DOI :10.31357/fapsmph.2005.00572

Forecasting Physical, Chemical and Biological Water Quality Parameters of Kotmale, Victoria, Randenigala and Rantambe Reservoirs Using DYRESM-CAEDYM Model

by

Karandagolle Gedara Abeysinghe Mudiyanselage
Chandana Sanjeewa Abeysinghe

Thesis submitted to the University of Sri Jayewardenepura for the award of the Degree of Master of Philosophy in Zoology on 2005.

DECLARATION

The work described in this thesis was carried out by me under the supervision of Prof. S. Piyasiri and Prof. K.D.W. Nandalal and a report on thesis has not been submitted in whole or in part to any University or any other institution for another Degree/Diploma.

.... 01/10/07

Signature of the candidate Date

We certify that the above statement made by the candidate is true and that this thesis is suitable for submission to the University for the purpose of evaluation.

.... Signature

05/10/07 .... Date

.... Signature

01/10/07 .... Date

Prof. S. Piyasiri
Department of Zoology,
University of Sri Jayewardenepura,
Nugegoda, Sri Lanka.

Prof. K.D.W. Nandalal
Department of Civil Engineering,
University of Peradeniya,
Peradeniya, Sri Lanka.

DEDICATION

TO

MY PARENTS

AND

MY WIFE

CONTENTS

CONTENTS i

LIST OF TABLES v

LIST OF FIGURES vii

ABBREVIATIONS xi

ACKNOLEDGEMENTS xii

ABSTRACT xiii

1 INTRODUCTION 1

1.1 Processes in Reservoirs and their Modelling 3

1.2 Water Quality Considerations in Reservoir Management 7

1.2.1 Water Use and Water Quality 8

1.2.2 Treatment and Control Techniques 10

1.3 Objectives of the Study 11

1.4 Description of the Study Area 12

1.4.1 Kotmale Reservoir 12

1.4.2 Victoria Reservoir 16

1.4.3 Randenigala Reservoir 20

1.4.4 Rantambe Reservoir 24

1.5 Description of the Model 26

1.5.1 Hydrodynamic model 26

1.5.2 Ecological model 28

1.5.3 Input Requirements 29

1.5.4 Model Output 31

2 LITERATURE REVIEW 32

2.1 Stratification of Lakes and Reservoirs 32

2.2 Reservoir modeling 34

2.3 Operations of Reservoirs for Quality Control 43

3 METHODOLOGY 50

3.1 Data collection 50

3.2 Reservoir simulation model DYRESM-CAEDYM 51

3.3 Estimation of Short wave Radiation 51

3.4 Estimation of Daily inflow temperature 52

3.5 Model Calibration and Verification 52

3.6 Statistical Analysis 53

3.7 Impact of Releases on Reservoir Water Quality 54

4 RESULTS 55

4.1 Model Calibration, Verification and Application for the Kotmale Reservoir 55

4.1.1 Calibration of the DYRESM 55

4.1.1.1 Reservoir mass balance 56

4.1.1.2 Water Temperature 56

4.1.1.3 Sensitivity analysis 59

4.1.2 Verification of the DYRESM 61

4.1.2.1 Water Temperature 61

4.1.3 Calibration of the DYRESM-CAEDYM 64

4.1.3.1 Nitrate 66

4.1.3.2 Ammonia 66

4.1.3.3 Orthophosphorus 69

4.1.3.4 pH 69

4.1.3.5 Dissolved Oxygen 72

4.1.3.6 Sensitivity analysis 72

4.1.4 Verification of the DYRESM-CAEDYM 74
4.1.4.1 Nitrate 74
4.1.4.2 Ammonia 74
4.4.4.3 Orthophosphorus 77
4.1.4.4 pH 77
4.1.4.5 Dissolved Oxygen 80
4.1.5 Application of the model 82
4.1.5.1 Simulation of understanding stratification cycle 82
4.1.5.2 Simulation of impact of the withdrawal quantity 84
4.1.5.3 Simulation of impact of the withdrawal level 85
4.2 Model Calibration and Verification for the Victoria Reservoir 92
4.2.1 Calibration of the DYRESM 92
4.2.1.1 Reservoir mass balance 92
4.2.1.2 Water Temperature 93
4.2.2 Verification of the DYRESM 96
4.2.2.1 Water Temperature 96
4.2.3 Application of the model 99
4.2.3.1 Simulation of understanding stratification cycle 99
4.2.3.2 Simulation of impact of the withdrawal quantity 100
4.2.3.3 Simulation of impact of the withdrawal level 100
4.3 Model Calibration and Verification for the Randenigala Reservoir 103
4.3.1 Calibration of the DYRESM 103
4.3.1.1 Reservoir mass balance 103
4.3.1.2 Water Temperature 104
4.3.2 Verification of the DYRESM 107
4.3.2.1 Water Temperature 107
4.3.3 Application of the model 110
4.3.3.1 Simulation of understanding stratification cycle 110
4.3.3.2 Simulation of impact of the withdrawal quantity 111
4.3.3.3 Simulation of impact of the withdrawal level 111

