for the degree of Master of
Engineering in Civil Engineering

Supervised by

Professor N.T.S. Wijesekera

Department of Civil Engineering

University of Moratuwa

Sri Lanka

October 2015

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 expect 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).

.....

Dorji Khandu

.....

Date

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

.....

Professor N.T.S. Wijesekera

.....

Date

This Thesis is gratefully dedicated to my family.

For their endless love, support and encouragement

ACKNOWLEDGEMENT

Over the past twelve months I received support and encouragement from a great number of individuals. In full gratitude I would like to acknowledge the following individuals who encouraged, inspired, supported, assisted, and sacrificed themselves to help my pursuit of a high education degree.

First of all I would like to extend my sincere and heartfelt 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 calibre was due to his strong commitment and conviction. He has been a true guardian and one of the profound mentors with vast experience and ocean of wisdom.

I would like to express my deep appreciation to Dr. R.L.H Lalith Rajapakse for rendering his unending support and guidance provided both in terms of academic and logistic welfare during my stay. He has been a source of inspiration and his guidance has made this a thoughtful and rewarding journey.

For all technical assistance and moral support I would like to thank Mr. D.A Jayasinghearachchi, Deputy Director and Ms. Sandamali Subasinghe of Department of Meteorology, Mr. Susil Ratnayka, Senior Hydrologist Assistant and Mr. L.R.H. Perera, Chief Engineer, Department of Irrigation.

I also wish to express my gratitude to Ms. Gayani Edirisinghe, Mr. Wajira Kumarasinghe and all other support staff for their assistance to make my stay comfortable. My sincere heartfelt gratitude goes to late Madanjeet Singh for his visionary and noble idea of providing scholarship to pursue this course.

Finally, to my caring, loving, and supportive wife, Pema Seldon Dorji: my deepest gratitude. Her encouragement when the times got rough are much appreciated and duly valued. Her undertaking to take care of our daughter during my study period away from home was a great comfort and a relief which I will remember throughout my life.

ABSTRACT

The availability and distribution of freshwater resources will be greatly affected by climate change and the vulnerability to water scarcity of affected populations currently experience could increase. Studies relating climate change and hydrology are becoming prevalent but few published studies focus on changes in Sri Lanka streamflow. There is ample evidence to suggest that the climate of South Asian region has already changed. Climate change or its increased variability is expected to alter the timing and magnitude of runoff. As a result it has important implications for existing water resources systems as well as for future water resources planning and management. A two-parameter monthly water balance model is adopted to simulate the runoff for the evaluation of climate change impacts on the streamflow of two major catchments in Kelani Ganga and Gin Ganga basins in Sri Lanka. The model was successfully calibrated and verified for Kelani Ganga & Gin Ganga basins showing that average values of 0.485 and 1110.50 mm for parameters c & SC respectively could simulate monthly streamflow with average MRAE 0.088 and average Nash-Sutcliffe efficiency 0.957. Application results show that the model efficiencies are high in both the calibration and verification periods. This study demonstrated the models capability and applicability to evaluate the climate change impacts on the streamflow and also to forecast for future scenarios. It is suggested that this two parameter model can be easily and efficiently incorporated in the climate impact studies to simulate monthly runoff and as well as in the water resources planning program.

TABLE OF CONTENTS

Declaration	i
Acknowledgement	iii
Abstract	iv
Table of Contents.....	v
List of Figures	x
List of Tables.....	xiii
List of Abbreviations	xv
1 Introduction	1
1.1 General.....	1
1.2 Problem Statement.....	5
1.3 Objectives.....	5
1.4 Specific Objective(s)	5
2 Literature Review.....	6
2.1 Modelling concept and classification	6
2.2 Types of Monthly Water Balance Model.....	7
2.2.1 Model Composition	7
2.2.2 Comparison of the types	8
2.3 Application Potential of Monthly Water Balance Models.....	8
2.4 Selected Water Balance Model	9
2.4.1 Precipitations.....	10
2.4.2 Monthly evapotranspiration	10
2.4.3 Streamflow	11
2.4.4 Determination of initial soil water content	13
2.5 Model Testing and Parameter Optimization	13
2.5.1 Nash-Sutcliffe efficiency E.....	14
2.5.2 Relative Error.....	15
2.5.3 Mean Ratio of Absolute Error (MRAE)	16
2.5.4 Ratio of Absolute Error to Mean (RAEM)	17
2.5.5 Objective Function Evaluation.....	18
2.5.6 Parameter Optimization	21

