An Economic Analysis of Policies for Managing Industrial Water Pollution in the Kelani River, Sri Lanka

R. A. Asha Dilshani Gunawardena

M.B.A (Management of Technology)

University of Moratuwa, Sri Lanka

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Coordinating Supervisor Signature ……………………………………………………………………………….

Certification

I certify that this thesis has been substantially completed during the course of enrolment in this degree at the University of Western Australia and has not previously been accepted for a degree at this or any other institution. I certify that the help received in preparing this thesis and all sources of data used have been acknowledged.

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Acronyms

APEAR	A package for Productivity and Efficiency Analysis in R
BOD	Biochemical Oxygen Demand
BOI	Board of Investment
CAC	Command and Control
CEA	Central Environmental Authority
COD	Chemical Oxygen Demand
CWT	Common Waste Treatment
DCS	Department of Census and Statistics
DEM	Digital Elevation Model
DHI	Danish Hydraulic Institute
DO	Dissolved Oxygen
EAIP	Environmental Action 1 Project
Eco Lab	Module of DHI-MIKE for Ecological modelling
EPL	Environmental Protection Licences
FC	Faecal Coliforms
HD	Hydrodynamic
IB	Industrial Zone - Biyagama
IS	Industrial Zone - Seethawaka
MAC	Marginal Abatement Cost
MBI	Market- based Instruments
MIKE- SHE	Module of DHI-MIKE for Catchment Modelling
NWSDB	National Water Supply and Drainage Broad
OECD	The Organization for Economic Cooperation and Development
PLP	Parametric Linear Programming
SFA	Stochastic Frontier Analysis
TC	Total Coliforms
TSS	Total Suspended Solids
WDF	Waterwater Discharge Fee
WHO	World Health Organization
ZTC	Zonal Transfer Coefficient

Abstract

This thesis investigates policy instruments to manage riverine industrial water pollution in the context of a rapidly industrializing developing country. Rapid industrialization and urbanization poses serious threats to surface water resources for drinking water and a range of ecosystem services. Kelani River exemplifies many of the challenges developing countries face in managing surface water resources. The river is economically the most important in Sri Lanka in terms of the market and non-market benefits it provides. The water quality of the lower segment of the river has been deteriorating since the 1980s. However, managing water quality has been challenging due to the complexity of river dynamics in a tropical river and influence of both natural and anthropogenic processes. The regulator's management problem has been made more difficult by: a lack of data on abatement costs for industries; inadequate water quality data in terms of temporal and spatial coverage; and the lack of pollution regulation and legislation which is consistent with river water quality objectives.

Three research questions are addressed in this thesis through three papers with the overall objective of managing industrial water pollution in the Kelani River. The first research question is: *What are the abatement costs for firms located in the river catchment under current "command-and-control" regulations that specify effluent concentration standards?* This research question is addressed by estimating the marginal abatement cost for a representative sample of firms. The study estimates multi-input and multi-output parametric distance functions using mathematical programming techniques. Marginal abatement costs as shadow prices for three water pollutants were derived using the behavioural assumption of cost minimization and the duality between the cost function and input distance function. Total abatement costs for each firm under current regulations were also computed. The results reveal a wide variation of shadow prices among industries as well as firms. The heterogeneity of abatement costs makes a strong case for redesigning pollution control policy to make use of market-based instruments.

The second research question is: *What are the effects on river water quality due to the spatial distribution of pollution sources on the river catchment?* Due to non-uniform mixing of water pollutants, the location of pollution sources in relation to the river and

the hydrological system is an important factor in determining the effect of each pollution source on ambient water quality. The study analyses these effects by estimating transfer coefficients from a catchment-based hydrology model of water quality. Given the large number of firms located in the lower river catchment and long computational times of hydrology model, it was not practical to estimate transfer coefficient for each firm. Therefore, the study developed a zonal approach to divide the lower catchment into 6 zones based on hydrodynamic, water quality and water use characteristics. With the use of experimental model simulations, transfer coefficients were estimated for each zone which describes the spatial effects of pollution sources on river water quality. Transfer coefficients provide valuable information for regulators in terms of locating new industries, prioritizing pollution control among industries and industrial parks and designing socially optimal policies in river water management.

The third research question is: *What is the optimal policy mix to manage industrial water pollution*? We examine this by devising an integrated hydro-economic model where we combine transfer coefficients from the water quality model and the estimated abatement costs with an economic optimization model. The study evaluates the cost-effectiveness of five policy options ranging from current effluent concentration standard to multiple zone system. The analysis shows that the current policy does not achieve ambient water quality targets and does not account for the variability in effluent loads and abatement costs. Tradeable permits or taxes with multiple zones would be the cost effective policy option if water quality improvements in more than one zone is targeted. As current institutional capabilities are more geared towards collecting an effluent charge, an effluent tax differentiated by zones would be easier to implement. The revenue from zonal taxes could be used to improve the regulator’s capacity to implement more complex market-based policies.

The thesis contributes to the empirical literature by evaluating a range of policy options from the current regulation to a spatially heterogeneous multiple zone system in a rapidly industrializing and urbanizing river catchment within the constraints of a developing country. Those include lack of data on abatement costs, limited data on water quality and limited institutional capabilities to implement comprehensive policy instruments.

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Chapter 1 : Introduction

1.1 Overview

Poor surface water quality is a major environmental and economic issue for many developed and developing countries. Extensive regulations have been applied to control both point[1] (industries, sewage treatment plants) and non-point sources[2] (agricultural land use) of water pollution (O'Shea, 2002). Advanced economies have been successful in managing point sources and their current priority is on managing non-point source pollution (Olmstead, 2010, Shortle and Horan, 2008). Managing the latter is a challenge due to information asymmetry between the regulator and firms (Segerson, 1988, Braden and Segerson, 1993, Cochard et al., 2005) and the stochastic nature of pollution (Segerson, 1988, Horan et al., 1998, Xepapadeas, 2011).

For many emerging and developing countries, where rapid industrialization and urbanization is taking place (Schaffner et al., 2009), managing point source pollution has become a high priority (Olmstead, 2010, Coria and Sterner, 2010). This is mainly due to a lag in the development of public and private water treatment infrastructure behind urban population growth and industrialisation (Biswas & Tortajada, 2009; Qin, Su, & Khu, 2011). The deterioration in water quality has resulted in increased costs of water treatment, adverse human health effects and degraded aquatic and terrestrial ecosystems (Schaffner et al., 2009).

As a result, policy makers are confronted with the challenge of improving surface water quality without imposing excess costs on households and industry. This is where the design of policy instruments is of key importance to increasing social welfare by internalizing the external cost of water pollution efficiently. Broadly speaking, policy instruments available to the regulator can be classified into four categories: (1) direct command-and-control (CAC) regulations; (2) economic or market based instruments

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[1] *Pollution comes from a single, identifiable discrete place such as a pipe, ditch or a channel.*

[2] *Non-point source pollution refers to either water or air pollution due to diffuse sources. The main characteristic is neither source nor size of the pollution can be observed with reasonable accuracy at reasonable cost.*

(MBI); (3) informational or voluntary approaches (VA)[3]; and (4) support mechanisms such as capacity building (Taylor et al., 2013). The economic literature on pollution control mainly focuses on (1) and (2), given their current importance in terms of pollution control, while the other instruments are often considered as complementary to CAC and MBI instruments (Fére and Reynaud, 2012, Arimura et al., 2008, Hettige et al., 1996). However, empirical studies for developing countries find that CAC approaches such as uniform emission standards and technology standards are costly to administer and ineffective at achieving pollution standards (Blackman et al., 2010, Blackman, 2008, Kathuria, 2007, Hettige et al., 1996).

Environmental policy seeks to strike a balance between economic efficiency and environmental effectiveness, but in the context of water pollution selecting the best instrument is often difficult due to the complex nature of water pollution (Goulder and Parry, 2008, Bennear and Stavins, 2007). Cost-effectiveness is a desirable attribute of a policy instrument as are equity, political acceptability, effectiveness, ease of implementation and monitoring and information requirements (Perman, 2003, Keohane et al., 1998, Goulder and Parry, 2008). Evaluating policy instruments based on cost-effectiveness is difficult due to the information requirements for abatement costs and other related transaction and administrative costs. Nevertheless, some empirical studies have found significant cost savings from adopting MBIs relative to existing CAC policies (Tietenberg, 2006, Newell and Stavins, 2003, Hanley et al., 1998). Therefore, economists strongly advocate the use of MBIs that encourage polluters to behave differently by altering market signals. Economic efficiency gains can be static, where efficiency refers to achieving pollution reduction targets at least resource cost by equating the marginal abatement cost across all polluters (Montgomery, 1972, Baumol and Oates, 1988, Tietenberg, 2006), or dynamic, where the policy instrument creates continual incentives to adopt new technologies that reduce pollution in innovative ways (Newell and Stavins, 2003, Harrington and Morgenstern, 2007). It is also argued that MBIs perform better in situations where cost heterogeneity among pollution sources is high (Newell and Stavins, 2003).

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[3] *For example: public disclosure of pollution information of industries and participation in voluntary environmental standards such as certification (Fére and Reynaud, 2012, Kathuria, 2007, Blackman, 2008, Blackman and Guerrero, 2012, Blackman et al., 2010)*

Despite the potential for cost savings, the use of MBIs such as emission taxes (price based) and permits (quantity based) on controlling water pollution in developing countries has been limited (O'Connor, 1999) and evaluations of their success have shown mixed results. For example, use of effluent taxes has been favoured due to two main reasons: promotion of innovation (Requate and Unold, 2003, Requate, 2005) where costs of abatement are heterogeneous among the pollution sources and the generation of revenue which can be used to invest in infrastructure (Boyd, 2003). In developing countries, given the information requirements, implementing a welfare maximizing Pigouvian tax (first best solution) is not possible (Bluffstone, 2003). In these countries, second best taxes, where tax rates are exogenously determined by the regulator are the most usual form of MBI. Case studies from three developing and transition countries in three different parts of the world (Malaysia, Poland and Colombia) showed that combinations of taxes with active enforcement contributed to an overall improvement in environmental compliance (Kathuria, 2006, Bluffstone, 2003). Industries in China reduced wastewater emissions in response to the pollution levy system (Wang and Wheeler, 2003, Managi and Kaneko, 2009). On the other hand, a few studies argue that design deficiencies and pervasive constraints may hinder the implementation of economic instruments in developing countries (Blackman and Harrington, 2000). For example, implementation of effluent charges for wastewater in Thailand was hindered by the political constraints at local government level (Rammont and Amin, 2010). Overall empirical evidence suggests that even with some deficiencies in implementation, most of these countries have been able to implement effective second-best emission tax schemes (Bluffstone, 2003).

Among incentive-based alternatives to the tax, the application of tradeable permits in controlling water pollution has received most attention in the literature mainly due to a few successful applications found in the US (Nutrient Trading program in North Carolina), Australia (The Hunt River salinity programme) and Canada (South Nation River Phosphorous management programme)(Kraemer et al., 2004). However, the global experience in water quality trading is limited (Shortle, 2013, Kraemer et al., 2004). The emission trading refers to a system where transfer of pollution rights among dischargers is permitted. The main elements in trading programs are type of pollutants, geographic scope, eligibility rules, trading ratios and type of trading (Nishizawa, 2003). Benefits of a well-designed permit trading program are: (1) the ability to achieve high water quality at lowest social cost (dischargers with high abatement cost would be allowed to purchase permits from the dischargers with lower costs); (2) encourage innovation in pollution reduction (as there are opportunities to sell the extra permits); (3) address broader environmental goals (for example sharing cost among point and non-point sources); and (4) effective protection of the environment in the face of changing levels of economic activity, technology and inflation (Howe, 1994).

Studies on implementation of tradeable permits in developing countries are limited with some notable exceptions. Transitional countries such as Kazakhstan, Poland and China have taken some efforts to introduce permit trading programs (Coria and Sterner, 2010). Lessons learned from Chile show that challenges in designing a well-functioning trading program in a less developed country should not be underestimated (Coria et al., 2010, Coria and Sterner, 2010). On the other hand, there is no reason to believe that developing countries cannot implement such a system (Coria et al., 2010). For example, China has piloted a tradeable discharge permit system for water pollution control for certain river basins. A study on industrial wastewater control in Tianjin estimated potential cost savings with trading discharge permits relative to non-tradeable permits (Tao et al., 2000). Other studies on China have assessed cost savings as well as design issues to avoid potential problems such as the creation of hot spots[4] due to trading (Cao and Ikeda, 2005) and designing trading ratios among zones (Zhang et al., 2013, Hung and Shaw, 2005).

To summarise, the experience from both developed and developing countries on the use of tradeable permits highlights some key points. First, tradeable permits can be the most challenging MBIs in terms of design and implementation requirements. Second, monitoring and enforcement capabilities contribute significantly to the success of trading programs and these resources tend to be limited in developing countries. Third, knowledge and experience in the design of the key attributes of a

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[4] *Localized areas where water quality standards are exceeded due to permit transactions*

trading system are essential to developing a successful trading system (Kraemer et al., 2004).

Therefore, introducing a tradeable permit system needs careful consideration of several factors: (1) the potential economic benefits of trading (such as the existence of cost heterogeneity and market size); (2) monitoring and enforcement capabilities as well as the capacity for change in the legal system; (3) a good scientific understanding of pollution issues including hydrological modelling; (4) reliable and transparent information on pollution sources and loads; (5) capacity to design instruments with careful consideration of the context; (6) importance of consultation with stakeholders; and (7) the importance of trialling programs using pilot projects. In the case of a developing country, where most of these requirements are not met, it is useful to consider implementing comparatively simpler instruments such as emission taxes first. Once the institutional capabilities are developed and information and other required systems are in place, developing countries can then move towards implementing trading systems (Kraemer et al., 2004, Coria and Sterner, 2010).

The instrument design challenges can be greater when the resource being protected is affected by spatially heterogeneous externalities. An empirical analysis in the context of a river catchment needs an integrated approach. To make socially optimal policy decisions given the complexity of river dynamics, nature of pollutants and social and economic aspects, one would need to use hydro-economic models that integrate hydrological, engineering, environmental and economic aspects of the problem (Heinz et al., 2007). Hydro-economic models are widely used to manage different aspects of water resources, but their application in the study of policy options to control wastewater pollution has been limited. For example, the European Union Water Framework Directive for nitrate pollution management led to a number of key studies (Gömann et al., 2005, Peña-Haro et al., 2009, Cools et al., 2011, Aftab et al., 2007) and a smaller number of studies addressed BOD[5] emissions (Moffatt et al., 1991, Hanley

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[5] *Biochemical Oxygen Demand SIMONOVIC, S. P. & FAHMY, H. 1999. A new modeling approach for water resources policy analysis. Water Resources Research, 35, 295-304. is a measure of quantity of oxygen used by microorganisms in the oxidation of organic matter. This is a commonly used measure of water quality.*

and Moffatt, 1993, Hanley et al., 1998). There are few such studies on emerging and developing countries (Qin et al., 2011, Rahman and Ancev, 2014).

As most of the water pollutants are non-uniformly mixing, the extent of damage due to pollutants depend not only on effluent loads and characteristics of the pollutants but also upon the location of the pollution sources in the hydrological, social and the economic landscape (Hung and Shaw, 2005, Boyd, 2009, Bai et al., 2011). The effect of location of pollution source on ambient water quality are described using transfer coefficients (Boyd, 2003, Perman, 2003, Hanley et al., 2007) and the latter can be estimated using a hydrology model of water quality (Hanley et al., 1998, Moffatt et al., 1991, Boyd, 2003). Combining transfer coefficients with an economic optimization model, various policy options can be evaluated with the objective of minimizing the aggregate social cost to achieve water quality objectives (Hanley et al., 2007, Perman, 2003, Fang et al., 2008, Hanley et al., 1998, Moffatt et al., 1991).

1.2 Context

In common with many developing countries, continued deterioration of ambient water quality of many inland water bodies in Sri Lanka has been a major economic issue due to its significant impact on water users. These inland water bodies are the main drinking water sources of the country. Therefore, the protection of the catchment areas from various sources of pollution has become a priority.