4.4 Model Calibration and Verification for the Rantambe Reservoir 114

4.4.1 Calibration of the DYRESM 114

4.4.1.1 Reservoir mass balance 114

4.4.1.2 Water Temperature 115

4.4.2 Verification of the DYRESM 118

4.4.2.1 Water Temperature 118

4.4.3 Application of the model 121

4.4.3.1 Simulation of understanding stratification cycle 121

4.4.3.2 Simulation of impact of the withdrawal quantity 122

4.4.3.3 Simulation of impact of the withdrawal level 122

5 DISCUSSION 123

6 CONCLUSIONS 129

7 REFERENCES 132

8 APPENDICES

APPENDIX 1: LIST OF PUBLICATIONS 144

APPENDIX 2: DYRESM Model 146

APPENDIX 3: CAEDYM Model 165

LIST OF TABLES

1.1	General and morphometric characteristics and Physico-chemical data of the Kotmale reservoir	14
1.2	Average monthly climatological elements of the Kotmale reservoir for the period 1990-1999	15
1.3	General and morphometric characteristics and Physico-chemical data of the Victoria reservoir	18
1.4	Average monthly climatological elements of the Victoria reservoir for the period 1992-1999	19
1.5	General and morphometric characteristics and Physico-chemical data of the Randenigala reservoir	22
1.6	Average monthly climatological elements of the Randenigala reservoir for the period 1993-2000	23
1.7	General and morphometric characteristics and physico-chemical data of the Rantambe reservoir	25
4.1	Hydraulic and thermal parameters specified as Kotmale reservoir model (DYRESM) input	55
4.2	Goodness-of-fit statistics between observed and simulated temperatures during the calibration period for the Kotmale reservoir	59
4.3	Goodness-of-fit statistics between observed and simulated temperatures during the verification period for the Kotmale reservoir	62
4.4	Rate coefficients used in the water chemistry simulations and specified as Kotmale reservoir model (CAEDYM) input	64
4.5	Hydraulic and thermal parameters specified as Victoria reservoir model (DYRESM) input	92
4.6	Goodness-of-fit statistics between observed and simulated temperatures during the calibration period for the Victoria reservoir	94

4.7	Goodness-of-fit statistics between observed and simulated temperatures during the verification period for the Victoria reservoir	97
4.8	Hydraulic and thermal parameters specified as Randenigala reservoir model (DYRESM) input	103
4.9	Goodness-of-fit statistics between observed and simulated temperatures during the calibration period for the Randenigala reservoir	105
4.10	Goodness-of-fit statistics between observed and simulated temperatures during the verification period for the Randenigala reservoir	108
4.11	Goodness-of-fit statistics between observed and simulated temperatures during the calibration period for the Rantambe reservoir	116
4.12	Goodness-of-fit statistics between observed and simulated temperatures during the verification period for the Rantambe reservoir	119

LIST OF FIGURES

1.1	Sampling stations and major inflowing rivers of the Kotmale reservoir	12
1.2	Sampling stations and major inflowing rivers of the Victoria reservoir	16
1.3	Sampling stations and major inflowing rivers of the Randenigala reservoir	20
1.4	Sampling stations and major inflowing rivers of the Rantambe reservoir	24
4.1	Observed and simulated reservoir level in the Kotmale reservoir at St 1 during calibration	56
4.2	Observed and Simulated near-surface and near-bottom water temperatures in the Kotmale reservoir at St 1 during calibration	57
4.3	Measured and simulated vertical profiles of water temperature at Kotmale reservoir St 1, during 1995.	58
4.4	Sensitivity analysis of DYRESM parameters, mean albedo of water, emissivity of a water surface and light extinction coefficient based on temperature profiles on 21/3/1995, 3/6/1995, 25/9/1995 and 28/12/1995.	60
4.5	Measured and simulated near-surface and near-bottom water temperatures in the Kotmale reservoir at St 1 during the verification period.	61
4.6	Measured and simulated vertical profiles of water temperature at Kotmale reservoir St 1, during 1996.	63
4.7	Measured and simulated vertical profiles of nitrate concentrations at Kotmale reservoir St 1, during 1995.	67
4.8	Measured and simulated vertical profiles of NH_4 at Kotmale reservoir St 1, during 1995.	68
4.9	Measured and simulated vertical profiles of Orthophosphorus at Kotmale reservoir St 1, during 1995.	70