2.6	Calibration & Validation.....	23
2.7	Climate Change in Sri Lanka	24
2.7.1	Observed Changes in Climate	24
2.7.2	Future Climate Projections	25
3	Methodology.....	26
3.1	General Descriptions	27
3.2	Calibration & Validation.....	27
4	Data & Data Checking	29
4.1	Kelani Ganga Watershed at Deraniyagala	29
4.2	Gin Ganga Watershed at Tawalama	31
4.3	Thiessen Average Rainfall	33
4.4	Data and Data Checking	36
4.4.1	Data.....	36
4.4.2	Data Errors	36
4.4.3	Data Checking Methods.....	36
4.5	Monthly Comparison.....	38
4.5.1	Precipitation	38
4.5.2	Evaporation of Kelani Ganga at Deraniyagala.....	40
4.5.3	Evaporation of Gin Ganga at Tawalama.....	41
4.5.4	Streamflow of Kelani Ganga at Deraniyagala	41
4.5.5	Streamflow of Gin Ganga at Tawalama	42
4.6	Annual Comparison.....	43
4.6.1	Rainfall and Streamflow	43
4.6.2	Water Balance and Pan Evaporation	45
4.7	Seasonal Comparison.....	46
4.8	Runoff Coefficient.....	48
5	Analysis	51
5.1	Determination of High, Medium and Low Flows	51
5.1.1	Kelani Ganga.....	51
5.1.2	Gin Ganga	52
5.2	Average Flow Duration	53

5.2.1	Kelani Ganga.....	53
5.2.2	Gin Ganga	54
5.3	Overall Flow Duration.....	55
5.3.1	Kelani Ganga.....	55
5.3.2	Gin Ganga	56
5.4	Behavior of Hyperbolic Tangent Function	57
5.5	Relationship between $E(t)$ and $EP(t)$	58
5.6	Comparison of Actual Evaporation and Pan Evaporation	59
5.7	Model Calibration.....	60
5.7.1	Initial Soil Moisture Content, c and SC	60
5.7.2	Objective function	60
5.7.3	Optimization Methods	60
5.7.4	Methods/Parameter trial ranges.....	61
5.7.5	MRAE behavior during calibration period	61
5.7.6	Nash-Sutcliffe efficiency behavior during calibration period.....	63
5.7.7	Estimated Streamflow.....	66
5.7.8	Flow duration curves	70
5.7.9	Estimated Evaporation (Actual).....	71
5.7.10	Estimated Soil Moisture Content	74
5.8	Model Verification	77
5.8.1	Estimated Streamflow.....	77
5.8.2	Flow duration curves	81
5.8.3	Estimated Evaporation (Actual).....	82
5.8.4	Estimated Soil Moisture Content	85
5.9	Climate Change	88
5.9.1	Climate Change in Sri Lanka	88
5.9.2	Influence on Model Inputs	88
5.9.3	Critical Climate Change Scenario	90
5.9.4	Anticipated Model Estimations with Climate Change	91
5.9.5	Soil Moisture Content.....	92
6	Results	93