This thesis focuses on water quality in the Kelani River, which plays an important role in Sri Lanka’s economy. The lower river catchment is heavily industrialised and urbanized (Figure 1.1). It is the main source of drinking water for Colombo’s resident population of 2.3 million (DCS, 2012). The river and its tributaries are intensively utilised for various basic needs such as bathing, washing and homestead agriculture. Water quality in the Kelani River has been a concern since the 1980s due to sporadic fish mortality events. The absence of systematic monitoring of water quality and the health of the aquatic ecosystem made it difficult to assess the level of pollution and potential human health impacts (Silva, 1996). In 1999, a study undertaken by the Danish Hydraulic Institute identified that pollution levels at Ambatale (the main intake point for drinking water for Colombo) had reached a level that threatened the quality of drinking water given the current purification methods and infrastructure. As a result, the government decided to ban new highly polluting industries upstream of Ambatale as some industrial pollutants are difficult to remove by common water treatment processes (Herath and Amaresekera, 2007) .

A program to monitor the water quality of the river basin started in 2002 with the objectives of reviewing existing policy on locating industries and reviewing the existing effluent concentration standards. The analysis of data collected in this program revealed that the water quality at Ambatale is not suitable for drinking without intensive treatment (for instance, using a conventional method which is a combination of chemical and physical processes such as coagulation, segmentation, filtration and disinfection).

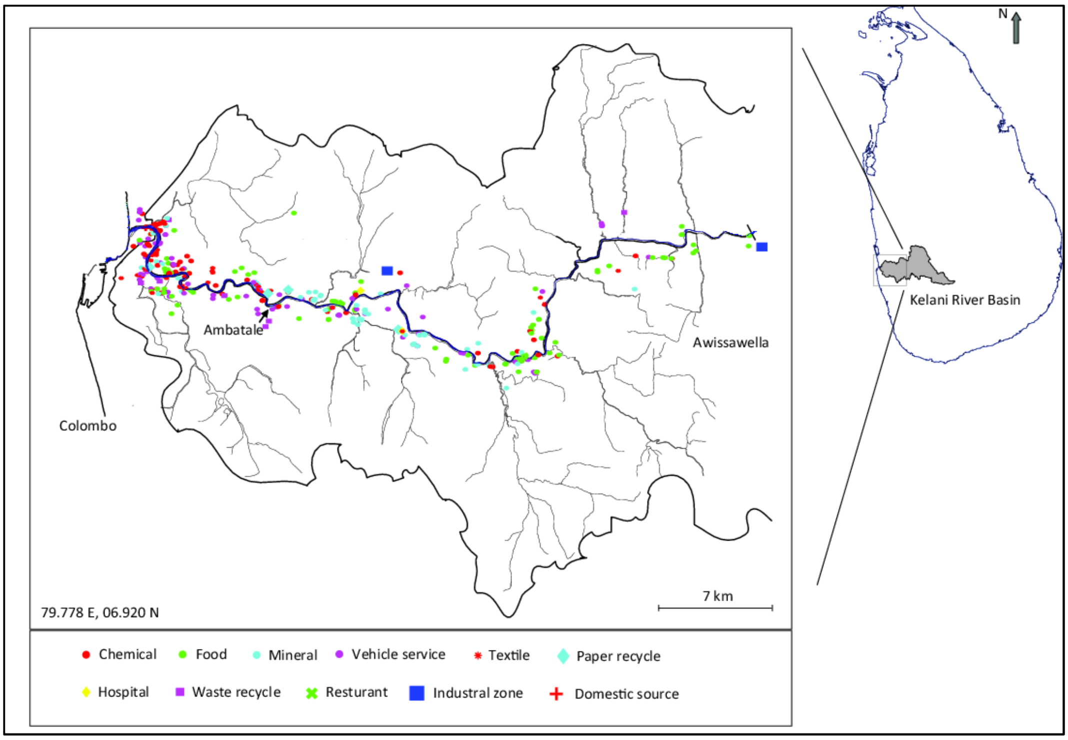

Figure 1.1: Lower Kelani catchment with spatial distribution of point sources

The river below Ambatale has poor water quality and this has degraded the ecosystem of the estuary and the economic outcomes of fishing industry. In addition to accounting for the largest share of organic discharges, industry is also responsible for heavy metals such as Chromium and Lead which are both high relative to WHO standards. The presence of nutrients loads was lower than expected perhaps, due to trapping of nutrients such as phosphates by hydropower reservoirs located in the upper catchment of the river (Herath and Amaresekera, 2007).

Currently, Sri Lanka uses CAC regulatory measures such as effluent (concentration based) standards to control pollution of water bodies from industries. The Central Environmental Authority (CEA) is the regulatory authority responsible for mandatory Environment Protection Licenses (EPLs) that are required by new business in Sri Lanka. These licenses are renewed every year for high polluting industries and every three years for medium to low polluting industries. The main purpose of EPL is to control effluents of polluting industries to a certain level while implicitly allowing them to pollute while maintaining regulatory effluent concentration standards. Therefore these licences can be considered as a weak form of property rights. One of the main challenges in water governance and management is poorly defined property rights which occurs due to the information gap between authorities and other stakeholders (Crase et al., 2011). Therefore, such weaker property rights do not result in expected environmental outcomes. This situation is further aggravated by poor monitoring and enforcement capabilities in developing countries like Sri Lanka.

There is strong evidence that the current approach to pollution regulation is ineffective in maintaining water quality (AECEN, 2006, Vasantha, 2008). Since 2002, CEA has been exploring new options such as market based instruments for effective control of industrial wastewater pollution (Vasantha, 2008). There are very few studies available related to this issue in Sri Lanka. A study by Steele and Hassan (1998) analysed the feasibility of introducing an effluent charge system - a fee based on pollution load - as a means of controlling industrial wastewater pollution. In 2002, implementation of a load based licensing fee was proposed for high polluting industries by a study undertaken under the Environment Action One Project (EAIP) funded by the World Bank (Vasantha, 2008). None of these proposals were implemented due to a lack of political interest and legal and institutional constraints in charging a fee.

In 2007, CEA proposed a wastewater discharge fee (WDF) program in Sri Lanka. However, implementing such program in Sri Lanka presented a number of challenges due to overlapping legal and institutional jurisdictions and lack of procedures to design and collect fees. In addition, lack of technology to measure pollution levels at firm level and the absence of systematic up-to-date industrial pollution database make implementation of this program difficult. Moreover, practicalities in earmarking of funds collected from charging WDF need to be solved.

Several steps have been taken to establish the basic requirements of setting WDF program; amendment of National Environmental Act of 1980 and regulations to eliminate legislative and regulatory constraints; development of institutional capacity of the regulatory authority and appointment of a technical support committee representing all relevant institutions[6]. A sector wise implementation of WDF has been proposed (Vasantha, 2008). Apart from the above mentioned steps taken forward, the program has not been implemented so far due to lack of systematic information on abatement cost and some design and implementation problems. Moreover, the proposed program is not consistent with water quality objectives for inland water bodies.

1.3 Research problem and objectives

Given the importance of the Kelani River as the main source of drinking water and other market and non-market services, there is an urgent need to improve river water quality. However, managing rivers has been challenging due to complexity of river dynamics and influence of both natural and anthropogenic processes. Moreover, the regulator's problem in managing the river becomes harder due to: a lack of data on abatement costs of firms; inadequate water quality data covering spatial and temporal variations of the lower river; and lack of pollution regulations which are consistent with river water quality objectives.

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[6] *Such as Ministry of Water Supply and Sanitation, Ministry of Industry, Ministry of Environment and Natural Resources and National Water Supply and Drainage Board.*

Therefore, the main objective of this thesis is to investigate the choice of policy instruments to manage industrial wastewater pollution in Kelani River. The thesis addresses three specific research questions in the form of journal papers:

1. *What are the abatement costs for firms located in the river catchment under the current CAC regulations that specify effluent concentration standards?*
2. *What are the effects on ambient river water quality due to the spatial distribution of pollution sources on the River catchment?*
3. *What is the optimal policy or policy mix to manage industrial water pollution?*

1.4 Conceptual framework

The conceptual framework of the thesis presented in Figure 1. 2,shows how three papers are connected in order to achieve the overall research objective. Paper 1 (chapter 2) investigates the industrial efficiency and abatement costs using parametric input distance functions for a representative sample of manufacturing firms located in the Kelani catchment.

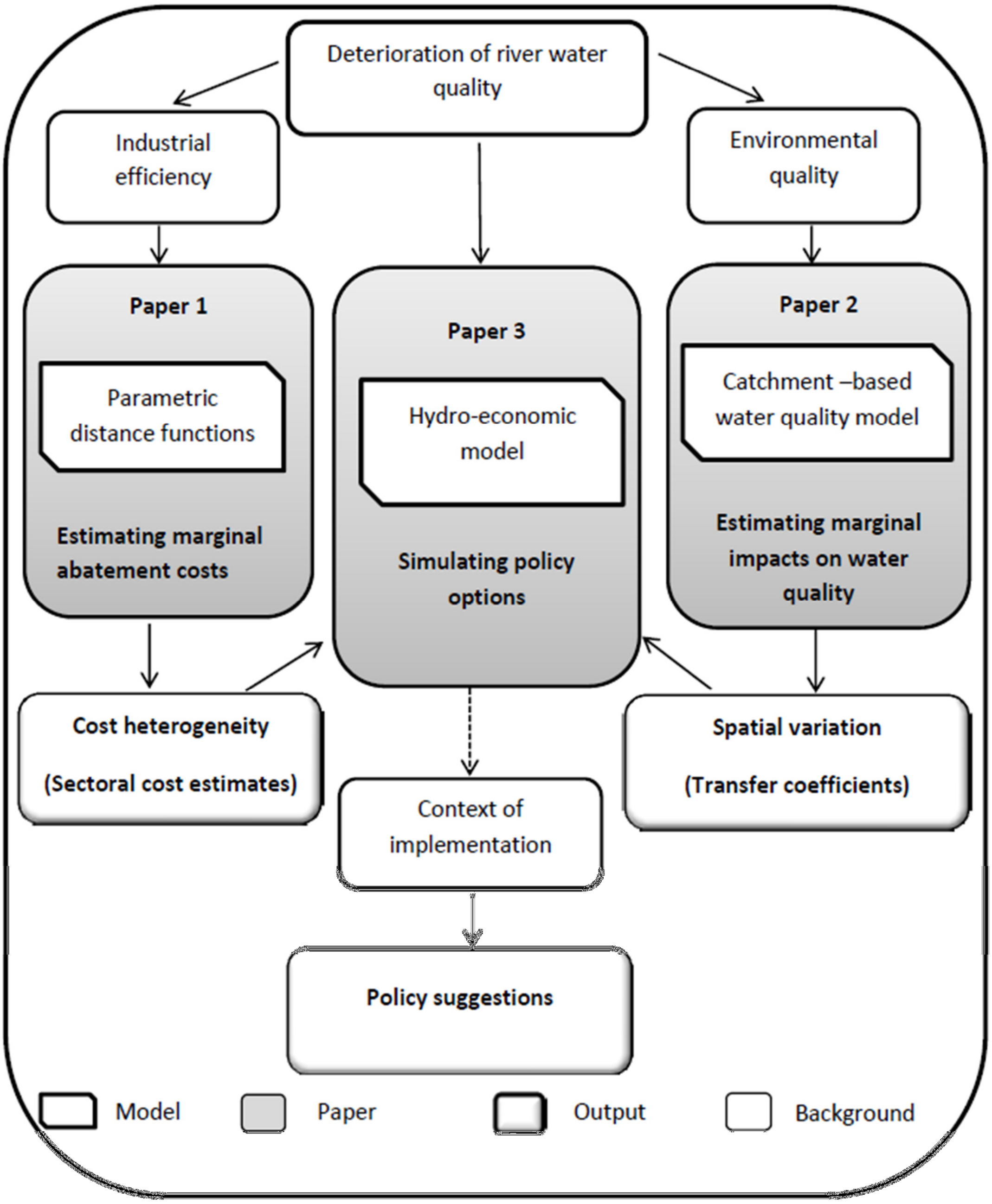

Figure 1.2: Thesis conceptual diagram

Paper 2 focuses on representing the hydrological system in a way that can be used in policy analysis. Configuring a hydrology model of water quality, this paper: (1) estimates contribution of different pollution sources on river ambient water quality; (2) suggests river zoning based on the simulated hydrodynamic and water quality variations and the actual purposes for water use along the river; and (3) generates estimates of zonal transfer coefficients.

The marginal abatement cost information from Paper 1 (Chapter 1) and information on spatial variability of pollution sources estimated as transfer coefficients in Paper 2 (Chapter 3) are combined in the economic optimization model to simulate policy instruments in the third paper (Chapter 4). The policy simulations are analysed based on cost-effectiveness in achieving different water quality targets. Then the optimal choice of policy instruments are discussed based on contextual issues associated with the design and implementation challenges.

1.5 Contribution to the scholarship

Paper 1 (Chapter 2) estimates the marginal abatement costs as shadow prices of water pollutants of manufacturing firms using parametric input distance functions. Numerous empirical studies have estimated shadow prices. However, very few studies are available from developing countries. To our knowledge this is the first study conducted on manufacturing firms in Sri Lanka. We further extended our analysis to estimate total abatement cost for firms under different policy scenarios related to different effluent concentration levels including current regulatory standards.

Paper 2 (Chapter 3) contributes to the literature in three ways: First the chapter develops a method to estimate contribution of different point and non-point sources to ambient water quality. This is done by configuring a catchment based hydrology model of water quality with limited available water quality and pollution data. Second, given the large number of pollution sources located in the river catchment, the chapter introduces a river zoning strategy based on the variability of hydrodynamic and water quality characteristics water use types along the river. Third, the chapter develops a method to estimate transfer coefficients that describe impact of pollution sources on ambient water quality using the hydrology model and simulations. Very few empirical studies have estimated transfer coefficients (Rahman and Ancev, 2014); to our knowledge this is the first study conducted using catchment based hydrology model of water quality to estimate transfer coefficients in a developing country setting where rapid industrialization and urbanization are taking place.

Paper 3 (Chapter 4) develops an integrated river catchment based hydro-economic model (combining a hydrological model of water quality with an economic model of the behaviour of polluting firms) to examine the choice of policy instruments to manage river water quality. Optimization studies that investigate policy instruments using integrated hydro-economic models were applied in water pollution in advanced economies mostly on non-point sources (Cools et al., 2011, Peña-Haro et al., 2009, Gömann et al., 2005) and few studies on point sources (Moffatt et al., 1991, Hanley et al., 1998, Brill et al., 1984). Apart from few recent studies conducted in emerging countries (Cao and Ikeda, 2005, Ning and Chang, 2007, Qin et al., 2011) and one in Bangladesh(Rahman and Ancev, 2014), there are no river catchment based economic analyses of alternative policies in less developed countries. To our knowledge, this would be the first empirical study to evaluate a range of policy options including the current simple effluent standards approach and more complex, multiple zone approaches, in a developing country context.

1.6 Organization of the thesis

This thesis is composed of 5 chapters. Chapter 1 presents the introduction to the thesis. Chapter 2, 3 and 4 present three research papers, that cover three research questions addressed in the thesis. These chapters are written as stand-alone papers. Therefore, there can be some unavoidable repetitions. Chapter 5 presents conclusions and policy implications.

Chapter 2 : Estimating Marginal Abatement Cost for Industrial Water Pollution in Colombo: A Parametric Distance Function Approach

Abstract

This paper estimates the cost of effluent discharge regulations for firms located in the lower Kelani River catchment in Sri Lanka. The river provides water for many economic purposes including drinking water to the capital city, Colombo and a variety of ecosystem services. Employing multi-input and multi-output translog production technology, we estimate shadow prices of effluents and technical efficiency of firms belonging to eight industries. With the given level of compliance, we extend our analysis to compute total abatement cost for firms under different policy scenarios, related to simultaneous reduction in concentration of three water pollutants including current regulatory standards. The evidence on of poor compliance and wide variations in firm and industry specific shadow prices (marginal abatement costs) provide a strong case for a comprehensive redesign of environmental policy to control water pollution by industries in the heavily industrialized river catchment.

Keywords:
Shadow prices, Technical efficiency, Environmental regulation, Water pollution, Distance functions, Sri Lanka

2.1 Introduction

Degradation of water quality of major urban rivers due to point and non-point sources has become a serious challenge in many developing countries (Schaffner et al., 2009). This is mainly due to rapid urbanization accompanied by population and industrial expansion in these countries where development of water purification infrastructure facilities and policy has lagged behind industrialization (Qin et al., 2011, Biswas and Tortajada, 2009). While the cost of environmental asset degradation is significant to society in these countries, the full cost of environmental externalities has not been accounted for because value of ecosystem services is not readily measured or accounted for in national or regional accounts.

