

TOWARDS AN INTEGRATED POLLUTION MANAGEMENT APPROACH FOR THE BURIGANGA RIVER IN BANGLADESH

**A thesis submitted in fulfilment of the requirements for the degree of
Doctor of Philosophy**

By

Md. Ashiqur Rahman

BScCivilEngg, MEnvEngg (BUET), MEnvMgt&Dev (ANU)



THE UNIVERSITY OF
SYDNEY

**Faculty of Agriculture, Food and Natural Resources
The University of Sydney, Australia**

March 2011

Declaration

This thesis contains no material which has been accepted for the award of any other degree or diploma at any university and that to the best of my knowledge and belief, it contains no material previously published or written by another person, except where due reference is made in the text of the thesis.

I give consent for this copy of my thesis to be available for loan and photocopying when deposited in the University Library.

Md. Ashiqur Rahman
Sydney, 30 March, 2011

*I dedicate this work to my dear parents who have been strongly encouraging
and eagerly awaiting to see the success of my studies.*

Acknowledgements

First of all, I would like to express my sincerest gratitude to my Principal Supervisor, Dr Tihomir Ancev (Senior Lecturer in Resource and Environmental Economics, University of Sydney) for his endless support and encouragement during my research candidacy. His scholarly advice especially for the economics part of this research and his thoughtful comments on the draft chapters is greatly acknowledged.

I am indeed thankful to my Associate Supervisor Dr AKM Mostafizur Rahman (Senior Quarantine Officer, Department of Agriculture, Fisheries and Forestry, NSW, Australia) for his valuable suggestions and help on the study of water quality and feedback on the draft chapters. I also appreciate the help provided by my other Associate Supervisor Dr Md. Abdul Khaleque (Assistant Professor, Independent University, Bangladesh) especially during the stages of sampling and testing of water samples in Bangladesh. My special thanks also go to my former supervisor Dr Dhia Al Bakri (Ex-Senior Lecturer in Environmental Management, University of Sydney) for his intellectual support and cooperation in initiating and designing this research project.

I would like to offer my sincere gratitude to many other learned persons who provided their kind help on technical and analytical issues during different phases of this work. I am especially indebted to the following people: Professor Donald Burn (Department of Civil and Environmental Engineering, University of Waterloo, Canada) for calculating oxygen transfer coefficients; Professor Gary Merkley (Biological and Irrigation Engineering, Utah State University, USA) for reviewing and suggesting on my draft chapters; Mr Steven Schauer (San Antonio River Authority, Texas, USA) and Mr Brian Mast (San Antonio River Authority, Texas, USA) for the detailed demonstration on San Antonio River management systems, which was a fruitful learning experience for me; and Mr James Daniel (John Morris Scientific Private Ltd., NSW, Australia) for providing necessary technical support on YSI field analyser.

Special thanks also go to a number of people in Bangladesh who provided tremendous help during my field work. These people furnished relevant information, documents and

data for the study as well as provided moral support and guidance during the research work when it was needed most. I want to express my gratitude to all these distinguished people by mentioning their names: Dr Mizan R Khan (Department of Environmental Science and Management, North South University); Dr Gour Goswami (Department of Economics, North South University); Dr Md Delwar Hossain, Dr ABM Badruzzaman, Dr Md. Mujibur Rahman, Dr Rezaur Rahman, Dr Tarekul Islam and Dr Saiful Amin from Bangladesh University of Engineering and Technology (BUET); Mr Md. Ziaul Haque and Mr Syed Nazmul Ahsan from the Department of Environment (DOE); Dr Nasir Uddin Khan (Adroit Environment Consultants Ltd.); Dr Md. Liakath Ali and Engr. Md. Serajuddin of Dhaka Water Supply and Sewerage Authority (DWASA); Engr. Abu Saleh Khan, Engr. Mir Mostafa Kamal and Engr. Tarun Kanti Magumdar from the Institute of Water Modelling (IWM).

I take this opportunity to thank Prof Mark Adams, Prof John Crawford, Prof Ivan Kennedy, Dr Willem Vervoort, Dr Edith Lees, Dr Damien Field, Dr Shyamal Chowdhury, Dr Inakwu Odeh, Ms Pamela Stern, Ms Fortunee Cantrell, Ms Clare Higgins, Mr Arnold Lai and Mr Kyle Kiefer from the Faculty of Agriculture, Food and Natural Resources of the University of Sydney for their academic and administrative support during the course of this study. I also appreciate the assistance provided by the office of the Information and Communications Technology (ICT) and the International Office at the University of Sydney. My sincerest acknowledgement goes to Mr Adrian Cardinali from the Sydney University Postgraduate Representative Association (SUPRA) for his tireless efforts, which helped me to overcome the difficulties during my candidature.