6.1	Results for Kelani Ganga.....	93
6.1.1	Calibration.....	93
6.1.2	Verification	98
6.2	Results for Gin Ganga.....	103
6.2.1	Calibration.....	103
6.2.2	Verification	108
6.3	Summary Results.....	113
6.3.1	Thiessen Averaged Rainfall.....	113
6.3.2	Streamflow	114
6.3.3	Pan Evaporation	115
6.3.4	Soil Moisture (From the Model)	116
6.3.5	Actual Evaporation (From the Model)	117
6.3.6	Annual Water Balance	118
6.3.7	Parameter Optimization	119
7	Discussion.....	120
7.1	Discussion of Summary Results.....	120
7.1.1	Thiessen Averaged Rainfall.....	120
7.1.2	Streamflow	120
7.1.3	Pan Evaporation	121
7.1.4	Soil Moisture Content.....	121
7.1.5	Actual Evaporation.....	122
7.1.6	Annual water balance	122
7.1.7	Parameter Optimization	123
7.2	Model Performance	124
7.3	Modelling Difficulties.....	125
8	Conclusion & Recommendation.....	126
8.1	Conclusion	126
8.2	Recommendation.....	126
	References.....	127
	Appendix A: Data checking Kelani Ganga.....	142
	Appendix-B: Data checking Gin Ganga	150

Appendix-C: Analysis Kelani Ganga	159
Appendix-D: Analysis Gin Ganga.....	165
Appendix-E: Calibration Results Kelani Ganga	171
Appendix-F: Calibration Results Gin Ganga	176
Appendix-G: Verification Results Kelani Ganga.....	181
Appendix-H: Verification Results Gin Ganga	184
Appendix-I: Specimen Calculations	187

LIST OF FIGURES

Figure 2-1: Classification of Hydrological Models (Moreda, 1999).....	6
Figure 2-2: Conceptual representation of Two Parameter Monthly Water Balance Model.....	10
Figure 3-1: Methodology Flow Chart.....	26
Figure 4-1: Kelani Ganga Watershed at Deraniyagala	29
Figure 4-2: Gin Ganga Watershed at Tawalama	31
Figure 4-3: Thiessen Polygons and Rainfall Stations at Deraniyagala.....	34
Figure 4-4: Thiessen Polygons and Rainfall Stations at Tawalama	34
Figure 4-5: Land-use of Deraniyagala	35
Figure 4-6: Land-use of Tawalama	35
Figure 4-7: Monthly Comparison of Thiessen Average Rainfall at Deraniyagala.....	39
Figure 4-8: Monthly Comparison of Thiessen Average Rainfall at Tawalama	40
Figure 4-9: Monthly Comparison of Pan Evaporation at Deraniyagala	40
Figure 4-10: Monthly Comparison of Pan Evaporation at Tawalama.....	41
Figure 4-11: Monthly Comparison of Streamflow at Deraniyagala.....	42
Figure 4-12: Monthly Comparison of Streamflow at Tawalama	42
Figure 4-13: Annual Comparison of Rainfall & Streamflow at Deraniyagala	43
Figure 4-14: Annual Comparison of Rainfall & Streamflow at Tawalama.....	43
Figure 4-15: Annual Comparison of Rainfall & Streamflow at Deraniyagala	44
Figure 4-16: Annual Comparison of Rainfall & Streamflow at Tawalama.....	44
Figure 4-17: Annual Water Balance & Pan Evaporation at Deraniyagala	45
Figure 4-18: Annual Water Balance & Pan Evaporation at Tawalama.....	46
Figure 4-19: Seasonal Comparison of Streamflow & Rainfall at Deraniyagala	47
Figure 4-20: Seasonal Comparison of Streamflow & Rainfall at Tawalama	47
Figure 4-21: Frequency Analysis Before & After Data Corrections (Kelani Ganga)	49
Figure 4-22: Frequency Analysis Before & After Data Corrections (Kelani Ganga)	50
Figure 5-1: Flow duration curves plotted for each year at Kelani Ganga (1966-2014)	51
Figure 5-2: Flow duration curves plotted for each year at Gin Ganga (1972-2012)..	52
Figure 5-3: Flow Duration Curve of Average Streamflow for Kelani Ganga (Normal and Logarithmic Plot).....	53
Figure 5-4: Flow Duration Curve of Average Monthly Streamflow for Gin Ganga (Normal and Logarithmic Plot)	54
Figure 5-5: Flow Duration Curve of Overall Monthly Streamflow for Kelani Ganga (Normal and Logarithmic Plot)	55
Figure 5-6: Flow Duration Curve of Overall Monthly Streamflow for Gin Ganga (Normal Logarithmic Plot).....	56
Figure 5-7: Inter-Relationship of Evaporation and Rainfall	57
Figure 5-8: E(t) and EP(t) Relationship for parameter c at Kelani Ganga.....	58