This study focuses on water polluting industries in the lower Kelani River catchment. The river is the main source of drinking water for the city of Colombo. Apart from provision of drinking water, the river is a source of hydropower generation, industrial and irrigation water, and is used for washing, bathing, fishing and recreation. Due to population growth and industrialization, water quality in the lower river has deteriorated rapidly over the last 20 years. Therefore, managing river water quality has become a critical issue due to the cost of maintaining drinking water standards and the costs of deteriorating ecosystem services. Recent studies report that the river is of poor quality endangering the aquatic life and degrading the ecology of the estuary ecosystem (Herath and Amaresekera, 2007). The urgent need to improve river water quality has, created a strong interest among policy makers to experiment with different policy instruments in addition to the existing regulatory standards.

The use of market based instruments to control environmental pollution has been strongly encouraged by economists despite inconclusive evidence in developing and emerging countries where institutional, financial, political and human resource limitations restrict the development of such instruments (Blackman, 2009, Blackman and Harrington, 2000, Kathuria, 2006). These instruments create economic incentives for industries to reduce pollution by imposing implicit or explicit price on emissions. Well-designed and implemented market based instruments have the ability to provide the overall least cost means of achieving desirable levels of emission reductions

(Stavins, 2003) by equalizing the marginal or incremental abatement cost across polluters (Tietenberg, 2006, Baumol and Oates, 1988) . In many cases, the marginal cost of abatement among firms varies due to size, industrial category, location, price and quality of inputs and differences in abatement technology. The potential cost savings achieved by implementing a market based instrument tends to be high where marginal abatement costs are heterogeneous across firms (Newell and Stavins, 2003).

However, information on abatement costs is not readily available to policy makers due to the absence of markets and observable prices for pollutants. There are two main economic approaches that can be used to estimate the cost of abatement of undesirable outputs: cost function approach and distance function approach. The estimation of firm level efficiency and shadow prices using distance function approach has been widely employed over the cost function approach (Hailu and Veeman, 2000; Lee et al., 2002; Lee, 2005). The distance functions can be used to characterize environmental production technology in a multi-input and multi-output setting including undesirable outputs where information on regulations and input prices is not required. Using duality theory (Shephard, 1953, 1970), that provides the fundamental link between traditional measures of productivity and the distance function productivity measures, can be used to calculate shadow prices. from microeconomics, For example, cost function is dual to input distance function and the revenue function is dual to output distance function. The calculated shadow prices with respect to a particular pollutant can be defined as the marginal cost of abatement (MAC) for this pollutant as it represents the additional cost incurred to reduce the pollution by one unit. The MAC provides useful information at a firm level linking current emission levels to the cost of reducing emissions. At a policy level, these values can be used as an important tool to determine the economically efficient levels of pollution reductions to maximize societal welfare (Vijay et al., 2010).

Estimation of shadow prices using distance functions has followed three main approaches: non-parametric or Data Envelopment Analysis (DEA) approach, parametric functions estimated using linear programming (PLP)approach and the parametric Stochastic Frontier Analysis (SFA) approach (Zhou et al., 2014). The DEA is a frontier analysis technique (Cooper et al., 2011) which constructs a piece-wise production boundary combining observed input and output data (Du et al., 2015). The advantage of DEA is that it is not necessary to specify a functional form for the underlying production technology (Zhou et al., 2014). However, it does not guarantee the differentiability of the estimated distance function which is important in estimating shadow prices. This is because DEA derivatives are not defined at the vertices of the piece-wise linear frontier.

In contrast, parametric distance function methods have become popular in the literature due to their differentiability which is an essential feature for estimating shadow prices (Zhang and Choi, 2014). PLP methods allow simple imposition of important constraints in the frontier estimation. The only shortcoming of this estimation approach is that it ignores statistical noise and attributes all deviations from the frontier to inefficiency. On the other hand, the stochastic frontier approach allows stochastic treatment of these deviations; by decomposing into an inefficiency term and a random disturbance term that accounts for measurement errors and the other random noise. In addition, SFA allows for hypothesis testing (Kuosmanen and Kortelainen, 2012). However, SFA approach limits the researchers' ability to apply prior monotonicity restrictions on the parametric distance function (Rezek and Campbell, 2007).

Shephard distance functions (and radial) and directional distance function have been used in the literature. Both can be specified as flexible forms – radial as translog and directional as generalised quadratic, allowing for the global imposition of linear homogeneity and translation properties, respectively. Many recent studies have tended to use the directional distance function that can allow for increases of desirable output(s) while contracting the undesirable output(s). Nevertheless, the shadow price estimates vary depending on the directional vector which is used to expand or contract the input and output set. Therefore, the choice of an appropriate directional vector plays a key role in shadow price estimations (Zhou et al., 2014). However, there is no consensus in the literature regarding the choice of directional vector. Further, the use of a direction that implies a radical change in input or output mix is akin to assumption of a structural change that is more consistent with long-run rather than short-run possibilities. Therefore, the use of shadow prices based on a radial distance functions can be more appropriate as these functions maintain quantity mixes at observed levels (Ma and Hailu, 2016)

A few studies have calculated shadow prices using distance functions in developing country context (Murty et al., 2007, Murty et al., 2006, Murty and Kumar, 2003, Mandal, 2010, Xu et al., 2010, Dutta and Narayanan, 2011, Van Ha et al., 2008) . To our knowledge this is the first study carried out in Sri Lanka to estimate shadow prices of water pollutants in manufacturing industries. In this study, we calculate firm and industry specific shadow prices for Biochemical Oxygen Demand (Simonovic and Fahmy), Chemical Oxygen Demand (COD) and Total Suspended Solids (TSS) using input distance functions estimated by PLP (Hailu and Veeman, 2000, Coelli et al., 2013). Given the importance of cost information on policy decisions, we extended our analysis to simulate total abatement cost for different policy scenarios based on simultaneous reduction of pollutant concentration to different levels including those consistent with the current regulatory standards. Our choice of input distance functions in this study is based on the following three reasons: (1) in the presence of undesirable outputs, an input-based efficiency measure is easy to interpret as it represents the proportional change in inputs with both desirable and undesirable outputs held constant (Hailu and Veeman, 2000, Murty et al., 2006); (2) input based efficiency is more appropriate as most firms have more control over inputs than outputs; (3) shadow price estimates using input distance function do not depend on the choice with the direction vector as it is the case of directional distance functions.

The paper is organized as follows. Section 2 presents the current policy context and Section 3 explains the theoretical concepts behind the methodology we used. Section 4 describes the data and Section 5 reports and discusses the empirical results. Section 6 concludes the paper.

2.2 Policy Context

Sri Lanka uses command-and-control regulatory measures administered by the Central Environmental Authority (CEA) to control industrial pollution. The key regulatory measures adopted by CEA are Environmental Protection Licencing (EPL) and concentration standards[7]. The CEA issues Environment Protection Licenses (EPLs) to firms, a mandatory provision to start a new business in Sri Lanka. These licenses are renewed for existing businesses, annually for high polluting industries[8] and triennially for medium to low polluting industries, after checks and verification on whether the wastewater quality meets the existing effluent standards. There are no river specific policies to manage the water quality, except the ban on establishing new pollution intensive industries upstream of the water extraction point in the Kelani River.

Empirical evidence on water quality evidence in Sri Lanka suggests that the current approach to pollution regulation in rivers is ineffective (AECEN 2006; Vasantha 2008). Firstly, emission standards are based on discharge concentrations which do not restrict total pollution loads. Secondly, EPLs provide no incentive to reduce pollution by industries with varying emission levels as all industries under the same pollution category are charged a uniform fee irrespective of their emission levels. Thirdly, CEA has limited regulatory and weak enforcement powers. The number of cases handled by the legal unit of the CEA was about 252 in 2012 where 64 were new cases related to industrial pollution (CEA, 2012). Fourth, budgetary constraints have resulted in limited resources within CEA. The lack of a well-managed information system is also a hindrance to effective monitoring and enforcement. In addition, the lack of public pressure on polluting industries because of limited public awareness and ineffective public complaint processes has resulted in poor compliance.

Recently, the CEA has been exploring new options[9] such as market-based instruments for effective control of industrial wastewater pollution (Vasantha, 2008). In 2007, CEA

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[7] *The national concentration standards for water pollutants discharge into inland water bodies are given as 30mg/l for BOD, 250 mg/l for COD and 50 mg/l for TSS.*

[8] *Industries have been categorised by the CEA based on their level of pollution under three main categories; A-high polluter, B-medium level polluters and C-small scale polluters*

[9] *CEA also initiated a program in 2011 to increase the voluntary compliance named as the national Green Award Scheme. This program recognizes and publicizes private and public sector institutions that operate in environmental friendly manner.*

proposed a Wastewater Discharge Fee (WDF) program in Sri Lanka. However, implementing such a program presents a number of challenges due to overlapping legal and institutional functions and lack of procedures to design and collect fees. In addition, a lack of technology to measure pollution levels at the firm level and the absence of systematic up-to-date industrial pollution database make implementation of this program difficult. In many cases, it is difficult for government agencies such as CEA to set appropriate fees on industrial emissions due to unavailability of empirical information. This study is the first to address and provide much needed information on abatement costs which policy makers could potentially use to develop more effective and efficient policies. This is done in the context of production efficiency frontiers allowing us to also to generate useful information about the performance of water polluting industries in Colombo, Sri Lanka

2.3 Methodology

Shephard (1953) was the first to introduce distance functions. The functions can be employed to describe multi-input and multi-output production technology in order to estimate technical efficiency and productivity measures without resorting to specific behavioural assumptions such as profit maximization and cost minimization (Coelli et al., 2005). There are two types of distance functions: output distance functions and input distance functions. An output distance function characterizes production technology by considering maximum proportional expansion of the firm's output vector for a given set of inputs. An input distance function represents the production technology by looking at the maximal proportional contraction of the input vector for a given output vector.

In this paper, we use input distance function which provides meaningful and explicit measure of production efficiency as it considers proportional savings of inputs (costs) while keeping both desirable and undesirable outputs constant. In the case of output efficiency measures, efficiency is defined in terms of proportional expansion of both desirable and undesirable outputs but the net welfare gain from such an expansion cannot be determined. The net welfare gain or loss depends on the difference between benefits gained from the expansion of desirable output and the damage caused by simultaneous expansion of undesirable outputs. Therefore, interpretation of radial output efficiency changes is ambiguous in the presence of undesirable outputs (Hailu and Veeman, 2000, Murty et al., 2006).

2.3.1 The technology set and input distance function

The production technology of each water polluting firm can be described using input sets, $L\ (u)$, representing the set of all input vectors $x \in \Re_{+}^{N}$ that produce output vector $u \in \Re_{+}^{M}$ with the output vector consisting of both desirable and undesirable outputs (for example water pollutants). The input distance function can be defined against the input requirement set as follows:

$$D_i\ (x, u) = Max_{\rho} \left\{ \rho : \left({}^{x}/_{\rho}, \right) \in L(u) \right\} \qquad \forall\ u \in \Re_{+}^{M} \tag{2.1}$$

That is the input distance function indicates the maximum amount by which an input vector x can be deflated or contracted given the output vector and the production technology.

The input distance function is linearly homogenous, non-decreasing and concave in x and non-increasing and quasi-concave in u (Coelli et al., 2005). The value of the distance function is equal to 1 (if x is located on the inner boundary of the frontier) or greater than 1 if x is able to produce u. In other words, the distance function provides a complete representation of the production technology.

$$D_i\ (x, u) \geq 1\ if\ x \in L(u) \tag{2.2}$$

2.3.2 Derivation of Shadow prices

We employed input distance function to calculate shadow prices of pollutants following (Hailu and Veeman, 2000) . Shadow prices of pollutants can be derived from the cost function (3) and (4) using the behavioural assumption of cost minimization and the duality between cost function and input distance function. A formula for shadow price can be derived using envelope theorem on the first order conditions of the cost minimization problem defined against a distance function representation of the technology as shown in Eq. (5) and (6) below.

$$C\ (u,p) = Min\{p.x\text{:}\ x \in L(u)\} \tag{2.3}$$

$$C\ (u,p) = Min\{p.x\text{:} D(u.x \geq 1), x \in \Re^N_+\} \tag{2.4}$$

$$\nabla_u\ C\ (u,p) = -\pi(u,p).\nabla_u\ D\ (u,x) \tag{2.5}$$

$$\nabla_u\ C\ (u,p) = -C(u,p).\nabla_u\ D\ (u,x) \tag{2.6}$$

where π is the Lagrangian multiplier and equals the value of optimized cost function, allowing us to derive (2.7 from (2.5). Using (2.6), the ratio of shadow prices of outputs can be written as:

$$\frac{r_i^*}{r_j^*} = -\frac{\frac{\partial D(u,x)}{\partial u_i}}{\frac{\partial D(u,x)}{\partial u_j}} \tag{2. 7}$$

This ratio reflects the trade-off between two outputs in the production technology. For example, if i is an undesirable output and *j* is desirable output, the ratio represents the number of units of desirable output *j* that would be forgone to reduce the emission of one unit of pollutant *j* is the producer shadow price for i^{th} pollutant.

If we assume (as is commonly done) that the market price for the desirable output equals its shadow price (Shephard, 1970, Fare et al., 1993, Färe et al., 2005, Hailu and Veeman, 2000), then the shadow price for undesirable output r_i^*can be witten as:

$$r_i^* = -\frac{\frac{\partial D(u,x)}{\partial u_i}}{\frac{\partial D(u,x)}{\partial u_j}} \bullet r_j^* \tag{2.8}$$

The shadow price of undesirable output is positive as the input distance function is non-decreasing in pollutant outputs and the derivatives have opposite signs. We use Eq. (2.8) to calculate shadow prices for three water pollutants (BOD, COD and TSS).

2.3.3 Estimation of parametric input distance function

The input distance function is homogenous in inputs. The flexible functional form that allows us to improve this property globally is the translog form. We estimate the translog parametric input distance function frontier with linear programming techniques.

$$
\begin{aligned}
\ln D_i\ (u,x) =&\propto_0 + \sum_{n=1}^{N} \propto_n\ \ln x_n\ + \sum_{m=1}^{M} \beta_m\ \ln u_m \\
&+ (0.5) \sum_{n=1}^{N} \sum_{n'=1}^{N}\ \propto_{nn'}\ \ln x_n \ln x_{n'} \\
&+ (0.5) \sum_{m=1}^{M} \sum_{m'=1}^{M}\ \beta_{mm'} \ln u_m \ln u_{m'} \\
&+ \sum_{n=1}^{N} \sum_{m=1}^{M}\ \Upsilon_{nm} \ln x_n \ln u_m
\end{aligned}
\qquad (2.9)
$$

Aigner and Chu (1968) were the first to use mathematical programming techniques to estimate parameters of production function. This method minimizes the sum of deviations of the values of the function from the unknown frontier that is being estimated subject to monotonicity and homogeneity restrictions as specified in Hailu and Veeman (2000). For this study, the ability to impose inequality constraints is very important as we need to treat desirable and undesirable outputs asymmetrically in the specification of technology.

The objective function of linear program is to choose a set of parameter estimates that minimize the sum of deviations of log values of the input distance function from zero. We impose monotonicity, homogeneity and symmetry conditions as constraints. Also we impose the constraint that estimated input distance value should be equal or greater than one. The derivative properties of the input distance function with respect to desirable and undesirable outputs are different. As Input distance function measures maximum proportional reduction of inputs while outputs held constant, the function should be non-decreasing in inputs (10) and non-increasing in desirable outputs (11). While desirable outputs can be freely disposable, reduction undesirable outputs can be achieved at the expense of desirable outputs or increase of inputs.

Therefore, input distance function should be non-decreasing in undesirable outputs (12). The implementation of these monotonicity conditions can be done through the derivative signs imposed on the estimation of parameters.

$$\partial \ln D_i \ (u,x)/\partial x_n \geq 0 \ , \qquad n=1,..4 \qquad (10)$$

$$\partial \ln D_i \ (u,x)/\partial U_m \geq 0 \ , \qquad m=1 \qquad (11)$$

$$\partial \ln D_i \ (u,x)/\partial u_m \geq 0 \ , \qquad m=2,..4 \qquad (12)$$

To implement the estimation we use *APEAR*, an R based package for productivity and efficiency analysis (Hailu, 2013).