I will never forget the contribution of Dr Lyn Riddett for her constructive comments, intellectual advice and moral support during the most difficult time of my candidature. My grateful thanks also go to my colleagues and many family friends and well wishers, particularly Dr Tarik Zaman, Dr Anowarul Bokshi, Andres, Dia, Floris, Claire, Peter, Samad and Saana for their support, encouragement and friendship on many occasions during the journey of my research work in Australia.

My acknowledgement also goes to the Australian Agency for International Development (AusAID) for offering me the prestigious Australian Leadership Award (ALA) with

which to conduct this study. I convey my thanks to Ms Rebecca Scott (AusAID Coordinator) for her support and assistance. I am also thankful to the North South University (NSU) Foundation and to the Authority for granting me a long study leave to carry out this research work.

I deeply recognize the sacrifice of my family during the last four years of my study. I express my love and affection for my son Ahnaf and my daughter Nafeesa, whose innocent faces sensitised me to the issue, to provide a pollution free world for the coming generations. Most importantly, my heartiest appreciations go to my beloved wife Sonia Saadullah for her constant support, encouragement during this research work and editorial assistance, which shaped the thesis writing. This journey would never have been possible without my family's wholehearted daily support and care. I am also grateful to my parents, brothers and the extended family for their unconditional love, affection and constant prayers, as well as to my in-laws for their continuous inspiration and good wishes.

Finally, I want to express my gratitude to Almighty Allah the most righteous and the most merciful, Who has provided me the strength and the capability to complete this research project successfully and within time limits.

Abstract

Water pollution management in the Buriganga River, which encompasses the southwestern periphery of the capital city Dhaka, has been a major concern for the Government of Bangladesh at least for the last two decades. Several policies based on direct regulatory measures have been adopted by the government in different times to address this issue. In spite of this, no significant improvement in the river water quality has been achieved. In addition, an updated, detailed and systematic analysis of water quality along the full length of the river has not been conducted for some time.

Hence, this research aimed to postulate a new management system to control pollution in the Buriganga River based on a recently conducted qualitative and quantitative assessment of river water and wastewater that are discharged into the river. The study also aimed to evaluate the existing system for river pollution control and to determine the economic costs that are likely to result under alternative policy instruments for pollution mitigation, such as, uniform reduction, uniform taxes and tradable permit system. In the study, a conceptual framework was recommended for an integrated pollution management approach in the Buriganga River.

The river water quality was found to be unacceptable (as per the standards set by the Department of Environment in Bangladesh) for the parameters such as dissolved oxygen (DO), biochemical oxygen demand on five days (BOD₅), chemical oxygen demand (COD), ammonia-nitrogen (NH₃-N) and chromium (Cr) during both dry (low flow condition) and wet (high flow condition) seasons and for electrical conductivity in water (EC_w) during only dry season. For the river water, the average concentration of DO ranges between 0.9 mg/L in dry and 2.8 mg/L in wet season, BOD₅ between 34.5 mg/L in dry and 2.5 mg/L in wet season, COD between 60.1 mg/L in dry and 17.2 mg/L in wet season, EC_w between 661 μS/cm in dry and 83 μS/cm in wet season, NH₃-N between 4.1 mg/L in dry and 3.3 mg/L in wet season, Cr between 0.06 mg/L in dry and 0.07 mg/L in wet season. Temperature, pH, phosphate-phosphorus (PO₄-P) and lead (Pb) were found within the DOE acceptable limits in both dry and wet seasons. Moreover, along the length of the river, relatively higher ambient concentration of BOD₅, COD, NH₃-N and Cr was

observed at Kholamora station for both dry and wet seasons compared to four other selected stations (receptor points) along the river.