Figure 5-9: E(t) and EP(t) Relationship parameter c at Gin Ganga	58
Figure 5-10: Actual Evaporation and Pan Evaporation Comparison at Kelani Ganga	59
Figure 5-11: Actual Evaporation and Pan Evaporation Comparison at Gin Ganga...	59
Figure 5-12: MRAE and Parameter c at Kelani Ganga	61
Figure 5-13: MRAE and Parameter SC at Kelani Ganga	62
Figure 5-14: MRAE and Parameter c at Gin Ganga.....	62
Figure 5-15: MRAE and Parameter SC at Gin Ganga.....	63
Figure 5-16: Nash-Sutcliffe efficiency and Parameter c at Kelani Ganga.....	64
Figure 5-17: Nash-Sutcliffe efficiency and Parameter SC at Kelani Ganga.....	64
Figure 5-18: Nash-Sutcliffe efficiency and Parameter c at Gin Ganga	65
Figure 5-19: Nash-Sutcliffe efficiency and Parameter SC at Gin Ganga	65
Figure 5-20: Annual Water Balance at Kelani Ganga (1966-1990).....	66
Figure 5-21: Annual Water Balance for Gin Ganga (1972-1992).....	66
Figure 5-22: Maha Season Streamflow at Kelani Ganga (1966-1990)	67
Figure 5-23: Yala Season Streamflow at Kelani Ganga (1966-1990).....	67
Figure 5-24: Maha Season Streamflow at Gin Ganga (1972-1992).....	68
Figure 5-25: Yala Season Streamflow at Gin Ganga (1972-1992)	68
Figure 5-26: Monthly Streamflow at Kelani Ganga (1966-1990).....	69
Figure 5-27: Monthly Streamflow at Gin Ganga (1972-1992)	69
Figure 5-28: Annual Actual E(t) at Kelani Ganga (1966-1990)	71
Figure 5-29: Seasonal Actual E(t) at Kelani Ganga (1966-1990)	71
Figure 5-30: Monthly Actual E(t) at Kelani Ganga (1966-1990)	72
Figure 5-31: Annual Actual E(t) at Gin Ganga (1972-1992).....	72
Figure 5-32: Seasonal Actual E(t) at Gin Ganga (1972-1992).....	73
Figure 5-33: Monthly Actual E(t) at Gin Ganga (1972-1992).....	73
Figure 5-34: Annual Estimated Soil Moisture Content at Kelani Ganga (1966-1990)	74
Figure 5-35: Seasonal Estimated Soil Moisture Content at Kelani Ganga (1966-1990)	74
Figure 5-36: Monthly Estimated Soil Moisture Content at Kelani Ganga (1966-1990)	75
Figure 5-37: Annual Estimated Soil Moisture Content at Gin Ganga (1972-1992)...	75
Figure 5-38: Seasonal Estimated Soil Moisture Content at Gin Ganga (1972-1992)	76
Figure 5-39: Monthly Estimated Soil Moisture Content at Gin Ganga (1972-1992).	76
Figure 5-40: Annual Water Balance at Kelani Ganga (1990-2014).....	77
Figure 5-41: Annual Water Balance for Gin Ganga (1992-2012).....	77
Figure 5-42: Maha Season Streamflow at Kelani Ganga (1990-2014)	78
Figure 5-43: Yala Season Streamflow at Kelani Ganga (1990-2014).....	78
Figure 5-44: Maha Season Streamflow at Gin Ganga (1992-2012).....	79
Figure 5-45: Yala Season Streamflow at Gin Ganga(1992-2012)	79