2.4 Data

The data used in this paper come from a survey of water polluting industries that was conducted in 2013 in Sri Lanka. A representative sample of firms was selected from the database of industries available from the environmental agency (CEA). The sample consists of high polluters and medium level of polluters located within 1 km of the river (see Figure 1). There were 324 water polluting individual firms in total and our sample comprised 74 of them. We interviewed production and administrative managers of 74 firms to collect information on inputs, desirable outputs and other required firm specific data for the year 2012.

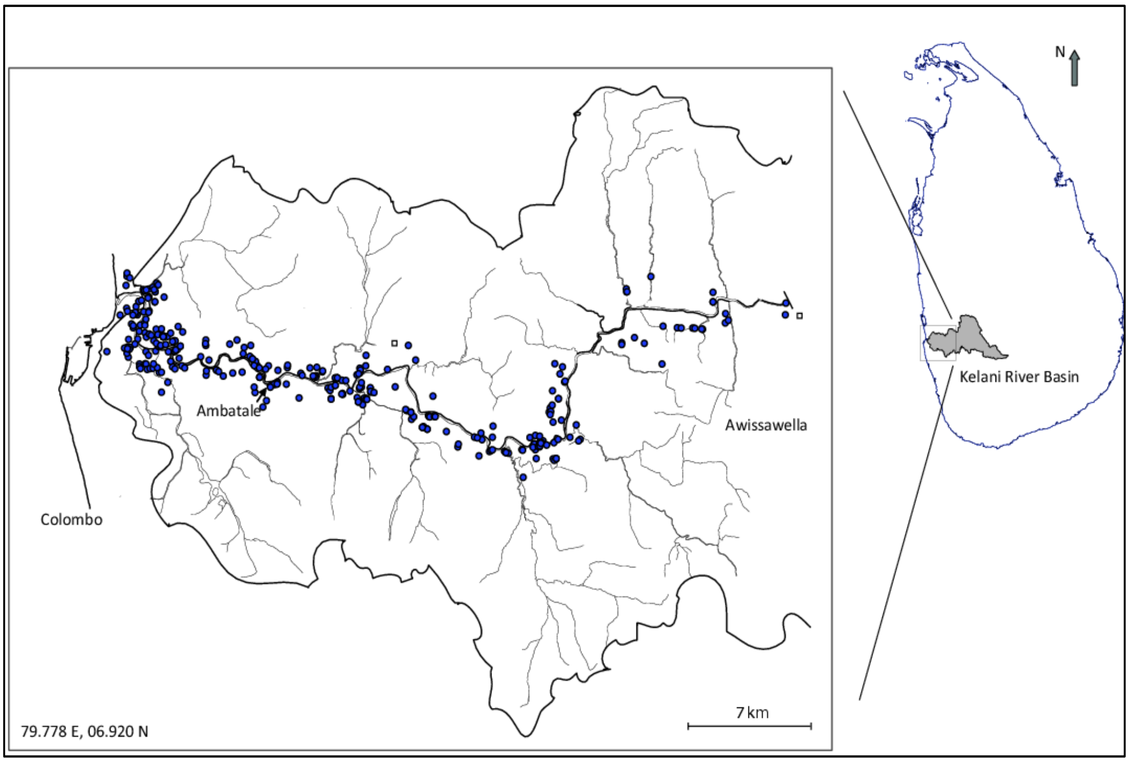

Figure 2.1: Spatial distribution of water polluting firms within the lower Kelani catchment

In addition to desirable outputs, these firms produce wastewater (i.e. undesirable output) in their industrial processes. The wastewater is discharged into the Kelani River either treated or untreated. The quantity of wastewater discharged by each firm was recorded during the survey. However, the quality of the wastewater (concentration of BOD, COD and TSS in mg/l) discharged by each firm was not available for the entire sample. Water quality data were available with the CEA only for 25 firms. Therefore, wastewater samples were collected, from the rest of the firms by visiting them (without prearranged appointments) with an environmental officer of the CEA and an officer from a private laboratory. Information on undesirable outputs was estimated based on water samples collected from the firms at the survey time. Therefore, we assumed the waste water volumes and concentration levels were not changing throughout the year.

The majority of firms (66 per cent) in our sample are high polluters. Although having an environmental protection licence (EPL) is a mandatory requirement for these industries, only 53 per cent of the firms currently have licences. Little more than half of the firms have end–of-the-pipe treatment plants and only 29 per cent of firms are found in compliance [10]with the existing concentration standards for all three pollutants. Even though firms classified as high polluters are monitored annually by the CEA, only 63 per cent of them have treatment plants. In this category, only 53 per cent currently own licenses with an even smaller proportion (49 per cent) complying with existing concentration standards. Among medium level polluters which accounts for 33 per cent of the sample and are monitored once every three years, only 52 per cent possess licences, 40 per cent own treatment facilities and 12 per cent comply with current standards.

Table 2.1: Descriptive statistics of output and input variables ('000s)

	Variable	Unit	Mean	Standard deviation
1	Total sales	US$	4700.36	17900.00
2	BOD load	Kg	3.78	15.67
3	COD load	Kg	6.74	26.87
4	TSS load	Kg	3.33	19.39
5	Raw materials	US$	1936.74	11700.00
6	Labour	US$	96.21	267.83
7	Energy use	US$	65.48	284.48
8	Service and operations	US$	42.74	204.44
9	Treatment cost	US$	3.02	6.09

For the estimation, we aggregated inputs into four categories: raw materials, labour, energy use, and services and operations as their costs. We also aggregated outputs into four: one desirable output (total sales) and three undesirable outputs (pollution loads of BOD, COD and TSS). Total sales are aggregated in US$ and pollution loads are reported in kilograms. Only some firms had end-of-pipe treatment facilities to for wastewater. For these firms, we recorded the cost of annualized capital and operating cost under treatment costs (Table 2.1).

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[10] Having a license or a treatment plant does not assure that a firm comply with regulations. We checked the compliance using concertation of pollutants in the wastewater samples.

Table 2.2: Mean cost share of each input by industry

Industry	No of Firms	Raw material	Labour	Energy use	Services and operations	Wastewater treatment
Chemical	6	0.607	0.235	0.092	0.065	0.001
Food	12	0.666	0.147	0.133	0.051	0.002
Beverages	5	0.509	0.242	0.123	0.092	0.035
Livestock farms	10	0.674	0.232	0.018	0.032	0.044
Vehicle service	25	0.469	0.375	0.038	0.083	0.034
Textile & leather	8	0.463	0.351	0.090	0.069	0.027
Mineral	5	0.773	0.109	0.093	0.021	0.004
Waste recycling	3	0.434	0.329	0.045	0.192	0.000
Total	74	0.561	0.276	0.070	0.069	0.024

Table 2.2 shows the cost share of each input by industry. Raw materials account for the biggest cost share in all industries followed by cost of labour, power and service and maintenance and the cost of wastewater treatment. The share of waste treatment is comparatively small, 0 to 4.4%; however, information on treatment cost is available only for the firms that have end-of-pipe emission treatment facilities.

2.5 Empirical results

In this section, we report shadow price estimates, abatement cost under different policy scenarios and the technical efficiency scores obtained from PLP (parameter estimates are shown in Table 2.3).

Table 2.3: Parametric estimates of input distance function for water polluting firms

Variable	Parameter	Values	Variable	Param	Values
lny1	∝1	-0.7923	lnx2x2	β13	-0.0209
lnx1	∝2	0.4261	lnx3x2	β14	-0.0098
lnx2	∝3	0.1110	lnx4x2	β23	0.0739
lnx3	∝4	0.0550	lnb1x2	β24	0.0001
lnx4	β1	0.4078	lnb2x2	β34	0.0000
lnb1	β2	0.0002	lnb3x2	γ11	0.0000
lnb2	β3	0.0014	lnx3x3	γ12	0.0192
lnb3	β4	0.0002	lnx4x3	γ13	-0.0017
lny1y1	∝11	-0.0932	lnb1x3	γ14	-0.0002
lny1x1	∝22	-0.0106	lnb2x3	γ21	-0.0005
lny1x2	∝33	0.0336	lnb3x3	γ22	0.0000
lny1x3	∝44	0.0135	lnx4x4	γ23	-0.0685
lny1x4	∝12	-0.0365	lnb1x4	γ24	0.0003
lny1b1	∝13	0.0000	lnb2x4	γ31	0.0002
lny1b2	∝14	-0.0003	lnb3x4	γ32	-0.0001
lny1b3	∝23	-0.0001	lnb1b1	γ33	-0.0001
lnx1x1	∝24	0.0545	lnb2b1	γ34	0.0001
lnx2x1	∝34	-0.0431	lnb3b1	γ41	0.0000
lnx3x1	β11	-0.0077	lnb2b2	γ42	-0.0004
lnx4x1	β22	-0.0037	lnb3b2	γ43	0.0002
lnb1x1	β33	-0.0001	lnb3b3	γ44	-0.0002
lnb2x1	β44	0.0004	Intercept	∝0	2.4205
lnb3x1	β12	0.0000			

Y1 : Total Sales (US$)
x1: Raw materials (US$)
x2 : Cost of labour (US$)
x3 : Cost of energy (US$)
x4 : Cost of services and operations (US$)

b1 : BOD load (kg)
b2 : COD load (kg)
b3 : COD load (kg)

2.5.1 Shadow prices

We computed shadow prices for the undesirable outputs (BOD, COD and TSS) using the parameters (Table 2.4) of the input distance function estimated by PLP. This was done using the shadow prices ratios as illustrated in the Eq. (2.8). The shadow price values are based on the marginal rate of transformation between undesirable and desirable outputs. Therefore, these values can be interpreted as marginal cost for pollution abatement for industries.

Table 2.4: Shadow prices of BOD, COD and TSS (US$/ kg)

Industry	No. of firms	BOD		COD		TSS	
		Median	Mean	Median	Mean	Medi	Mean
Chemical	6	16.57	43.26	6.22	15.74	6.61	10.60
Food	12	1.83	13.20	2.02	6.13	2.02	12.73
Beverages	5	.0008	60.11	0.01	65.22	0	0.00
Livestock farms	10	0.825	40.37	5.72	11.13	0.49	1.55
Vehicle service	25	2.51	12.85	5.68	12.52	7.46	19.61
Textile and leather	8	3.86	26.65	2.52	5.66	6.42	13.83
Mineral	5	18.4	42.30	7.24	24.95	7.13	19.31
Waste recycling	3	0.506	5.76	0.01	1.49	1.03	25.73
Total	74	3.02	25.48	4.41	14.76	3.24	13.59

On average, the cost of abatement of a kilogram of undesirable outputs is found to be US$ 25.48 for BOD, US$ 14.76 for COD and US$ 13.39 for TSS (Table 2.4). The shadow prices show a wide variation across firms: US$ 0 to 325.5 for BOD, US$ 0 to 251.8 for COD and US$ 0 to 168.37 for TSS. Figure 2.2 depicts the distribution of shadow prices for the three pollutants. The graph shows that shadow prices for three pollutants are within the range of 0-20 for majority of firms.

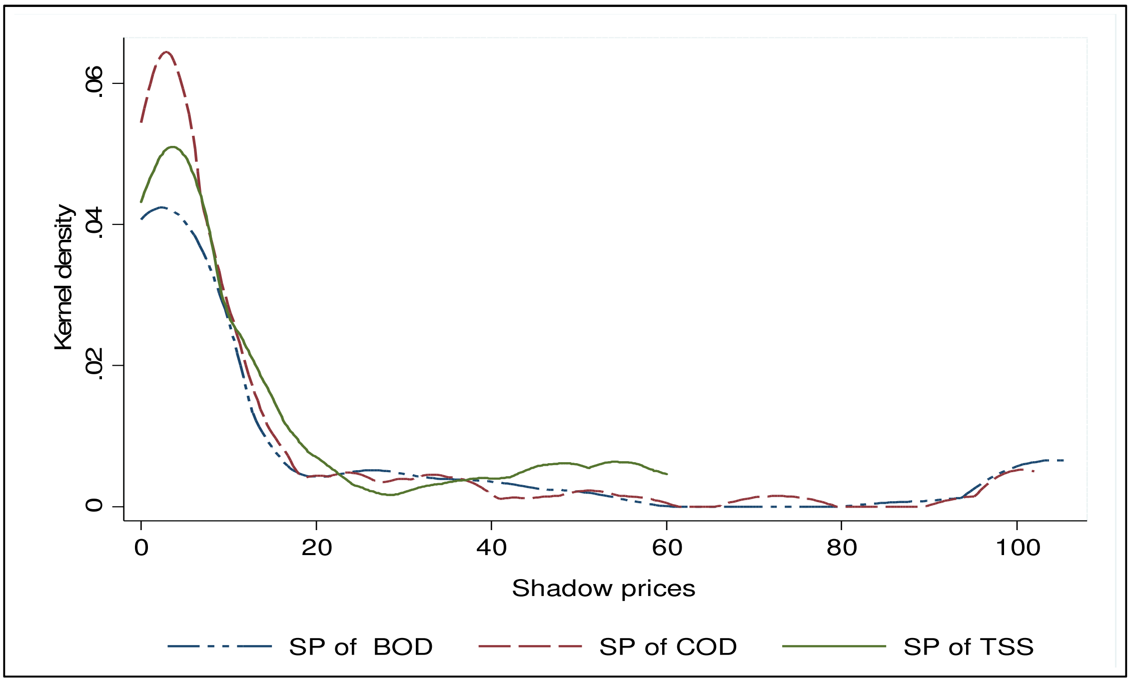

Figure 2.2: Kernel distribution of shadow prices

We undertook further an empirical analysis to understand the main reasons for variations in shadow prices of BOD (Table 2.5). The variation can be explained by the fact that our sample firms comes from different industries. For example, compared to vehicle servicing firms, the shadow prices for beverages and livestock firms are significantly higher. The variation of shadow prices of firms within the same industry is due to scale of operations[11] and the compliance to environmental regulations even though all firms are operating under the same regulatory emission standards (Table 2.5). Firms with bigger pollution loads tend to have lower shadow prices. However, whether a firm categorised by the CEA as a higher polluter was not found to be statistically significant in explaining the pollution load variations. We undertook similar analyses for COD and TSS and found the same set of variables significantly influencing the shadow prices.

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[11] *We used water consumption by firms as a proxy for scale of operation for water polluting firms.*

Table 2.5: Empirical analysis of factors affecting shadow prices

Dependant variable: Shadow price of BOD (USD/kg)		Adjusted R2 =0.2524	
Variable	Coefficient	Std. Err.	P>t
High polluters (A)	-4.083	15.824	0.797
Water consumption (in 1000 m3)	-0.009**	0.003	0.002
Industrial category			
Chemical	18.097	25.184	0.475
Food	25.371	19.746	0.204
Beverages	105.770**	33.373	0.002
Livestock	47.466*	20.405	0.023
Mineral	11.773	26.859	0.663
Textile	30.970	23.142	0.186
Waste recycling	24.668	33.580	0.465
Compliance with BOD standard	72.993***	15.621	0.000
Constant	-15.685	14.610	0.287

The Table 2.6 compares the differences in shadow prices of pollutants for compliant and non-compliant firms. Firms that are already complying with standards have very high shadow prices for all three water pollutants (Table 2.6). This means that those who are in compliance already operate in the upper segment of their MAC, because they've already abated. Hence the higher shadow prices. The mean shadow price for firms that do not adhere to existing standards is US$ 6.40, US$ 7.32 and US$ 9.75 for BOD, COD and TSS, respectively (Table 2.6).

Table 2.6: Shadow prices by compliance to the existing concentration standards

	Compliant firms			Non-compliant firms		
	BOD	COD	TSS	BOD	COD	TSS
Number of firms (n)	27	40	38	47	34	36
Mean shadow price (US$/ kg)	58.70 (16.25)*	21.10 (6.85)	17.25 (4.55)	6.40 (2.26)	7.32 (2.00)	9.75 (2.71)

** Standard deviations are reported in brackets*

2.5.2 Abatement cost under different policy scenarios

The results presented above provide information on abatement costs at the margin, given existing compliance patterns. It is also possible to use the estimated distance function to derive abatement cost curves under different levels of pollution. The cost curves can be generated for individual pollutants or a simultaneous pollution reduction of pollutants. For each firm, we simulated the marginal abatement cost of simultaneous reductions under the assumption that the firm's efficiency level would remain the same. Given the fact that the current regulation on effluent discharge to the water bodies based on concentration standards, we simulated total cost for firms to meet a range of concentration standards.