The study established that the water of the Buriganga River is polluted by a combination of wastewater from both municipal and industrial sources, located within its basin area, which are discharged through three main drainage channels. The wastewater was found hypoxic to anoxic in most cases associated with very high concentration of BOD₅, COD, EC_w, Cr and NH₃-N compared to the guidelines. For the incoming wastewater, the minimum and the maximum average concentration (including three major discharge points) of BOD₅ ranges between 251.0 to 1003.4 mg/L, COD between 378.9 to 1261.1 mg/L, EC_w between 458.9 to 3939.3 μ S/cm, Cr between 0.02 to 13.3 mg/L and NH₃-N between 4.1 to 83.5 mg/L throughout the year. The average BOD₅ pollution loading rates for the three major discharge points at Rayerbazar sluice gate, Shahidnagar drainage outlet and Pagla Sewage Treatment Plant (PSTP) effluent outfall were estimated as 83, 71 and 32 tons/day respectively.

The study identified that the existing command and control (CAC) based regulatory approaches to pollution management for the Buriganga River are not functioning effectively. The compliance and enforcement of these regulatory measures are not satisfactory, which contributes to continuing pollution problems. The present pollution control measures do not provide any economic incentives for pollution prevention and adoption of new technologies. Despite the provisions made within the national policies, no specific role has been outlined to ensure the effective contribution of Non-Government Organisations/Community Based Organisations for pollution control. However, the current study found that the local community is willing, and has the potential, to directly participate in the pollution control process of this river.

The research used a spreadsheet based decision support tool in order to conduct a simulation exercise for evaluating the economic efficiency of the several alternative pollution abatement policies, while meeting specific water quality targets. The method generated empirical estimates on costs of BOD₅ reduction from three major discharge points in the Buriganga River using three alternative policies. The results from the simulation exercise showed that application of the approaches based on economic incentives (uniform tax or tradable permit system) could achieve significant cost savings

(up to about 50 per cent) for BOD₅ pollution control in the Buriganga River in contrast to the CAC based approach (uniform reduction system). Further, considering the prerequisites for the tradable permit system and the marginal difference of economic benefit to be gained from this system compared to the uniform tax system, it is recommended that at this stage the uniform pollution tax system with revenue recycling should be considered as an effective alternative policy for water quality improvement in the Buriganga River.

Finally, through this interdisciplinary study a conceptual framework of an integrated pollution management system for the Buriganga River was developed taking into account the state of water quality, the weaknesses encountered in the present system, the empirical evidence of the potential benefits from economic incentive based approaches to regulating pollution and from the experiences of river pollution management in other countries. The integrated management framework was recommended by combining appropriate pollution control instruments which encourages coordination of different stakeholders, public participation and application of economic incentive based measures. The proposed new approaches (economic incentive and community involvement) do not replace the present regulatory measures (particularly the ambient water quality standards) but they rather complement them.

The research also proposed a set of policy initiatives that should be implemented within the integrated management framework. It would necessitate legislative changes to incorporate a legal basis for pollution taxing. The legal reform should incorporate the scope to vary the emission tax rate from time to time and/or to impose strict regulations in short notice in case of emergency situation. In this context, legal agreements between polluters and regulatory authorities could be formed in order to ensure the proper collection of pollution taxes. The study also suggested the strengthening of organisational capacity at the cost of aborting the involvement of multiple government authorities, in favour of a single authority that would be invested with full power and responsibility for pollution control in the Buriganga River. Hence it was recommended that a *Buriganga River Management Authority* be established, to work under the supervision of the Ministry of Environment and Forests (MOEF). This agency could be assigned with legislative power and would hold sole responsibility to manage and coordinate all activities related to pollution control and conservation of the Buriganga River.

Moreover, the study noted the significant positive contributions of community participation and commitments towards managing the pollution problem of the Buriganga River and the catalytic role it could play. With this end in view, the proposed integrated approach recommended formulating a standard procedure and guideline for water quality monitoring by community groups to ensure ease and efficiency of their work. In addition, necessary training programs should be directed by experts in the field to equip in the community for this purpose. Giving the community a responsible role in monitoring and recording failures and improvements could provide the necessary focus of attention and impetus required to resolve the Buriganga River pollution problem. Application of economic incentive based instruments and continual disclosure of information were also recommended in the study. The study concluded that a sustainable pollution management system for the Buriganga River could be achieved by bringing together all the stakeholders concerned at a local level and by applying appropriate pollution control measures along with the suggested set of policies.