Figure 5-46: Monthly Streamflow at Kelani Ganga (1990-2014).....	80
Figure 5-47: Monthly Streamflow at Gin Ganga (1992-2012)	80
Figure 5-48: Annual Actual E(t) at Kelani Ganga (1990-2014)	82
Figure 5-49: Seasonal Actual E(t) at Kelani Ganga (1990-2014).....	82
Figure 5-50: Monthly Actual E(t) at Kelani Ganga (1990-2014)	83
Figure 5-51: Annual Actual E(t) at Gin Ganga (1992-2012).....	83
Figure 5-52: Seasonal Actual E(t) at Gin Ganga (1992-2012).....	84
Figure 5-53: Monthly Actual E(t) at Gin Ganga (1992-2012).....	84
Figure 5-54: Annual Estimated Soil Moisture Content at Kelani Ganga (1990-2014)	85
Figure 5-55: Seasonal Estimated Soil Moisture Content at Kelani Ganga (1990-2014)	85
Figure 5-56: Monthly Estimated Soil Moisture Content at Kelani Ganga (1990-2014)	86
Figure 5-57: Annual Estimated Soil Moisture Content at Gin Ganga (1992-2012)...	86
Figure 5-58: Seasonal Estimated Soil Moisture Content at Gin Ganga (1992-2012)	87
Figure 5-59: Monthly Estimated Soil Moisture Content at Gin Ganga (1992-2012).	87
Figure 5-60: Climate change influence on rainfall up to year 2070.....	89
Figure 5-61: Climate change influence on evaporation up to year 2070.....	90
Figure 5-62: Simulated Streamflow with Climate Change.....	91
Figure 5-63: Soil Moisture Content with Climate Change	92
Figure 6-1: Annual Water Balance of Kelani Ganga (1966-1990)	95
Figure 6-2: Flow Duration (Normal Plot) of Kelani Ganga (1966-1990)	96
Figure 6-3: Flow Duration (Logarithmic Plot)of Kelani Ganga (1966-1990)	96
Figure 6-4: Outflow Hydrograph of Kelani Ganga from 1966-1990 (Normal & Logarithmic Plot).....	97
Figure 6-5: Annual Water Balance of Kelani Ganga (1990-2014)	100
Figure 6-6: Flow Duration (Normal Plot) of Kelani Ganga (1990-2014)	101
Figure 6-7: Flow Duration (Logarithmic Plot) of Kelani Ganga (1990-2014)	101
Figure 6-8: Outflow Hydrograph of Kelani Ganga from 1990-2014 (Normal & Logarithmic Plot).....	102
Figure 6-9: Annual Water Balance of Gin Ganga (1972-1992).....	105
Figure 6-10: Flow Duration (Normal Plot) of Gin Ganga (1972-1992).....	106
Figure 6-11: Flow Duration (Logarithmic Plot) of Gin Ganga (1972-1992).....	106
Figure 6-12: Outflow Hydrograph of Gin Ganga from 1972-1992 (Normal & Logarithmic Plot).....	107
Figure 6-13: Annual Water Balance of Gin Ganga (1992-2012).....	110
Figure 6-14: Flow Duration (Normal Plot) of Gin Ganga (1992-2012).....	111
Figure 6-15: Flow Duration (Logarithmic Plot) of Gin Ganga (1992-2012).....	111
Figure 6-16: Outflow Hydrograph of Gin Ganga from 1992-2012 (Normal & Logarithmic Plot).....	112