The scenarios (1-9) shown in Table 2.7 are based on different concentration levels of three main pollutants; BOD, COD and TSS. Scenario 9 shows the current effluent standards for three pollutants while scenario 1 shows the combination of highest concentration levels for three pollutants. Then we simulated the cost of simultaneous reduction of three pollutants from the current levels to the levels mentioned in each scenario. We report the corresponding abatement for each scenario as a percentage of effluent loads and also the abatement cost as percentage of total production cost and total revenue in the Table 2.7.

Table 2.7: Abatement cost simulations for policy scenarios based on simultaneous reduction of three pollutants.

Policy Scenarios	Concentration levels (mg/l)			Abatement as a % of effluent loads			Overall abatement cost (Million US$)	Abatement as a % of total production cost	Abatement as a % of total revenue
	BOD	COD	TSS	BOD	COD	TSS			
1	200	500	250	72	23	57	0.09	0.06	0.03
2	180	450	200	73	25	59	0.11	0.07	0.03
3	150	400	180	75	27	59	0.12	0.08	0.03
4	130	380	150	76	28	61	0.13	0.08	0.04
5	110	350	130	77	29	62	0.14	0.09	0.04
6	90	320	110	78	30	63	0.16	0.10	0.05
7	70	300	90	79	31	64	0.17	0.11	0.05
8	50	270	70	80	32	65	0.20	0.13	0.06
9	30*	250*	50*	81	33	67	0.23	0.15	0.07

**Indicates the current effluent standards for discharging wastewater to inland water bodies*

The cost estimates on overall industrial pollution treatment is not available in Sri Lanka. In India, for example the cost of water pollution treatment would account for 2.5 per cent of the industrial GDP (Kumar and Murty, 2011). A study on rubber industry conducted in Sri Lanka using data from 2003-2005 found that the pollution tax required to bring the average firm to compliance would be 8.7 percent of average annual turnover (Edirisinghe, 2014). Compared with these figures it is apparent that the overall cost for non-complying firms (in our sample) to meet the current regulatory standard is very low (0.15 per cent of total production cost and 0.07 percent of the industrial revenue). However, given the heterogeneity of firms and MAC, especially small firms and firms with high MAC cost would pay higher cost than the average values suggest.

The total abatement cost is comparatively high in the case of current concentration standards; 0.06 per cent of the total cost and 0.15 per cent of the total revenues for the firms (See Table 2.7) . As scale economies exist in pollution reduction, firms could save if they are allowed to first meet less stringent concentration standards. For example, lifting concentration standards from scenario 9 to 1 would reduce the costs significantly (Figure 2.3). The policy scenario 1 shows the pre-treatment standards of some common central waste treatment plants with considerably lower costs compared with existing emission standards. As the industries face higher individual costs in treating waste to very low concentrations, there would be a potential for cost saving if firms treat their waste to pre-treatment standards and direct the discharges to a common treatment plant. This would be a relatively low cost action to improving concentration levels from their current levels. However, currently this option is available only in certain industrial parks and areas of the country.

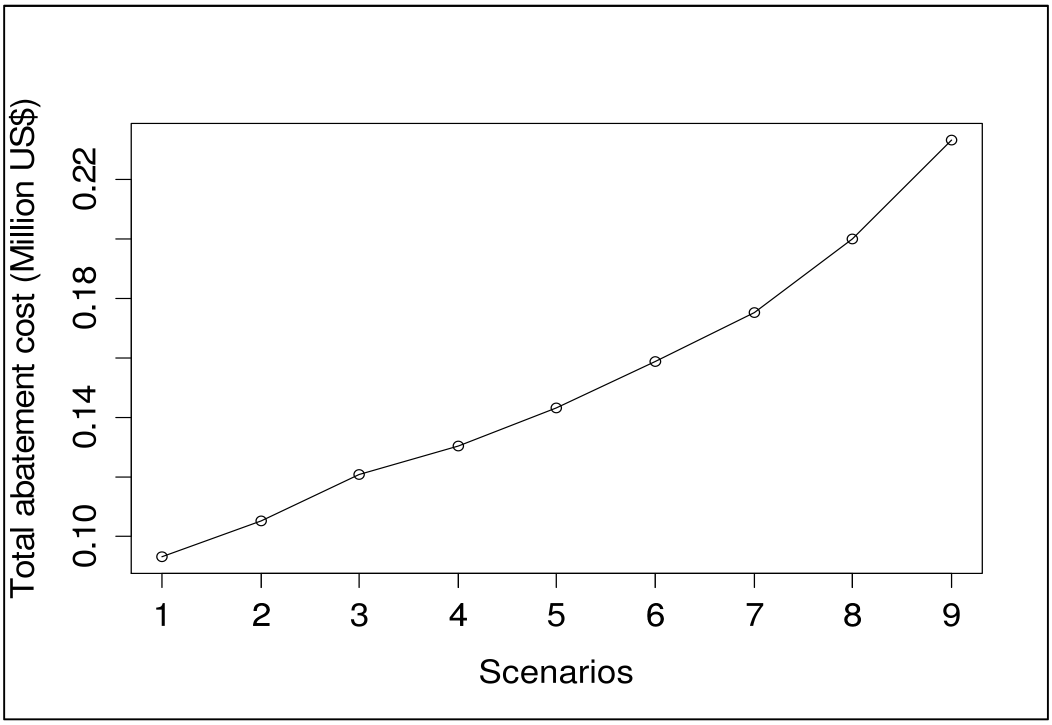

Figure 2.3: Total abatement cost and the policy scenarios [12]

2.5.3 Technical efficiency

The measures on technical (input) efficiency using input distance function frontiers are summarized by industry in Table 2.8. In general, technical efficiency estimates are low for all water polluting industries in the sample, indicating that there is untapped potential for efficiency improvement. The mean technical efficiency is 35 per cent implying that there is a substantial room for cost savings by reducing inputs while keeping the outputs constant. Similar studies that estimated technical efficiency scores for industries with undesirable outputs especially in developing countries report such low efficiency values. For example, the technical efficiency score for paper recycling units in Vietnam varied from 0.37- 1.00 (Van Ha et al., 2008) while the technical efficiency scores for Chines industrial provinces ranged from 0.16 to 1.00 (Zhang et al., 2008).

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[12] *The scenarios are based on concentration levels of pollutants and corresponding pollution loads, as reported in Table 2.7*

Table 2.8: Input efficiency based on parametric input distance functions

Industry	No of Firms	Efficiency	
		Mean	Median
Chemical	6	0.2671	0.1275
Food	12	0.2885	0.1589
Beverages	5	0.3106	0.1863
Livestock farms	10	0.4442	0.2968
Vehicle service	25	0.3938	0.3431
Textile and leather	8	0.1719	0.1322
Mineral	5	0.3438	0.2164
Waste recycling	3	0.6343	0.8259
Total	74	0.3500	0.2366

We carried out an empirical analysis of technical scores with industry categories, pollution category and degree of compliance to current regulation on concentration standards (Table 2. 9). Compared to vehicle services, food and textile industries found to be significantly less efficient. Firms with higher the degree of compliance, record low efficiency scores compared to other firms.

Table 2.9: Empirical analysis of factors affecting efficiency

Dependant variable: Firm efficiency	Adjusted R2 =0.0557		
Variable	Coefficient	Std. Err.	P>t
High polluters (A)	0.015	0.095	0.872
Industrial category			
Chemical	-0.124	0.138	0.372
Food	-0.325**	0.145	0.029
Beverages	-0.080	0.148	0.589
Livestock	-0.227	0.175	0.199
Mineral	-0.005	0.145	0.973
Textile	-0.326**	0.141	0.024
Waste recycling	0.007	0.216	0.975
Degree of compliance to standards	-0.004 *	0.002	0.050
Constant	0.725 ***	0.162	0.000

2.6 Conclusions and policy implications

Controlling water pollution in inland water bodies is one of the key challenges in developing countries given the dependence on surface water for drinking, industrial use, irrigation and recreational uses. In Sri Lanka, despite continuous deterioration of water bodies, there are no regulations that aim at achieving improved water quality targets or standards as the case of many developing countries. In other words, the environmental regulations in Sri Lanka are not linked to surface water quality objectives. In this study, we examined existing regulations on industrial water pollution, its cost implications and incentives for compliance by industries.

First, we investigated the cost of pollution for a representative sample of firms belonging to eight types of water polluting industries located in the Kelani river catchment. These industries operate under regulatory standards on emission concentrations but only 29 per cent of them are compliant with the standards. Using parametric input distance functions, we estimated industry and firm specific shadow prices (marginal costs) of water pollutants. Our results reveal a wide variation in shadow prices among firms and also firms within the same industry. The variations of firm-specific shadow prices are due to differences in scale of operation. The compliance with existing standards also contributes to the differences. Shadow price estimates for all three pollutants (BOD, COD and TSS) are significantly higher for the compliant firms compared to non-complaint firms.

Second, we simulated the potential total abatement cost for the firms under different policy scenarios for simultaneous reduction of concentrations including current regulation on three water pollutants. The overall abatement cost to bring non-complying firms to compliance is not very high considered as a percentage of total firm production cost and revenues. As marginal cost increases with lower concentration levels, firms with comparatively lower emission concentrations face higher marginal costs. Therefore, having regulation on uniform effluent concentration standards across all firms irrespective of their size and scale of production may not yield optimal results in terms of minimizing cost. Hence, the cost heterogeneity among firms makes a strong case for market based instruments such as effluent discharge tax that equalize marginal abatement cost among all polluting firms and provide least cost solution while achieving pollution reduction targets.

Third, we examine the technical efficiency of firms and our findings show that average efficiency is 35 per cent. This means the manufacturing firms can reduce 65 per cent of their inputs while keeping their current production constant. We also found that the firm efficiency is negatively related to the degree of compliance to current regulation; implying that there is no incentives for firms to comply.

The evidence on poor compliance and wide variations in shadow prices (MAC) makes a strong case for a new design of comprehensive environmental policy to control industrial pollution as an alternative to existing command-and-control regulations. The shadow price estimates can be used as guidelines to design market based policy instruments such as emission-based taxes or tradeable permits that would cap the level of pollution released into the river. The case for a serious consideration of alternative approaches is made stronger by the evidence of weak enforcement of current regulations. Therefore, setting appropriate economic instruments would provide incentives for firms to control emissions in socially optimum ways without imposing a greater burden on complying firms.

Chapter 3 : Industrial Pollution and the Management of River Water Quality: A model of Kelani River, Sri Lanka

Abstract

Water quality of the Kalani River has become a critical issue in Sri Lanka due to the high cost of maintaining drinking water standards and the market and non-market costs of deteriorating river ecosystem services. By integrating a catchment model with a river model of water quality, we develop a method to estimate the effect of pollution sources on ambient water quality. Using integrated model simulations, we estimate (1) the relative contribution from point (industrial and domestic) and non-point sources (river catchment) to river water quality and (2) pollutant transfer coefficients for zones along the lower segment of the river. Transfer coefficients provide the basis for policy analyses in relation to the location of new industries and the setting of priorities for industrial pollution control. They also offer valuable information to design socially optimal economic policy to manage industrialised river catchments.

Keywords:

transfer coefficients, industrial pollution, Integrated river model ,Kelani River, water quality

3.1 Introduction

The degradation of water quality in major rivers due to rapid urbanization and industrial development has become a major issue in developing countries (Schaffner et al., 2009). The development of infrastructure facilities supporting this expansion lags behind population growth and economic development (Qin et al., 2011, Biswas and Tortajada, 2009). As a result, the inadequate capacity of drinking water supply, sewer and wastewater treatment systems pose a serious threat to surface water resources and water quality. Poor water quality has adverse effects on the economy, human health and ecosystems (Schaffner et al., 2009). More effective management of surface water quality in developing countries is needed if the benefits of industrial development are not reduced by social and economic cost.

Water quality management is challenging due to the complexity of river dynamics and the influence of both natural and anthropogenic processes. Understanding the impact of anthropogenic activities requires information on pollutant discharge levels, the spatial distribution of pollution sources, and the spatial and temporal variation of water quality. Lack of systematic information in developing countries adds to this challenge. As most water pollutants are not uniformly mixed, the hydrological and chemical characteristics of a water body affect the mixing and transport of pollutants (Boyd, 2003). Therefore, the nature of the pollutants and the locations of discharges need to be considered in understanding the effect of pollutants on surface water quality (Benedetti et al., 2008). Water quality models can be used to estimate transfer coefficients that describe the impact of pollution sources on surface water quality (Boyd, 2003).

There are two broad approaches to water quality modelling: statistical (Bai et al., 2011) or numerical (Cox, 2003a) models. The use of statistical models requires comprehensive datasets representing spatial and temporal variations of physical and chemical parameters (Krishna et al., 2009, Shrestha and Kazama, 2007, Simeonov et al., 2003, Singh et al., 2005, Bai et al., 2011). Numerical models simulate hydrodynamic and water quality processes in rivers to model the surface water quality (Rauch et al., 1998, Schaffner et al., 2009, Wang et al., 2013, Chen et al., 2012, Momblanch et al., 2015, Cox, 2003a). These models are effective tools for simulating and predicting water pollution transport as a basis for river management (Wang et al., 2013).

Dissolved Oxygen (DO) and Biological Oxygen Demand (Simonovic and Fahmy) are key indicators of water quality and the health of the river ecosystem. BOD is a gross measure of oxygen demanding potential of the effluents. DO is largely affected by the waste influx, especially the organic particulate matter due to depletion of DO in the process of organic degradation (Babu et al., 2006). Many studies have been concentrated on DO-BOD modelling (Li et al., 2013, Purandara et al., 2012, Chen et al., 2012, Paliwal et al., 2007, Babu et al., 2006, Yang et al., 2011). However, few studies have estimated transfer coefficients for BOD or DO as a basis for economic policy analysis for river water quality management (Moffatt et al., 1991, O'Neil et al., 1983, Hanley and Moffatt, 1993, Hanley et al., 1998).

In this study, we configured a catchment- based hydrological model of water quality using MIKE[13] 21/3 Coupled model FM which is a state-of-the-art numerical tool to model river water quality. This was done by integrating a catchment model (MIKE-SHE) with a hydrodynamic and water quality (ECO Lab model). Using experimental simulations, we estimated zonal transfer coefficients (ZTCs). The ZTCs describes the impact of unit pollutant released in a particular zone on surface water quality with respect to a given river zone (Hanley, 2007, Boyd, 2003, Hung and Shaw, 2005). This information is vital for analysis of existing and alternative policies to manage river water quality. To our knowledge this is the first study to estimate river ZTCs of BOD and DO in a developing country context, given the limited availability of systematic data on the spatial and temporal variability of hydrological observation.

The Kelani River, is the most economically important river in Sri Lanka. It originates in the central hills of Sri Lanka and flows to the ocean through the capital Colombo. The lower section of the river runs through highly populated and two rapidly industrializing urban districts, Gampaha (2.3 million) and Colombo (2.3 million). These two districts

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[13] MIKE is a software tool for modelling water environments, developed by Danish Hydraulic Institute (DHI).

account for 25 per cent of the total population of the country (DCS, 2012). The population density is 3438 km^2 in Colombo and 1714km^2 in Gampaha. Only 31 per cent of the population in the country has access to piped water; but this rate is substantially higher (72 per cent) for Colombo and slightly lower (28 per cent) for Gampaha (DCS, 2012). On the other hand, the overall coverage of piped sewage facilities is only 2.5 per cent. Both districts have 25 per cent of total number of industries established in Sri Lanka (DCS 2004). The lower Kelani River catchment has individual firms as well as two main industrial parks: Biyagama and Seethawaka. Industrial parks are the areas specially designed for establishment of manufacturing industries with related facilities and also called export processing zones. Biyagama is the biggest industrial park in Sri Lanka, comprising of 65 firms, located in the area of about 180 hectares. The wastewater generated from Biyagama is discharged into Rakgahawatte canal (approximately 3km upstream from the Ambatale water intake) which connects to the main river stream at Rakgahawatte (see figure 3.1). Seethawaka industrial park employs about 30 firms is located in upstream Awissawella (about 55Km from the open ocean point in Colombo).

Apart from the ban on high polluting industries[14] upstream of Amabatale (Figure 3.1), where water is extracted for drinking, there are no other specific policies to manage river water quality. Ambient water quality standards are yet to be declared by the Central Environmental Authority (CEA), the regulatory authority for pollution control in Sri Lanka. Industries under high and medium polluting categories are legally required to comply with concentration standardswhen discharging effluentsto water bodies. The national concentration standards for water pollutants discharge into inland water bodies are given as 30mg/l for BOD, 250 mg/l for COD and 50 mg/l for TSS.