Publications and presentations from the thesis

- Rahman, M.A., 2010. 'An evaluation of river pollution control system in Bangladesh: moving towards an integrated approach', *Proceedings of the 11th APRU Doctoral Students Conference 2010*, 11-16 July 2010, Universitas Indonesia, Depok, Indonesia.
- Rahman, M.A. and Ancev, T., 2010. 'Possible application of economic incentives for water conservation: a case study on the Buriganga River, Bangladesh', *Proceedings of the International Conference on Knowledge Globalization-2010*, ISBN 978-984-33-1691-2, pp. 304-12, 8-10 May 2010, North South University, Dhaka, Bangladesh.
- Rahman, M.A., Ancev, T. and Al Bakri, D., 2010. 'Alternate management strategies for reduction of BOD along the river, Buriganga, Bangladesh', *Proceedings of the Water Management Conference 2010: Upgrading technology and infrastructure in a finance-challenged economy*, pp. 467-492, 23-26 March 2010, The U.S. Society for Irrigation and Drainage (USCID), Sacramento, California, USA.
- Rahman, M.A., and Al Bakri, D., 2010. 'A Study on Selected Water Quality Parameters along the River Buriganga, Bangladesh', *Iranica Journal of Energy and Environment*, vol. 1, no. 2, pp 81-92.
- Rahman, M.A., 2010. 'Pollution control in the river Buriganga, Bangladesh: CAC or EI based approach?', A poster presentation at the *Centenary Research Symposium*, 4th June 2010, Faculty of Agriculture, Food and Natural Resources (FAFNR), The University of Sydney, Australia.
- Rahman, M.A., 2009. 'A Review of Management Instruments for Water Pollution Control: sustainable options for the river Buriganga, Bangladesh', *The International Journal of Interdisciplinary Social Sciences*, vol. 3, no. 11, pp. 55-67.
- Rahman, M.A., 2009. 'Healthy existence of rivers for sustainable development: a case study on the river Buriganga, Bangladesh', An oral presentation at the *AusAID Annual Conference*, 27 November 2009, The University of Sydney, Australia.
- Rahman, M.A., Al Bakri, D. and Ancev, T., 2008. 'Towards a framework for integrated industrial effluent management system: a case study on the river Buriganga, Bangladesh', *Proceedings of the International Conference on Environment-2008*, 15-17 December 2008, Engineering Campus, Universiti Sains Malaysia, Penang, Malaysia.

Table of Contents

CONTENTS	PAGE
ACKNOWLEDGEMENTS	iv
ABSTRACT	vii
PUBLICATIONS AND PRESENTATIONS FROM THE THESIS	xi
TABLE OF CONTENTS	xii
LIST OF TABLES	xvii
LIST OF FIGURES	xviii
LIST OF APPENDICES	xxi
ABBREVIATIONS	xxiv
CHAPTER 1	1
INTRODUCTION	
1.1 Research background	1
1.2 Statement of the problem	2
1.3 Aim and objectives of the research	5
1.4 Components of the research project	6
1.5 Thesis structure	8
CHAPTER 2	10
LITERATURE REVIEW ON RIVER WATER QUALITY PARAMETERS AND POLLUTION MANAGEMENT POLICIES	
2.1 Purpose	10
2.2 Water quality parameters	10
2.3 Significance of selected water quality parameters	10
2.3.1 Temperature	10
2.3.2 pH	11
2.3.3 Dissolved oxygen	12

2.3.4 Biochemical oxygen demand	13
2.3.5 Chemical oxygen demand	14
2.3.6 Electrical conductivity	14
2.3.7 Heavy Metals: lead and chromium	15
2.3.8 Nutrients: ammonia nitrogen and phosphate phosphorus	16
2.4 Literature review on policy instruments for river pollution management	17
2.4.1 Command-and-Control based instruments	17
2.4.2 Economic incentive based instruments	21
2.5 Literature review on informal instruments for river pollution management	27
2.6 Comparison of alternative pollution control instruments	31
CHAPTER 3	33
CONTEXT OF POLLUTION IN THE BURIGANGA RIVER	
3.1 Purpose	33
3.2 Study area	33
3.2.1 Hydrodynamic features	33
3.2.2 Climatic condition	37
3.2.3 Drainage system	38
3.2.4 Socio-economic condition	39
3.3 Usefulness of the Buriganga River	41
3.3.1 Water supply	41
3.3.2 Inland water transportation	41
3.3.3 Cleaning and washing	42
3.3.4 Recreation	42
3.4 Sources and causes of pollution in the Buriganga River	43
3.4.1 Point sources	43
3.4.2 Non-point or diffuse sources	45
3.5 Water quality guideline values	46
3.6 Previous studies on the Buriganga River	47
3.6.1 Trend of water quality	48
3.6.2 Suggested measures for pollution management	52