4.10 Measured and simulated vertical profiles of pH at Kotmale reservoir St 1, during 1995. 71

4.11 Measured and simulated vertical profiles of dissolved oxygen concentrations at Kotmale reservoir St 1, during 1995. 73

4.12 Measured and simulated vertical profiles of nitrate concentrations at Kotmale reservoir St 1, during 1996. 75

4.13 Measured and simulated vertical profiles of NH_4 at Kotmale reservoir St 1, during 1996. 76

4.14 Measured and simulated vertical profiles of Phosphorus concentrations at Kotmale reservoir St 1, during 1996. 78

4.15 Measured and simulated vertical profiles of pH at Kotmale reservoir St 1, during 1996. 79

4.16 Measured and simulated vertical profiles of dissolved oxygen concentrations at Kotmale reservoir St1, during 1995. 81

4.17 Distribution of water temperature in the Kotmale reservoir St 1, from January 1997 to December 1999: (a) Historical operation, (b) Release quantity reduced, and (c) Release from outlets at different levels. 86

4.18 Distribution of nitrate concentrations in the Kotmale reservoir St 1, from January 1997 to December 1999: (a) Historical operation, (b) Release quantity reduced, and (c) Release from outlets at different levels. 87

4.19 Distribution of ammonia concentrations in the Kotmale reservoir St 1, from January 1997 to December 1999: (a) Historical operation, (b) Release quantity reduced, and (c) Release from outlets at different levels. 88

4.20 Distribution of orthophosphate concentrations in the Kotmale reservoir St 1, from January 1997 to December 1999: (a) Historical operation, (b) Release quantity reduced, and (c) Release from outlets at different levels. 89

4.21 Distribution of pH values in the Kotmale reservoir St 1, from January 1997 to December 1999: (a) Historical operation, (b) Release quantity reduced, and (c) Release from outlets at different levels. 90

4.22 Distribution of dissolved oxygen concentrations in the Kotmale reservoir St 1, from January 1997 to December 1999: (a) Historical operation, (b) Release quantity reduced, and (c) Release from outlets at different levels. 91

4.23 Observed and simulated reservoir level in the Victoria reservoir at St 2 during calibration 93

4.24 Measured and simulated vertical profiles of water temperature at Victoria reservoir St 2, during 1995. 95

4.25 Measured and simulated vertical profiles of water temperature at Victoria reservoir St 2, during 1996. 98

4.26 Distribution of water temperature in the Victoria reservoir St 2, from January 1997 to December 1999: (a) Historical operation, (b) Release quantity reduced, (c) Release quantity deduced, and (d) Release from outlets at different levels. 102

4.27 Observed and simulated reservoir level in the Randenigala reservoir at St3 during calibration 104

4.28 Measured and simulated vertical profiles of water temperature at Randenigala reservoir St 3, during 1995. 106

4.29 Measured and simulated vertical profiles of water temperature at Randenigala reservoir St 3, during 1996. 109

4.30 Distribution of water temperature in the Randenigala reservoir St 3, from January 1997 to December 1999: (a) Historical operation, (b) Release quantity reduced, (c) Release quantity deduced, and (d) Release from outlets at different levels. 113

4.31 Observed and simulated reservoir level in the Rantambe reservoir at St 1 during calibration 114

4.32 Measured and simulated vertical profiles of water temperature at Rantambe reservoir 117

4.33 Measured and simulated vertical profiles of water temperature at Rantambe reservoir St 1, during 1996. 120

4.34 Distribution of water temperature in the Rantambe reservoir St 1, from January 1997 to December 1999: (a) Historical operation, (b) Release quantity reduced, and (c) Release from outlets at different levels. 123

A-3.1 Relationship between the main state variables, shown in boxes, and the biochemical processes represented in the model. 165

A-3.2 Inverted Michaelis-Menton limitaiton function 168

ABBREVIATIONS

NH_4	-	Ammonia
CAEDYM	-	Computational Aquatic Ecosystem DYnamics Model)
DO	-	Dissolved Oxygen
DYRESM	-	DYnamic REservoir Simulation Model
EWS	-	Emissivity of a water surface
LEC	-	Light extinction coefficient
MARE	-	Mean absolute relative error
MAW	-	Mean albedo of water
NO_3	-	Nitrate
PO_4	-	Orthophosphorus
RMSE	-	Root mean squared error

ACKNOWLEDGEMENTS

I am most grateful to Prof. S. Piyasiri and Prof. K.D.W. Nandalal for providing the opportunity for me to carry out the present study under their supervision. I very much appreciate their excellent advice, enthusiastic guidance and continuous encouragement given towards the successful completion of this study. Their valuable suggestions and constructive criticism during the course of the study were invaluable.