Firms located in industrial parks are under different management regimes. Industrial parks are managed by the Board of Investment (Sado et al.) in cooperation with the CEA. The firms located in the industrial parks have access to a common central treatment plant. These firms have to comply with pre- treatment standard before discharging wastewater to the common treatment facility. The treated wastewater from the industrial parks is released into the river.

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[14] *Industries have been categorised by the CEA based on their level of pollution under three main categories; A-high polluter, B-medium level polluters and C-small scale polluters*

The pollution transport process in the lower river is complex due to the oceanic influence where river flow is influenced by tides and mean sea level variability. The surface water of the lower Kelani River is polluted due to both industrial and domestic effluents (Herath and Amaresekera, 2007). The analysis of organic loads confirmed that the contribution of industrial loads is higher than domestic loads. Water quality at Ambatale, the water extraction point for drinking water supply, is such that a relatively high level of treatment is required. Observed water quality at many other locations of the river is highly degraded. Further downstream from Ambatale, poor water quality has a negative effect on the river ecosystem (Herath and Amaresekera, 2007). Low DO level found in river estuary and the tributaries is an indication of poor water quality which is endangering fisheries and aquatic life. Therefore, the current policy and practice on effluent discharge into the lower Kelani River is inadequate.

The objectives of this paper are:(1) configure an integrated model of water quality to estimate the effect of pollution sources;(2) suggest river zones based on simulated spatial and temporal variation of river hydraulic conditions and water quality; and (3) estimate the ZTCs from experimental simulations.

The paper is structured as follows. Section 3.2 describes the study area, River Kelani. Section 3.3 presents the methods and materials including integrated model setup, forcing data and sensitivity analysis. Section 3.4 presents and discusses model results including estimation of transfer coefficients. Section 3.5 concludes the paper.

3.2 Kelani River

Kelani River is the fourth longest river (144 km) in Sri Lanka which originates from the mountain range in central hills mountain range and drains an area of 2292 km^2 until it reaches the Indian Ocean in Colombo on the west coast of Sri Lanka (Figure. 3.1). The land use in the upper catchment of the basin is mainly tea plantations and forested lands. The middle and lower catchments are covered with rubber plantations and paddy fields (Chandimala and Zubair, 2007). The entire catchment receives annual average precipitation of 3880 mm from two monsoons; Northeast monsoon during December to February and Southwest monsoon during May to September

(Chandimala and Zubair, 2007). The Northeast monsoon generates average rainfall of 124 mm/day varying from 49 to 223 mm/day. Rainfall from the Southwest monsoon varies from 144 to 307 mm/day. Out of annual surface runoff volume (8600 million m^3) of the river, 65 per cent discharges in to the Indian Ocean (Herath and Amaresekera, 2007). The flow rate of the river during monsoon periods is about 800 to1500 m^3/sec while 20-25 m^3/sec during the dry period.

The selection of the lower Kalani River (55 km from the open ocean point) for this study was guided by the fact that this is the most polluted segment of the river (Herath and Amaresekera, 2007). The lower end of the river is influenced by tides whose signals can reach about 15 km inland from river mouth in Colombo. The oceanic tide in this region is mixed-semi diurnal with spring tidal range of 0.7 m. There is also significant seasonal mean sea level signal with annual amplitude of about 0.3 m (Wijeratne et al., 2008). The mean sea level is highest during the Northeast monsoon and lowest during Southwest monsoon. Early in each year shows low rainfall and river discharge (16-200 m^3/s) and later in the year higher discharge varying from 18 to 800m^3/s. As a result of high mean sea level and low discharge, the extent of tidal signal and salt water intrusion distance is maximal during January to March.

The River supplies 80 per cent of Colombo’s drinking water. In addition, recreation, irrigation and use for livestock and industrial purposes are common along parts of the river. The river and its tributaries are intensively utilised for various basic needs such as bathing, washing and homestead agriculture. The main stream of the river and its estuaries are important ecosystems. Water quality in the river has been a concern since the 1980s due to sporadic fish mortality. The absence of regular monitoring of water quality has made it more difficult to assess the level of pollution and potential human health impacts (Silva, 1996). In 1999, a study undertaken by the Danish Hydraulic Institute identified that pollution levels at Ambatale (the main intake point for drinking water) due to industrial and domestic discharge as a threat to the Colombo water supply. Based on this finding, the government made a policy decision to restrict establishment of high polluting industries upstream of Ambatale as some industrial pollutants are difficult to remove by even intensive water treatment processes (Herath and Amaresekera, 2007). A program to monitor water quality was initiated in 2002 with the objectives of reviewing existing policy on pollution standards. The analysis of data collected in this program revealed that the water quality at Ambatale is not suited for drinking without intensive treatment such as conventional method which is a combination of chemical and physical processes such as coagulation, segmentation, filtration and disinfection.

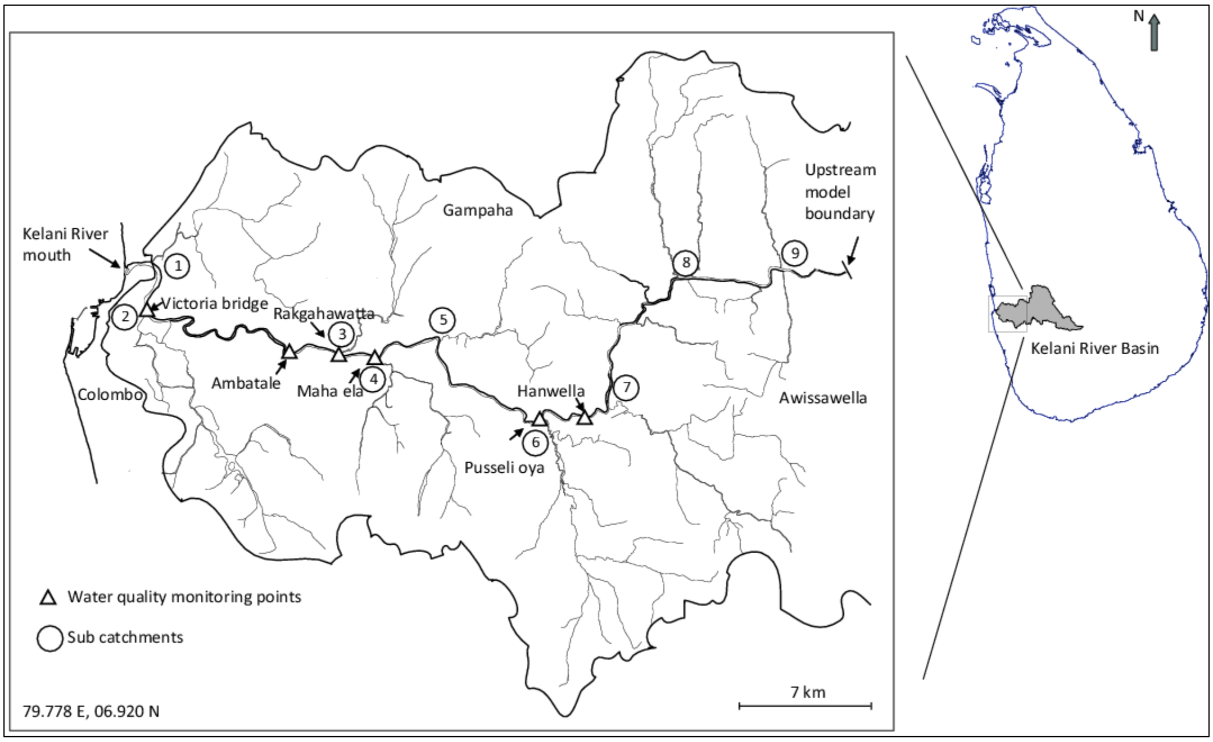

Figure 3.1: Study area -Lower Kelani river catchment and nine sub- catchments

Coliform levels in many monitoring points of the river exceeds the quality standard of drinking water even with conventional treatment. The presence of heavy metals such as Chromium and Lead was above acceptable levels while the presence of nutrients loads was lower than expected perhaps due to trapping of nutrients by hydropower reservoirs in the upper catchment of the river (Herath and Amaresekera, 2007).

3.3 Materials and methods

3.3.1 Model setup

We configured a catchment- based hydrological model of water quality for the River using DHI MIKE (DHI, 2004) modelling tool to simulate spatial and temporal variation of hydrodynamic and water quality measures. MIKE-SHE catchment model as inputs was coupled to a hydrodynamic (HD) and water quality (ECO Lab) model. The model setup is represented in Figure 3.2.

3.3.1.1 Catchment model

MIKE-SHE (DHI, 2012 c) uses a conceptual and physical-based method which is ideal for integrated catchment modelling with the flexibility of different spatial scales and complexity based on the requirements of the problem (Michael and Douglas, 2005). MIKE SHE hydrologic processes include overland flow, interception, infiltration into soils, evapotranspiration from vegetation and subsurface flow in the saturated and unsaturated zones, and their interactions (Refsgaard and Storm, 1995, Graham and Butts, 2005).

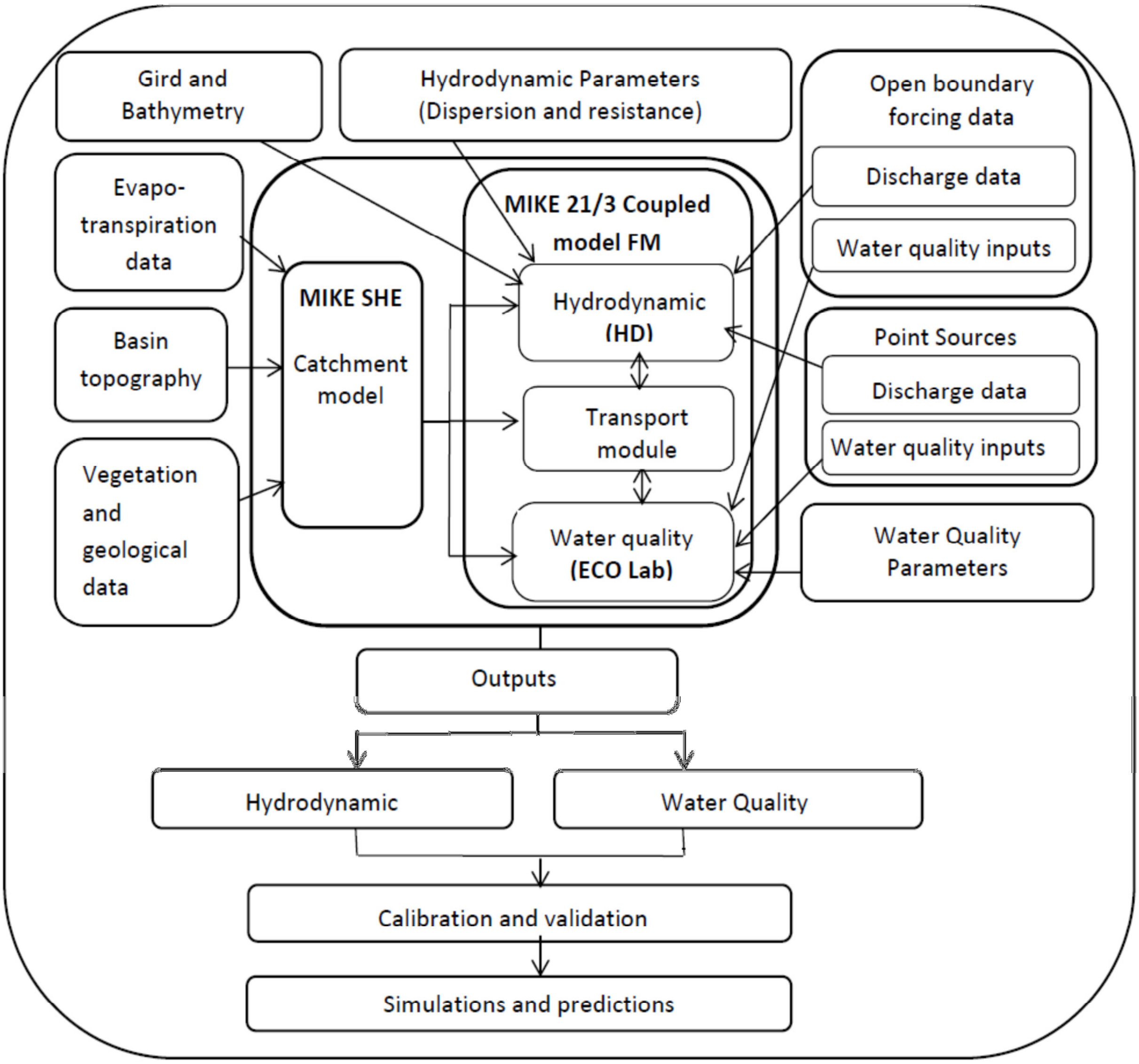

Figure 3.2: Model schematic

3.3.1.2 Hydrodynamic

The MIKE 21/3 Hydrodynamic model is based on the numerical solution of three-dimensional incompressible Reynolds averaged Navier-Stokes equations using Boussinesq and hydrostatic assumptions. The spatial discretization of the primitive equations is performed using a cell-centred finite volume method (DHI, 2012 a). The model consists of continuity, momentum, temperature, salinity and density equations, and is closed using a turbulent closure scheme (DHI, 2012 a). The transport and dilution mechanisms based on advection-dispersion can be integrated in the ECO Lab simulation.

Concentration of a pollutant in a water body can be expressed in the advection-dispersion equation (Eq. 3.1).

$$\partial C/\partial t = AD_c + P_c \tag{3.1}$$

Where AD_c is the rate of change in concentration due to advection (transport based on hydrodynamics) and dispersion including sources and sinks. P_c describes the biological and chemical transformation processes affecting state variables such as Dissolved oxygen (DO) in an ecosystem (DHI, 2012 b). DO is a key measure of river water quality (James, 2002). Low concentration of DO may result in fish mortality, odours and aesthetic nuisances (Cox, 2003b). Oxygen in the river water is produced by photosynthesis of aquatic plants and consumed by the respiration of plants, animals, bacteria, BOD degradation process and sediment oxygen demand. The river is re-aerated through the interchange of atmospheric oxygen. Concentration of DO is largely affected by the waste influx that causes depletion of oxygen due to the process of degradation of organic matter. BOD is a measure of oxygen demand potential of the waste. Therefore, DO and BOD is considered as two important parameters of waste assimilation capacity of coastal rivers (Babu et al., 2006).

3.3.1.3 Water quality

To simulate the dispersion and transport of the water quality measures, the water quality model ECO Lab (DHI 2011b) was coupled to the hydrodynamic model. ECO Lab uses predicted flow velocity from the hydrodynamic model to calculate the concentrations of the water quality measures. The ECO Lab module simulates the spatial distribution of state variable concentrations based on three processes; advective transport, physical, biological and chemical transformation processes and settling. The concentration of water quality variables; Biochemical Oxygen Demand (Simonovic and Fahmy), Dissolved Oxygen (DO), Faecal Coliforms (FC) and Total Coliforms (TC) were specified using field observations for each point source (Table 3.1) and open boundaries (open sea and river upstream). The advections of materials were incorporated using transport module (see Figure 3.2). This can include sources, connected sources and sink, therefore is an ideal tool for assessing the effect of discharged pollutants. The MIKE ECO Lab has several water quality templates starting from very simple DO- BOD modelling (level1) to advance modelling in different levels. Depending on data availability, we selected level 2, where the model calculates oxygen balance using only the processes modelled in equation (3.2). Therefore, the DO balance equation can be written as

$$\begin{aligned}
&dDO/dt = +K_2 \cdot (C_s - DO) \quad (re-aeration)\\
&-K_{d3}. \cdot BOD \cdot \theta_{d3}^{(T-20)} \cdot DO^2/K_s + DO^2 \quad (dissolved\ \ BOD)\\
&-R_{20}\ .\theta_2^{(T-20)} \quad (respiration)\\
&+P \quad (photosynthesis)\\
&-B_1 \quad (sediment\ oxygen\ demand)
\end{aligned} \tag{3.2}$$

Where,
$\mathrm{C_s}$ is the saturation concentration and $\mathrm{K_2}$ is the re-aeration constant. The constants included in the section on dissolved BOD are $\mathrm{K_{d3}}$ -degradation constant at 20^0 C for dissolved organic matter and $\mathrm{K_s}$- Half saturation constant, BOD decay and nitrification. θ_{d3} and θ_2 are Arrhenius temperature coefficient for dissolved organic matter and respiration respectively. $\mathrm{R_{20}}$ is the respiration rate at 20^0 C.