CHAPTER 4	55
ANALYSIS OF WATER QUALITY AND POLLUTION LOADING IN THE BURIGANGA RIVER	
4.1 Introduction	55
4.2 Methodology	55
4.2.1 Sampling locations	55
4.2.2 In situ measurements and chemical analysis	56
4.2.3 Flow measurements for wastewater	59
4.2.4 Estimation of pollution load	60
4.2.5 Statistical analysis	60
4.3 Results and discussions on river water quality parameters	61
4.3.1 Temperature	61
4.3.2 pH	63
4.3.3 Dissolved oxygen	65
4.3.4 Biochemical oxygen demand	67
4.3.5 Chemical oxygen demand	69
4.3.6 Electrical conductivity	71
4.3.7 Heavy metals: lead and chromium	72
4.3.8 Nutrients: ammonia nitrogen and phosphate phosphorus	76
4.3.9 Correlation of river water quality parameters	79
4.4 Waste water quality	79
4.5 Flow rates of wastewater	83
4.6 Loading rates of BOD ₅ at discharge points	84
4.7 Transfer coefficients for discharge-receptor pairs	85
4.8 Conclusion	87
CHAPTER 5	89
A CRITICAL ANALYSIS ON THE EXISTING ARRANGEMENTS FOR RIVER POLLUTION MANAGEMENT IN BANGLADESH	
5.1 Purpose and approach	89
5.2 Provisions for pollution control within national policies	90

5.3 Legislative framework and discussions on existing pollution control approach	92
5.4 Organisational capacity	96
5.5 Enforcement status of regulations	100
5.6 Public participation	101
5.6.1 Applicability of public participation in Bangladesh context	102
5.6.2 Scope for public participation in the Buriganga River	104
5.7 Specific measures taken to date to save the Buriganga River	106
5.8 Attributes of the existing system in terms of SWOT	108
CHAPTER 6	112
ECONOMIC ANALYSIS ON ALTERNATIVE ABATEMENT POLICIES FOR BOD₅	
6.1 Introduction	112
6.2 Methodology for economic analysis	112
6.2.1 Estimation of BOD ₅ abatement costs	112
6.2.2 Abatement cost functions for BOD ₅	115
6.2.3 River water quality classification	115
6.2.4 Model development and spreadsheet simulation	116
6.3 Results and discussions on alternative pollution abatement policies	125
6.3.1 Uniform reduction system	125
6.3.2 Uniform emission tax system	126
6.3.3 Tradable ambient permit system	128
6.3.4 Comparison of alternative policies	129
CHAPTER 7	133
FORMULATION AND APPLICATION OF AN INTEGRATED MANAGEMENT FRAMEWORK	
7.1 Introduction	133
7.2 International experience on application of river pollution control measures	134

7.2.1 Tradable permits for Fox River, Wisconsin, USA	134
7.2.2 Stakeholder participation for San Antonio River, Texas, USA	135
7.2.3 Salinity trading scheme for Hunter River, Australia	136
7.2.4 Political resolution for Parramatta River, Australia	137
7.2.5 Integrated pollution control for Huangpu River, China	139
7.2.6 Action plan for Ganga River, India	140
7.3 Lessons learned from the international experience	142
7.4 Appropriate measures and policies for pollution control in the Buriganga River	144
7.4.1 Legislative changes	146
7.4.2 Strong organisational capacity	146
7.4.3 Community participation and commitment	148
7.4.4 Application of economic incentive based measure	149
7.4.5 Disclosure of information	149
7.5 Conceptual framework of the proposed integrated management approach	150
7.6 Conclusion	152
CHAPTER 8	153
CONCLUSION	
8.1 Major findings and conclusion	153
8.1.1 Introduction	153
8.1.2 Poor state of water quality in the Buriganga River	153
8.1.3 Excessive pollution loading in the Buriganga River	154
8.1.4 Current management system for river pollution control is inadequate	155
8.1.5 Pollution taxation with revenue recycling as a preferred policy instrument	156
8.1.6 Integrated approach with inclusion of various stakeholders	157
8.2 Limitations and scope of this research	158
8.3 Recommendations for further research and investigations	159
REFERENCES	161