I wish to thank University of Sri Jayewardenepura and National Science Foundation, Sri Lanka for providing financial assistance.

I would like to thanks Headworks Administration, Operation and Maintenance unit of the Mahaweli Authority of Sri Lanka and Natural Resource Management Center of the Department of Agriculture at Peradeniya, Sri Lanka for providing necessary data.

Special thanks go to Centre for Water Research, University of Western Australia for giving permission to use the DYRESM-CAEDYM model.

Finally, I wish to thank Mr. K.P.G.W. Senadeera for his encouragement and kind corporation.

Forecasting Physical, Chemical and Biological Water Quality Parameters of Kotmale, Victoria, Randenigala and Rantambe Reservoirs Using DYRESM-CAEDYM Model.

K.G.A.M.C.S. Abeysinghe

ABSTRACT

The Mahaweli is the longest river (335 km) in Sri Lanka with an annual discharge of 8878×10^6 m^3 of water into the sea. Several dams have been built across the river for the purpose of irrigation and hydroelectric power generation. The four major reservoirs of the "Accelerated Mahaweli Project" are Kotmale, Victoria, Randenigala and Rantambe.

Strong thermal stratification in a reservoir may result in oxygen depletion along the vertical profile downwards leading to their eutrophication. Several reservoirs in the Mahaweli Project experienced water quality linked problems in recent times. A one-dimensional reservoir hydrodynamic model DYRESM was calibrated and validated for the Kotmale, Victoria, Randenigala and Rantambe reservoirs to predict water level, temperature, salinity and density in it. Calibration and validation are strengthened by calculating several goodness-of-fit statistics. After calibration and verification of hydrodynamic model DYRESM for the Kotmale reservoir, it was coupled with ecological model CAEDYM. The coupled model DYRESM-CAEDYM simulates water level, temperature, salinity, density and 5 water quality constituents (NO_3, NH_4, PO_4, pH, and DO).

The model enables the prediction of thermal stratification and water quality in the reservoir body using data that can be collected easily, such as climatological data and reservoir inflow quantity and quality. This can minimize huge cost involved in monitoring water quality in the reservoir body.

The calibrated and verified hydrodynamic model (DYRESM) was used to run different operational scenarios which useful to make decisions for improving water quality in the Mahaweli reservoirs (Kotmale, Victoria, Randenigala and Rantambe). Simulations were developed to evaluate the stratification cycle during a period of 3 years; impact of the withdrawal quantity on stratification; and simulations also were developed to assess the impact of the withdrawal level on stratification.

The three year long (1997-1999) simulations of Kotmale, Victoria, Randenigala and Rantambe reservoirs showed that the annual cycle of stratification clearly. Thermal stratification is strong during the relatively warm period of March-August in all the three years. Thermal stratification in a reservoir determines the water quality in it and thus the model enables predicting adverse effects with respect to water quality in the reservoir. Thermal stratification and other water quality are affected by the change in the release quantity. When release was decreased by 25% for the period of three month (at the onset of stratification period) in all the three years, reservoir stratification has slightly decreased and thus DO concentration has slightly improved in the Kotmale reservoir. However, the improvement in the reservoir during the warm period is trivial. Victoria, Randenigala and Rantambe reservoirs follow the same results with the same operation. The outlet elevation affects the thermal stratification and water quality in the reservoir. When water is released through both outlets (upper outlet 75% of water and lower one 25% of water) for the period of three month (during the onset of stratification period), the thermocline has becomes deeper. The surface temperature and other water quality have not changed, but the bottom water quality has improved considerably. This suggests the possibility to change the strong stratification in the Kotmale, Victoria, Randenigala and Rantambe reservoirs by manipulating the releases.

Reservoir managers will be able to take precautionary measures by controlling stratification in the reservoir by manipulating withdrawals. The study, based on two different withdrawal patterns, shows that stratification in these reservoirs could be altered by manipulating the withdrawal. Thus, the impact of many alternative operational patterns on thermal stratification in the reservoir could be studied with the help of the model in advance to avoid adverse water quality conditions in the reservoir as well as supplied from the reservoir.

Results from this study will provide reservoir management with information to better understand how changes in hydrology and water quality in the basin affects water quality in the reservoir. With this information, managers will be able to more effectively manage their reservoirs.