The equation (3.2) illustrates the major processes that affect changes in ambient DO levels; re-aeration, dissolved BOD levels, respiration, photosynthesis and sediment oxygen demand. Reaeration is the process describing the interchange of oxygen between the dissolved oxygen in the water and the atmosphere. The expression includes a saturation level for oxygen in water Cs that depends on the salinity and temperature. The Cs value of 8.7 mg/l (22 ^{o}C) was used in the model.

3.3.2 Model forcing/input data

The contribution of stream flows of nine sub-catchments connected to the lower Kelani River was captured as point sources with the use of hydrometric network (see Figure 3.1) to configure the catchment model using MIKE SHE. The Digital Elevation Model (Willmott et al.) was generated combining E-TOPO and digitized 1:10,000 survey topographical maps. The geology and land uses, remote sensing methods (aerial photographs) and field explorative geological mapping and Google earth were used to create the digital geological map and the land use map of the study area. The vegetation, crop cycles were assumed to be the same for whole simulation period. Meteorological variables such as rainfall and evaporation were obtained from three weather stations in the study area.

The coupled hydrodynamic and ECO Lab modules were initialized with the observed hydrodynamic and water quality parameters from 2004. A triangular element flexible mesh[15] (5-20 m) was applied for the lower Kelani River from open ocean point[16] in Colombo to Awissawella upper boundary (Figure 3.1).

The model river bathymetry was generated using cross sectional depth data[17]. The spatial resolution of the unstructured grid varies from 5 to 10 m horizontal cells in the lower river. The HD model was forced using river discharge data (from the Department of Irrigation) at upper boundary and water level data (Colombo tide gauge) at the open ocean boundary (see Figure 3.1). State variables for ECO Lab module; concentration of BOD, DO, FC and TC, temperature and salinity were specified under initial and boundary conditions and for each point source. The biweekly water quality data[18] for this study came from 2 institutes (The Central Environmental Authority (CEA) and The National Water Supply and Drainage Board (NWSDB). The simulated results from catchment model (MIKE SHE) served as inputs for the river coupled model.

Point source data for the coupled model were from industries, households in underserved settlements[19] and sewage outfall near to the river. We selected the industries located in the catchment area within 1 km of the river from the industrial database from the Central Environmental Authority (see Figure 3.3). Pollution loads from industries were estimated based on type of industry,[20] water usage, availability of treatment facility (see Table 3.1). Actual data on wastewater discharge from two main

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[15] *The grid cells vary in size and shape throughout the model domain (flexible mesh). Flexible meshes, also known as unstructured triangular grids.*

[16] *Referred as river mouth in the Figure 3.1*

[17] *Ten river cross sections were obtained from National Aquatic Resources Research and Development Agency (NARA), Sri Lanka*

[18] *The dataset of water quality along few monitoring points along the lower Kelani River has been collected under the Clean Rivers (Pavithra Ganga) programme, which was initiated to establish an integrated management framework for river basin management.*

19 *Poor communities live in shanties and slums are refereed as underserved settlements*

[20] *We conducted a survey of representative sample of industries with in the river catchment. Based on survey data, BOD loads were estimated for the industries which were not in the sample, taking industrial type, wastewater consumption and availability of treatment facility into account.*

industrial parks (Biyagama and Seethawaka) located closer to the lower Kelani river was collected from the Central Environmental Authority. The pollution loads from these two industrial parks were calculated assuming that they are complying with the existing concentration standards for selected water quality parameters.

The calculation of domestic waste loads was a difficult task as data on domestic discharge is not reported consistently. Using data from population Census collected by the Department of Census and Statistics (DCS), Sri Lanka, we selected underserved settlements without sanitation facilities located along the lower Kelani river.

Table 3.1: Daily wastewater discharge and pollution loads from point sources

		Daily discharge (cm^3/day)	Pollution load (BOD Kg/day)
Individual firms			
Chemical	(54)	1,059	156
Food	(83)	39,210	2,763
Hospital	(2)	97	31
Mineral	(61)	9,413	191
Plastic recycling	(5)	10	7
Hotels	(5)	108	14
Vehicle services	(69)	269	25
Solid waste	(8)	1,672	430
Textile	(36)	474	86
Industrial parks			
Seethawaka (~30)		10,000	300
Biyagama (~65)		15,000	450
Underserved settlements	(3177)	86,781	2,170
Sewage outlet		250,560	5,011
Total		**414,654**	**11,634**

We calculated pollution loads from the households based on average water consumption and the standard concentration of water quality parameters of domestic sewage. Apart from individual households, data[21] on sewage outfall located at Mutwal (located within the model domain) in few kilometres next to the ocean outfall in Colombo was included in the model.

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[21] *ADB Technical Assistance Consultant's Report 2009 on Sri Lanka: Assessing Colombo Municipality Wastewater Systems.(Financed by the Technical Assistance Special Fund) prepared by Lanka Hydraulic Institute Ltd, Colombo, Sri Lanka)*

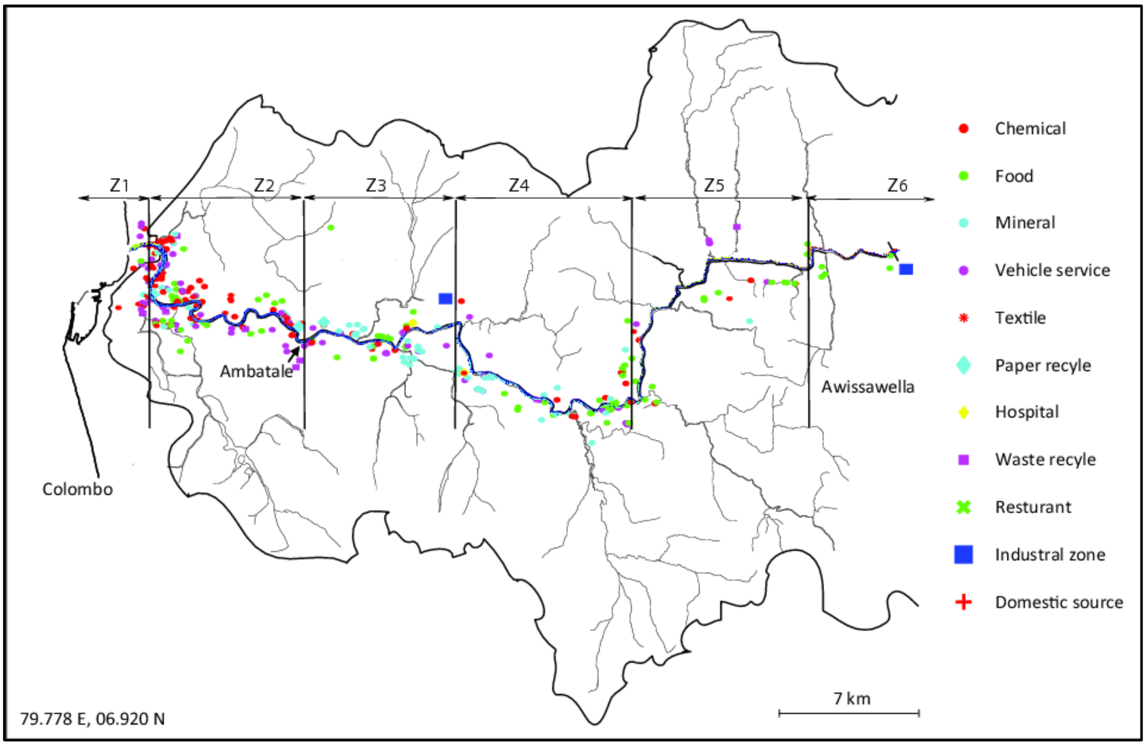

Figure 3.3 : Spatial distribution of point sources and demarcation of zones

Although we included main sources of coliforms (sewage outfall and underserved settlements and livestock industries) in our model, we couldn't capture all sources due to the haphazard nature of discharge data. Most discharges are not reported. In addition, during floods some of the septic tanks overflow into the river. Therefore, our study is mainly confined to industrial pollution where we can attribute to the effect of industries[22].

The baseline model simulations with realistic boundary forcing were conducted from 2004-2011. Our model time step was set to 30 sec, which satisfied hydrodynamic CFL condition. The model outputs of hydrodynamic and water quality were obtained in 6 hour intervals.

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[22] *We believe higher levels of coliforms need to be handled using a different management approaches than managing industrial pollution such as creating public awareness, relocation programs to eliminate underserved settlements on river banks and increase of public access to sewerage systems*

3.3.3 Sensitivity analysis

We performed sensitivity analysis to understand how model outputs change with respect to input parameters. Two parameters; sediment oxygen demand and BOD decay rate were simulated by changing one parameter at a time keeping all other variables constant. The changes in sediment oxygen demand did not change output results. However, the output results were changed with changes in BOD decay rate values. For example, the simulations with different BOD decay rates 0.1, 0.5 and 0.9 and output results of BOD and DO are shown in Figure 3.4. Higher BOD decay rates resulted in lower BOD levels and higher DO levels. Based on the nature of waste discharged into the river we selected BOD decay rate as 0.5 in our baseline and other simulations.

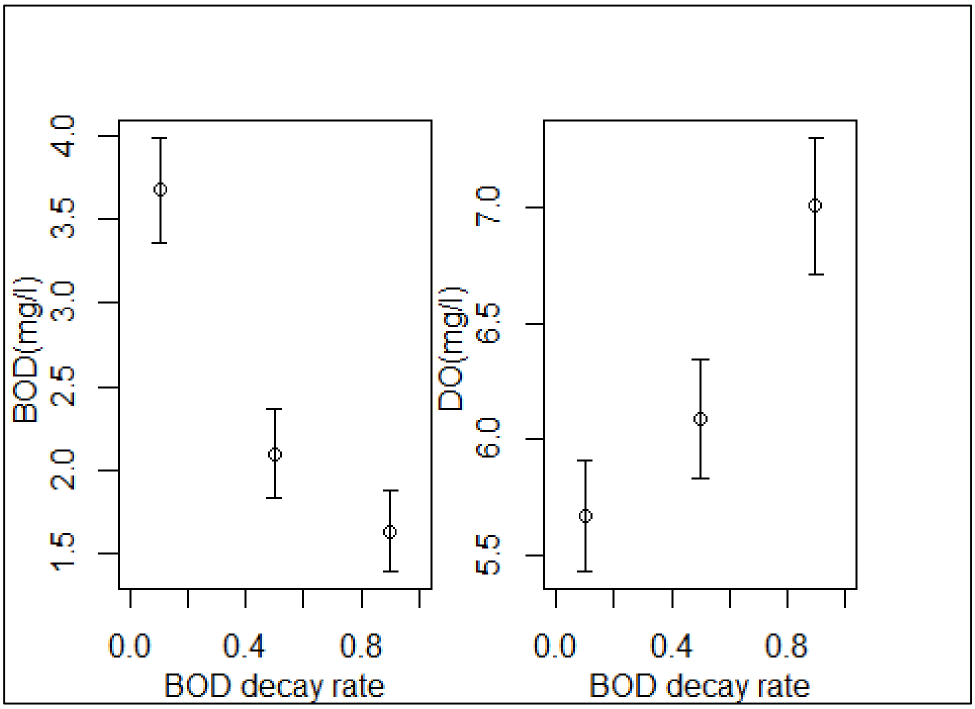

Figure 3.4: Sensitivity analysis; changes in BOD decay rate with ambient BOD and DO levels

3.4 Results and Discussion

3.4.1 Model and observational data comparison

We used refined statistical index of model performance (d_r) to validate model data with observations. It is a reformulation of Willmott's (1981) index of agreement (d).

The refined index of agreement (*d_r*) is dimensionless and takes values from -1 to 1 where -1 indicates poor agreement between the predicted *(P)* and the observed (*O*) and 1 indicates the perfect agreement (Willmott et al., 2012). The equation (3.3) and (3.4) show how the index values are calculated. C is a constant which is equal to 2.

The HD model was validated against measured water levels. The model reproduced the water level measured at Ambatale gauge site to a high degree of accuracy, with a skill level of 0.9 achieved in the comparison. We validated the baseline water quality model predictions for BOD and DO with the observational data at 4 locations, based on the availability of observational data with temperature and the time of measurements recorded (see Table 3.2) .The skill level index values (d_r) indicate a good agreement in most of the locations. The overall model performance in relation to BOD is 0.46 and 0.49 for DO. The overall model index value is closer to 0.5, which means the sum of error magnitudes is one half of the sum of the magnitudes of perfect model deviations and observed deviations.

$$d_r = 1 - \sum_{i=1}^{n} |P_i - O_i| \Big/ C \sum_{i=1}^{n} | O_i - \bar{O}| \ , \quad \text{when} \sum_{i=1}^{n} |P_i - O_i| \leq C \sum_{i=1}^{n} |O_i - \bar{O}| \tag{3.3}$$

$$d_r = C \sum_{i=1}^{n} |O_i - \bar{O}| \Big/ \sum_{i=1}^{n} | P_i - O_i | - 1 \ , \quad \text{when} \sum_{i=1}^{n} |P_i - O_i| \geq C \sum_{i=1}^{n} |O_i - \bar{O}| \tag{3.4}$$

Table 3.2: Model validation along the lower Kelani River

Monitoring locations	Chainage (km) from open ocean point	Refined index of model skill	
		d_r_BOD	d_r_DO
Victoria	4	0.44	0.32
Ambatale	15	0.46	-0.37
Mahaela	22	0.45	0.15
Pusselioya	32	0.39	0.44
Overall	55	0.49	0.46

The plots against simulated and observed data for downstream end and an upstream monitoring location are shown in Figure 3.5. Plot for each location shows the simulated BOD and DO values and 95 per cent confidence interval (upper and lower limits) and the corresponding observed values. Among 4 locations, only two locations (Victoria and Pusseli Oya) had regular data recorded with time of observations for every two weeks from 2004-2011.

3.4.2 Relative contribution of different sources to ambient water quality

Once the baseline was validated, we conducted series of experimental simulations. Our first experiment was to find out relative contribution of industrial and domestic sources, given the background contribution of sub-catchments. The contribution of sub-catchments may be due to natural processes (Sánchez-Chóliz and Duarte, 2005), urban runoff and non-point sources from agricultural lands. We performed two simulations; 1) baseline without all industrial sources and 2) baseline without industrial and domestic sources. Using simulated values, we computed the contribution of industries and domestic sources to the change of mean BOD and DO levels (Table 3.3 & 3.4). The contribution of industrial sources is high in upstream monitoring locations compared to locations closer to open ocean point. The contribution of domestic sources to the BOD levels is very low except in Victoria which is closer to the domestic sewage outlet located a few kilometres away from the river (see Table 3. 3).