LIST OF TABLES

Table 2.1 Comparison of selected alternative pollution control instruments	32
Table 3.1 Climatic condition of the study area	37
Table 3.2 Three main drainage zones of Buriganga River basin	39
Table 3.3 Occupation of the river bank side population	40
Table 3.4 Water and effluent quality guidelines (standards) of selected parameters for different uses as set by the DOE in Bangladesh	47
Table 3.5 Summary of water quality results for the Buriganga River during the dry period of 1994-95 for selected parameters	51
Table 4.1 Geographical position (latitude and longitude) of the sampling points	58
Table 4.2 Sampling dates and weather condition	58
Table 4.3 Test methods with detection limits and special equipments for chemical water quality parameters	59
Table 4.4 Correlation coefficients matrix for water quality parameters in the Buriganga River (n=50)	80
Table 4.5 Mean values with standard deviation of wastewater composition at different discharge points in the Buriganga River (n=10)	81
Table 4.6 BOD ₅ loading rate in the Buriganga River	84
Table 4.7 Average values of deoxygenation rate coefficient, K^i_1 and reaeration rate coefficient, K^{ij}_2 for different segments of the Buriganga River	87
Table 4.8 Dissolved oxygen transfer coefficients, d_{ij}	87
Table 5.1 Responsibilities of major government organisations for river pollution control	97
Table 5.2. Public participation and community consultation documents and guidelines in Bangladesh	103
Table 5.3 Recommendations of Task Force-2003 for river pollution control in Dhaka	107
Table: 5.4 Attributes of present pollution control system in Bangladesh	109

Table 6.1 Features to estimate the total abatement costs for BOD ₅ removal at different discharge points	113
Table 6.2 Grading of river water quality in terms of DO concentration	116
Table 6.3 Results from simulation exercise for uniform reduction system	126
Table 6.4 Results from simulation exercise for uniform emission tax system	127
Table 6.5 Results from simulation exercise for tradable ambient permit system	129
Table 8.1 Mean values of water quality parameters for the Buriganga River	154

LIST OF FIGURES

Figure 1.1 Components of the research project	7
Figure 2.1 Typical changes in DO downstream of a wastewater input to a river	13
Figure 3.1 The Buriganga River system	34
Figure 3.2 Buriganga River (a) water level, (b) surface water velocity and (c) discharge rate measured at Millbarak during 2005, 2006 and 2008	36
Figure 3.3 The historical trend of (a) DO and (b) BOD levels in Buriganga River at three different locations	50
Figure 4.1 (a) A satellite map showing water sampling points in Buriganga River (b) A schematic diagram (with chainage distance) of the sampling points	57
Figure 4.2 Illustration of a box-and-whisker plot	61
Figure 4.3 Spatial and seasonal variation of mean values of temperature compared to the DOE standard in Buriganga River water (2008-2009)	63
Figure 4.4 Box-and-whisker plot showing statistics on temperature of Buriganga River water for different sites and seasons (2008-2009)	63
Figure 4.5 Spatial and seasonal variation of mean values of pH compared to the DOE standard in Buriganga River water (2008-2009)	64
Figure 4.6 Box-and-whisker plot showing statistics on pH level of Buriganga River water for different sites and seasons (2008-2009)	64

Figure 4.7 Spatial and seasonal variation of mean values of dissolved oxygen compared to the DOE standard in Buriganga River water (2008-2009)	66
Figure 4.8 Box-and-whisker plot showing statistics on dissolved oxygen level of Buriganga River water for different sites and seasons (2008-2009)	66
Figure 4.9 Spatial and seasonal variation of mean values of Biochemical Oxygen Demand compared to the DOE standard in Buriganga River water (2008-2009)	68
Figure 4.10 Box-and-whisker plot showing statistics on biochemical oxygen demand of Buriganga River water for different sites and seasons (2008-2009)	68
Figure 4.11 Spatial and seasonal variation of mean values of chemical oxygen demand compared to the DOE standard in Buriganga River water (2008-2009)	70
Figure 4.12 Box-and-whisker plot showing statistics on chemical oxygen demand of Buriganga River water for different sites and seasons (2008-2009)	70
Figure 4.13 Spatial and seasonal variation of mean values of electrical conductivity compared to the DOE standard in Buriganga River water (2008-2009)	72
Figure 4.14 Box-and-whisker plot showing statistics on electrical conductivity of Buriganga River water for different sites and seasons (2008-2009)	72
Figure 4.15 Spatial and seasonal variation of mean values of lead compared to the DOE standard in Buriganga River water (2008-2009)	73
Figure 4.16 Box-and-whisker plot showing statistics on lead concentration of Buriganga River water for different sites and seasons (2008-2009)	74
Figure 4.17 Spatial and seasonal variation of mean values of chromium compared to the DOE standard in Buriganga River water (2008-2009)	75
Figure 4.18 Box-and-whisker plot showing statistics on chromium concentration of Buriganga River water for different sites and seasons (2008-2009)	75
Figure 4.19 Spatial and seasonal variation of mean values of ammonia nitrogen compared to the DOE standard in Buriganga River water (2008-2009)	77