LIST OF TABLES

Table 2-1: Objective function list summary.....	19
Table 2-2: Peak Flow Evaluation	19
Table 2-3: Intermediate Flow Evaluation	20
Table 2-4: Low Flow Evaluation.....	20
Table 2-5: Overall Flow Evaluation	21
Table 3-1: Calibration & Validation Data Summary of Deraniyagala in Kelani Ganga Basin	28
Table 3-2: Calibration & Validation Data Summary of Tawalama in Gin Ganga Basin	28
Table 4-1: Summary of Deraniyagala watershed	30
Table 4-2: Rainfall, Streamflow and Evaporation Gauging Station at Deraniyagala	30
Table 4-3: Landuse details of Deraniyagala watershed	30
Table 4-4: Summary of Tawalama watershed.....	32
Table 4-5: Rainfall, Streamflow and Evaporation Gauging Station at Tawalama	32
Table 4-6: Landuse details of Tawalama watershed	32
Table 4-7: Thiessen weights for Kelani Ganga at Deraniyagala.....	33
Table 4-8: Thiessen weights for Gin Ganga at Tawalama.....	33
Table 4-9: Data Sources and Resolutions of Kelani Ganga at Deraniyagala.....	37
Table 4-10: Data Sources and Resolutions of Gin Ganga at Tawalama.....	37
Table 4-11: Distribution of Gauging Stations of Kelani Ganga at Deraniyagala	37
Table 4-12: Distribution of Gauging Stations of Gin Ganga at Tawalama	37
Table 4-13: Data Points Analysis for Kelani Ganga	49
Table 4-14: Data Points Analysis for Gin Ganga.....	50
Table 5-1: Critical Climate Change Scenario	90
Table 5-2: Model Simulated Streamflow with Climate Change	91
Table 5-3: Soil Moisture Content with Climate Change	92
Table 6-1: Annual Water Balance of Kelani Ganga (1966-1990).....	94
Table 6-2: Kelani Ganga Parameter & Error Values of Flow(1966-1990)	96
Table 6-3: Annual Water Balance of Kelani Ganga (1990-2014).....	99
Table 6-4: Kelani Ganga Parameter & Error Values of Flow (1990-2014).....	101
Table 6-5: Annual Water Balance of Gin Ganga (1972-1992)	104
Table 6-6: Gin Ganga Parameter & Error Values of Flow (1972-1992).....	106
Table 6-7: Annual Water Balance of Gin Ganga (1922-2012)	109
Table 6-8: Gin Ganga Parameter & Error Values of Flow (1992-2012).....	111
Table 6-9: Annual Rainfall (mm/year)	113
Table 6-10: Monthly Rainfall (mm/month)	113
Table 6-11: Seasonal Rainfall (mm/season)	113
Table 6-12: Annual Streamflow (mm/year).....	114
Table 6-13: Monthly Streamflow (mm/month).....	114

Table 6-14: Seasonal Streamflow (mm/season).....	114
Table 6-15: Annual Pan Evaporation (mm/year)	115
Table 6-16: Monthly Pan Evaporation (mm/month)	115
Table 6-17: Seasonal Pan Evaporation (mm/season)	115
Table 6-18: Annual Soil Moisture (mm/year).....	116
Table 6-19: Monthly Soil Moisture (mm/month).....	116
Table 6-20: Seasonal Soil Moisture (mm/season) (Calibration)	116
Table 6-21: Seasonal Soil Moisture (mm/season) (Verification).....	117
Table 6-22: Annual Actual Evaporation (mm/year).....	117
Table 6-23: Monthly Actual Evaporation (mm/month).....	117
Table 6-24: Seasonal Actual Evaporation (mm/season) (Calibration)	117
Table 6-25: Seasonal Actual Evaporation (mm/season) (Verification).....	118
Table 6-26: Annual Water Balance (mm/year)	118
Table 6-27: Comparison of Optimized Parameters	119
Table 6-28: Comparison of Error Estimations	119

LIST OF ABBREVIATIONS

Abbreviation	Description
c	Parameter c
C	Runoff Coefficient
CC	Climate Change
DSD	Divisional Secretary Divisions
E	Nash–Sutcliffe coefficient
E (t)	Actual Evapotranspiration
EP (t)	Pan Evaporation
GCM	Global Circulation Model
IM1	Inter Monsoon 1
IPCC	Intergovernmental Panel on Climate Change
K	Pan Coefficient
MAR	Mean Annual Rainfall
MRAE	Mean Ratio of Absolute Error
MSE	Mean Square Error
NEM	North East Monsoon
P (t)	Rainfall
Q (t)	Runoff
RAEM	Ratio of Absolute Error to Mean
RE	Relative Error
RMSE	Root Mean Square Error
S (t)	Soil Moisture Content
SC	Field capacity of the catchment
SWM	South West Monsoon
TPMWBM	Two Parameter Monthly Water Balance Model
WMO	World Meteorological Organization