Figure 4.20 Box-and-whisker plot showing statistics on ammonia nitrogen concentration of Buriganga River water for different sites and seasons (2008-2009)	77
Figure 4.21 Spatial and seasonal variation of mean values of phosphate phosphorus compared to the DOE standard in Buriganga River water (2008-2009)	78
Figure 4.22 Box-and-whisker plot showing statistics on phosphate phosphorus concentration of Buriganga River water for different sites and seasons (2008-2009)	78
Figure 4.23 Flow rates of waste water at different discharge points	83
Figure 4.24 Estimated loading rate of BOD ₅ in the Buriganga River	84
Figure 5.1 Comparison between national and regional (Dhaka district) (a) average per capita annual income; (b) literacy rate	102
Figure 5.2 Media (The Daily Star) coverage on Buriganga River water quality issue	105
Figure 6.1 Total abatement costs (TAC) for different percentage of BOD ₅ removal at three discharge points	114
Figure 6.2 Elements of the decision support model for economic assessment of alternative BOD ₅ abatement policies	117
Figure 6.3 An example of EXCEL spreadsheet for uniform reduction system	119
Figure 6.4 An example of EXCEL spreadsheet for uniform emission tax system	121
Figure 6.5 An example of EXCEL spreadsheet for tradable ambient permit system	124
Figure 6.6 An example of sensitivity report from EXCEL solver	124
Figure 6.7 Summary results to compare the economic efficiency of different abatement policies (in logarithmic scale)	130
Figure 7.1 Conceptual framework and elements of the integrated management approach for pollution control in the Buriganga River	147

LIST OF APPENDICES

APPENDIX A: Context of pollution	193
Table A.1 Hydrological data on Buriganga River (measured at Millbarak)	193
Plate A.1 Different uses of Buriganga River water (a) Cleaning chemical containers (b) Cleaning polythene bags (c) Washing clothes (d) Bathing by riverside dwellers	194
Plate A.2 Hanging houses and latrines on the Buriganga River	195
Plate A.3 Disposing household garbage on the banks of the Buriganga River	195
APPENDIX B: Public awareness and media coverage	196
Plate B.1 Save water movement in the Buriganga River	196
Plate B.2 Save the Buriganga Movement, Bangladesh Paribesh Andolon and Nirbheek jointly organise a human chain on a boat on the Buriganga River in Swarighat area demanding steps to save rivers	196
Table B.1 to B.8 Year-wise titles of media reports on the Buriganga River water quality issue (covered by the Daily Star-a leading English daily newspaper in Bangladesh)	197
APPENDIX C: Descriptive statistics of river water quality data	204
Table C.1 Descriptive statistics for temperature	204
Table C.2 Descriptive statistics for pH	205
Table C.3 Descriptive statistics for DO	206
Table C.4 Descriptive statistics for BOD ₅	207
Table C.5 Descriptive statistics for COD	208
Table C.6 Descriptive statistics for EC _w	209
Table C.7 Descriptive statistics for Pb	210
Table C.8 Descriptive statistics for Cr	211
Table C.9 Descriptive statistics for NH ₃ -N	212
Table C.10 Descriptive statistics for PO ₄ -P	213

APPENDIX D: ANOVA results for river water quality data	214
Table D.1 ANOVA results for temperature	214
Table D.2 ANOVA results for pH	215
Table D.3 ANOVA results for DO	216
Table D.4 ANOVA results for BOD ₅	217
Table D.5 ANOVA results for COD	218
Table D.6 ANOVA results for EC _w	219
Table D.7 ANOVA results for Pb	220
Table D.8 ANOVA results for Cr	221
Table D.9 ANOVA results for NH ₃ -N	222
Table D.10 ANOVA results for PO ₄ -P	223
APPENDIX E: t-test results	224
Table E.1 Results from ‘t’ tests for river water quality parameters	224
APPENDIX F: Wastewater quality	228
Table F.1 Statistics on different parameters of wastewater quality data	228
APPENDIX G: Wastewater hydraulics	233
Table G.1 Velocity and flow rate of wastewater at discharge points	233
APPENDIX H: Dissolved oxygen transfer coefficients	234
Table H.1 Estimation of dissolved oxygen transfer coefficients for discharge-receptor pairs	234
APPENDIX I: Economics of removal of BOD₅	235
Table I.1 Cost estimation for removal of BOD ₅ from discharge point A	235
Table I.2 Abatement cost function for Discharge point A	236

Table I.3 Cost estimation for removal of BOD ₅ from discharge point B	237
Table I.4 Abatement cost function for Discharge point B	238
Table I.5 Cost estimation for removal of BOD ₅ from discharge point C	239
Table I.6 Abatement cost function for Discharge point C	240
APPENDIX J: Pollution abatement policies	241
Table J.1 Results on the comparison of different pollution abatement policies	241

ABBREVIATIONS

ANOVA	Analysis of Variance
ANU	The Australian National University
ANZECC	Australian and New Zealand Environment and Conservation Council
APHA	American Public Health Association
AusAID	Australian Agency for International Development
BAPA	Bangladesh Paribesh Andolon
BELA	Bangladesh Environmental Lawyers' Association
BIWTA	Bangladesh Inland Water Transport Authority
BOD	biochemical oxygen demand
BOD ₅	biochemical oxygen demand on five days
BRMA	Buriganga River Management Authority
BUET	Bangladesh University of Engineering and Technology
BWDB	Bangladesh Water Development Board
CAC	Command and Control
CBO	Community Based Organisation
CEGIS	Centre for Environmental Geographical Information Services
CGA	Central Ganga Authority
COD	chemical oxygen demand
CRP	Clean River Program
Cr	chromium
d	day
DCC	Dhaka City Corporation
DEC	Department of Environment and Conservation
DG	Director General
DO	Dissolved oxygen
DOE	Department of Environment
DWASA	Dhaka Water Supply and Sewerage Authority
EC _w	electrical conductivity in water
ECA	Environment Conservation Act
ECC	Environmental Clearance Certificate
ECR	Environmental Conservation Rules
EI	Economic incentive
EIA	Environmental Impact Assessment
EPA	Environmental Protection Authority
EPB	Environmental Protection Bureau
EPCO	Environmental Pollution Control Ordinance
EQS	Environmental Quality Standards
ETP	Effluent Treatment Plant
EU	European Union
GAP	Ganga Action Plan
GEMS	Global Environment Monitoring System
GPD	Ganga Project Directorate
hr	hour
IWM	Institute of Water Modelling
JBA	Jamuna Bridge Authority
km	kilometer
LBL	Load Based Licensing
LGED	Local Government Engineering Department

m	meter
mg/L	Milligrams per Litre
ml	millilitre
m ³ /sec	cubic meter per second
MAC	Marginal Abatement Cost
MLD	million litre per day
mm	millimeter
M/E	Mechanical and Electrical
MOEF	Ministry of Environment and Forests
MOI	Ministry of Industries
MTR	Marginal Tax Rate
MWR	Ministry of Water Resources
NBR	National Board of Revenue
NEMAP	National Environmental Management Action Plan
NEP	National Environmental Policy
NGO	Non-Government Organisation
NWP	National Water Policy
NRCD	National River Conservation Directorate
NSW	New South Wales
NH ₃ -N	ammonia-nitrogen
OECD	Organisation for Economic Co-operation and Development
O ₂	oxygen
O&M	Operation and Maintenance
PAC	Public Accounts Committee
Pb	lead
PO ₄ -P	phosphate-phosphorus
PSTP	Pagla Sewage Treatment Plant
RAJUK	Rajdhani Unnayan Kartripakkha (Capital Development Authority)
SARA	San Antonio River Authority
SIA	Social Impact Assessment
SME	Small to Medium Enterprise
sq. km	square kilometre
SWOT	Strengths, Weaknesses, Opportunities and Threats
TAC	Total Abatement Cost
TCEQ	Texas Commission on Environmental Quality
TDS	total dissolved solids
Temp	temperature
TMDL	Total Maximum Daily Load
UNEP	United Nations environment Programme
USA	United States of America
USEPA	United States Environmental Protection Agency
US\$	United States Dollar
WARPO	Water Resources Planning Organisation
WPCO	Water Pollution Control Ordinance
%	percentage
⁰ C	degree celsius
μS/cm	micro Siemens per centimetre