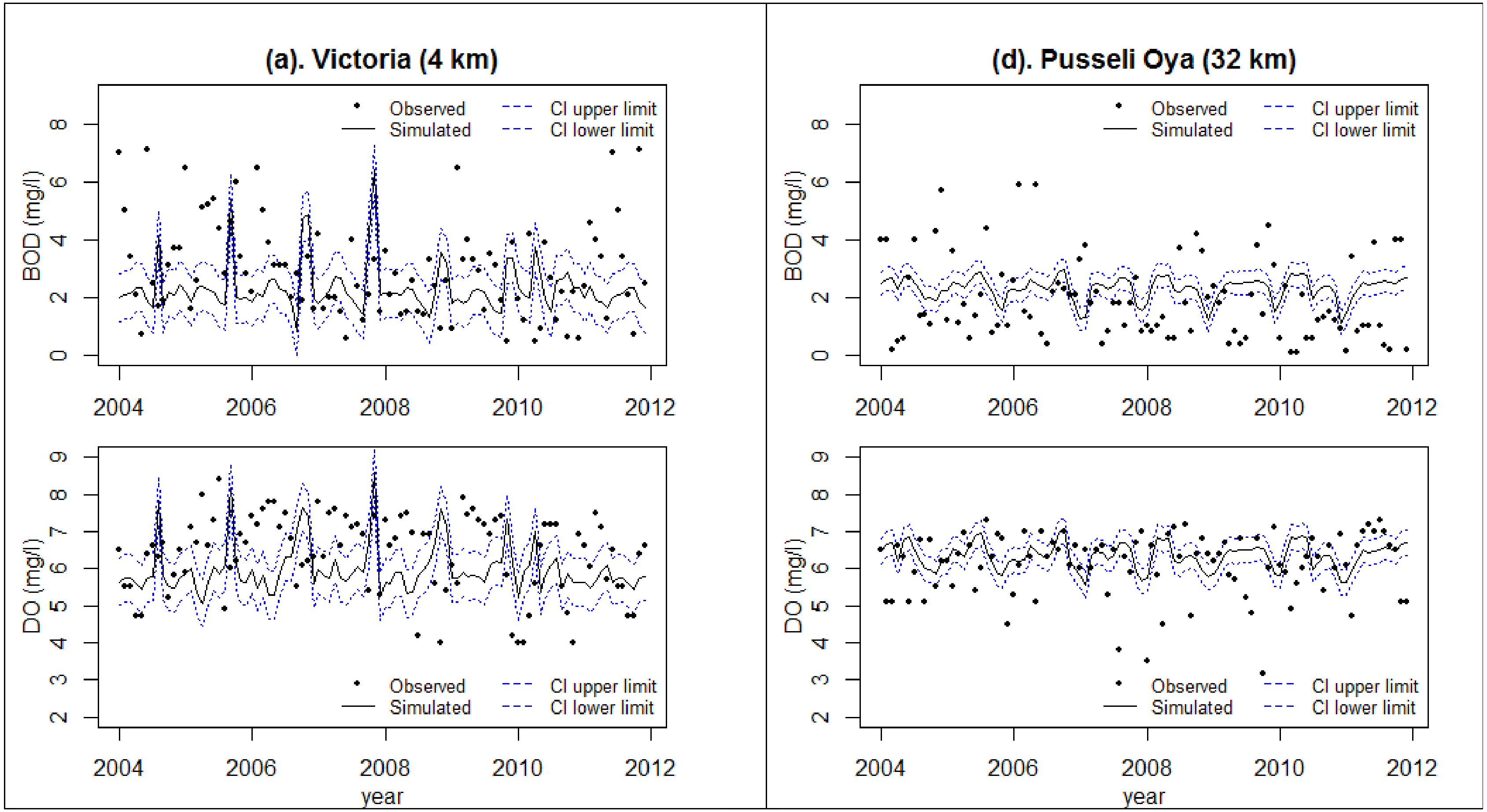

Figure 3.5: Validation plots for the downstream end (Victoria) and an upstream monitoring location at Pusseli oya

Industrial sources reduce the DO levels and the contribution has gradually increased from Open Ocean to upstream Hanwella. As observed in BOD levels, the contribution from domestic sources for DO is comparatively low except in Victoria where influence from the sewage outfall is substantial (Table 3. 4).

Table 3.3: Contribution of different sources to mean ambient BOD (mg/l) levels

Location	Chainage* (km)	Baseline model	Industrial contribution	Domestic contribution	Catchment contribution
Victoria	4	2.3493	0.1107	0.0310	2.2076
Ambatale	15	1.8129	0.1832	0.0000	1.6297
Kaduwela	20	2.0526	0.2267	0.0000	1.8259
Maha Ela	22	1.9876	0.2200	0.0001	1.7677
Pusseli Oya	32	2.2996	0.3387	0.0000	1.9609
Hanwella	34	2.4901	0.3717	0.0000	2.1185

** Distance along the River from the open ocean point*

The contributions of catchment came out as the biggest for both BOD and DO levels. However, it was not possible to separate out contribution of natural processes and anthropogenic non-point sources within catchment due to lack of data. This suggests a need of further research on non-point source pollution due to different agricultural practices in the middle and lower catchment.

Table 3.4: Contribution of different sources to mean ambient DO (mg/l) levels

Location	Chainage (km)*	Baseline model	Industrial contribution	Domestic contribution	Catchment contribution
Victoria	4	6.0658	-0.1189	-0.0014	6.1862
Ambatale	20	5.9288	-0.1743	-0.0001	6.1033
Kaduwela	15	6.1235	-0.2167	-0.0001	6.3403
Maha Ela	22	6.1640	-0.2129	-0.0001	6.3770
Pusseli Oya	32	6.3282	-0.2865	0.0000	6.6147
Hanwella	34	6.3949	-0.2849	0.0000	6.6798

** Distance from open ocean point*

3.4.3 River zoning and seasonal variability

Given the number of pollution sources it was not practical to find the impact of each pollution source. Therefore, we divided the lower Kelani River into 6 main zones based on the variation of simulated BOD and DO levels (Figure 3.3) and hydraulic characteristics along the river and actual purpose of the river water use. Zonal approaches has been used by many environmental authorities to reduce the transaction cost of managing water pollution where zones are defined on the basis of areas with very close dispersion characteristics of pollutants (Hung and Shaw, 2005, Yang et al., 2011).

The river zoning identifies the area from the open ocean point to Victoria as Zone 1, upstream Victoria to Ambatale as Zone 2, upstream Ambatale to Malwana as Zone 3, upstream Malwana to Hanwella as Zone 4, Hanwella to Ranwala as Zone 5 and Ranwala to Seethawaka as Zone 6. Exact spatial boundaries of the zones are marked in Figure 3.3.

We observed considerable variation in mean BOD values during dry period (January to April) and the wet period (May to December) in all locations. Dry periods record higher mean BOD values due to low flow conditions and high temperature. However, the pattern of variation along the river during both seasons was similar. In addition, variation of the DO along the river also followed the same pattern (see Figure 3.6).

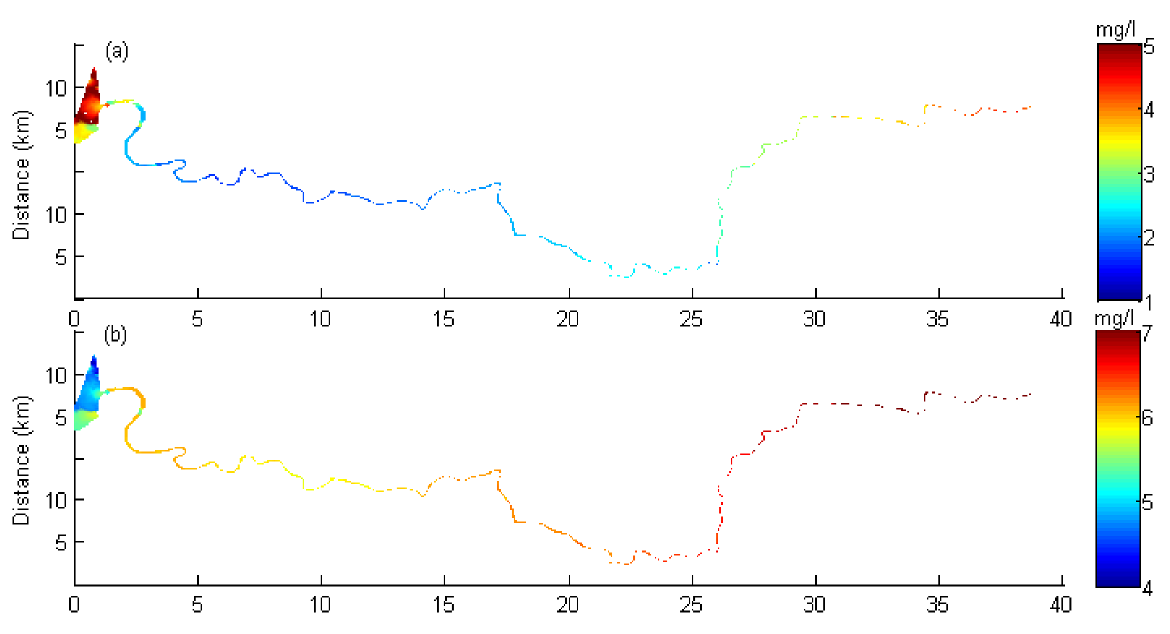

Figure 3.6: Variation of (a) BOD and (b) DO levels along the river

3.3.4 **Transfer Coefficients (TCs)**

The simulations were undertaken by excluding the pollution loads from each zone (see Figure 3.3). The Table 3.5 shows the experimental design that we utilized to calculate the impact of each zone on ambient water quality for specified zones along the lower Kelani River. Z1 – Z6 are six zones. For example in the experiment 1, we exclude industrial point sources located in the Zone 1 from our baseline model.

Apart from individual industries, Zone 3 includes Biyagama industrial park (IB) and zone 6 accommodates Seethawaka industrial park (IS). Therefore, we undertook two additional experimental simulations (Exp. 7 and Exp. 8) to understand the impact of these industrial parks. Each experiment was conducted over a two year period (2009-2010)[23]

Table 3.5: Experimental design for simulations

	Experimental simulations							
	Exp 1	Exp 2	Exp 3	Exp 4	Exp 5	Exp 6	Exp 7	Exp 8
Baseline (2009-2010)	Baseline excluding Z1	Baseline excluding Z2	Baseline excluding Z3	Baseline excluding Z4	Baseline excluding Z5	Baseline excluding Z6	Baseline excluding IB	Baseline excluding IS

Impact on BOD in a particular zone is calculated by deducting the BOD level of the baseline simulations from the respective BOD values gained from the simulations. For example, impact of Zone 1 in terms of BOD can be obtained by subtracting BOD simulations of the Exp1 from the BOD simulations of the baseline. Similarly we computed the values for changes in DO levels for all zones. The estimations were for both dry and wet periods. TCs were calculated using the impact and the pollution loads of each zone. The transfer coefficient of Zone 1 with respect to Zone 2 describes the ambient water quality change (in BOD /DO) of the zone 2 if 100kg of BOD per day is added to the Zone 1. For example, adding 100kg of BOD in Zone 1 will increase the ambient BOD levels in Zone 2 by 0.0106 and reduce DO levels by 0.0044. We report

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[23] *Baseline simulations were undertaken for 8 years period. Due to long computational times for model runs, we selected two representative years (2009-2010) for experimental simulations.*

mean ZTCs, minimum, maximum and standard deviations (SD) for BOD and DO in both dry and wet seasons (Table 3.6 and 3.7).

Transfer coefficient values for both BOD and DO are higher during the dry period (January to April) for all the zones (Table 3.6 & 3.7). Low flow conditions and high average temperature during the dry season may be the reason for higher BOD and lower DO levels. This means that the water quality of the river is comparatively poor during dry period in all the zones of the lower Kelani River. The TCs of BOD and DO for the zones follow the same pattern except the values are slightly different in magnitude and signs are opposite as expected.

The closer look at dispersion of industries in different zones provided a better understanding of the impact of individual firms and industrial parks on ambient water quality. The Zone 6 and 3 have relatively bigger TCs for BOD and DO with respect to all the other zones as these two zones accommodate two industrial parks in addition to individual firms(see Table 3.6 and 3.7). We estimated TCs of these two industrial parks separately with respect to all zones and found that the influence of industrial parks on these zones is the main reasons for bigger TCs. For example, transfer coefficient of BOD for Zone 6 with respect to Zone 1 during the dry period is 0.0217 and the transfer coefficient of Seethawaka industrial park with respect to Zone 1 during the corresponding period is 0.0186. Zone 3 records the second highest TCs for all the locations. Within the Zone 3, the contribution in terms of changes in BOD and DO by Biyagama industrial zone is very high compared to individual industries and households. The water extraction point at Ambatale located in Zone 2 (see Figure 3.3) is more influenced by the Zone 6 in upstream followed by Zone 3. Therefore, the TCs with respect to Ambatale shows that the BOD and DO levels of the water intake point has more impact from Seethawaka and Biyagama industrial zones compared to individual industries and households. As demonstrated, ZTCs can be used to estimate the impact of pollution sources on specified zones of the lower Kelani River. This information is useful in protecting sensitive and important zones of the river where water quality is very important.

3.5 Conclusions

In this paper, we develop a method to estimate the effect of pollution sources on ambient water quality in an industrialised and urbanized river in Sri Lanka .With limited data, we configured a catchment based hydrology model of water quality by integrating a catchment model (MIKE- SHE) with coupled hydrodynamic and water quality model (MIKE 21/3 coupled model FM). First, the baseline model simulations were carried out for 8 years. Having compared baseline with simulations excluding industries and households, we estimated the potential contribution of industries, households and the surrounding sub-catchments on ambient BOD and DO levels of the lower Kelani River. Our simulation results reveal that industries contribute to poor water quality in the river especially during the dry season, although the contributions vary between different sections of the river.

Second, given the large number of pollution sources, estimation of the effect of each point source is not practical. Therefore, we propose a strategy to manage lower Kelani River by zoning. Our approach to zoning, based on the variability of hydrological and water quality characteristics (Yang et al., 2011, Hung and Shaw, 2005) that we obtained from model simulations and the actual purpose of the river water use. Having large number of zones would increase the administration cost and small number of zones may not reflect the spatial variability of the lower Kelani River. We tried to make a trade off defining 6 zones with our model outputs and available information on river water use.

Using experimental simulations, we estimate zonal transfer coefficients that describe the effect of each zone on ambient DO and BOD levels. The zonal transfer coefficient matrix, reveal the effect of discharging 100kg BOD per day from one zone with respect to a receiving zone. The computed transfer coefficients of each zone provide useful numerical insights for policy planners and decision makers to locate new industries along the lower Kelani River. The transfer coefficients also allow regulators to target pollution sources. The estimated TCs reveal that industrial parks have considerably higher impact across all zones though these parks generally comply with existing effluent concentration standards. This provides valuable information on setting priorities in controlling industrial pollution in individual firms versus industrial parks. Given the situation of degradation of river water quality and absence of effective policy on river water quality management, the ZTCs provide valuable information on designing a socially optimal policy to control industrial pollution in the river catchment. For example, ZTCs can be used as inputs in designing zonal based effluent discharge tax or a permit system where both the spatial distribution of industries and their effluent loads are taken into consideration.

The method of estimating transfer coefficients developed can be applied to rivers that suffer from surface water quality problems as an approach to designing water quality regulations. This is especially applicable to developing countries where there is a lack of systematic spatial and temporal hydrological and water quality data. As the population of cities in developing countries increase and sewage and water treatment infrastructure lags behind the demand, there is an urgent requirement to understand and mange industrial pollution. This may be through regulating existing firms or, in the longer term, relocating industries.

Table 3.6: Zonal transfer coefficient matrix of BOD

		Dry period (January - April)								**Wet period (May to December)**							
		Z1	**Z2**	**Z3**	**Z4**	**Z5**	**Z6**	**IB**	**IS**	**Z1**	**Z2**	**Z3**	**Z4**	**Z5**	**Z6**	**IB**	**IS**
Z1	**Mean**	**0.0147**	**0.0051**	**0.0224**	**0.0136**	**0.0208**	**0.0217**	**0.0186**	**0.0186**	**0.0074**	**0.0026**	**0.0112**	**0.0071**	**0.0105**	**0.0111**	**0.0096**	**0.0095**
	Min	0.0051	0.0018	0.0078	0.0049	0.0073	0.0077	0.0067	0.0067	0.0043	0.0015	0.0066	0.0042	0.0062	0.0065	0.0056	0.0056
	Max	0.0329	0.0113	0.0500	0.0291	0.0464	0.0473	0.0403	0.0402	0.0142	0.0049	0.0216	0.0132	0.0201	0.0210	0.0180	0.0180
	SD	0.0083	0.0029	0.0127	0.0073	0.0117	0.0119	0.0102	0.0101	0.0023	0.0008	0.0035	0.0021	0.0032	0.0034	0.0029	0.0029
Z2	**Mean**	**0.0106**	**0.0038**	**0.0162**	**0.0106**	**0.0152**	**0.0163**	**0.0142**	**0.0142**	**0.0060**	**0.0021**	**0.0091**	**0.0059**	**0.0085**	**0.0091**	**0.0079**	**0.0079**
	Min	0.0043	0.0015	0.0065	0.0043	0.0061	0.0065	0.0057	0.0057	0.0037	0.0013	0.0056	0.0036	0.0053	0.0056	0.0049	0.0049
	Max	0.0208	0.0074	0.0319	0.0211	0.0296	0.0321	0.0281	0.0280	0.0103	0.0036	0.0157	0.0103	0.0147	0.0158	0.0137	0.0137
	SD	0.0050	0.0018	0.0077	0.0051	0.0072	0.0078	0.0068	0.0068	0.0016	0.0006	0.0025	0.0016	0.0023	0.0025	0.0022	0.0022
Z3	**Mean**	**0.0084**	**0.0030**	**0.0129**	**0.0089**	**0.0120**	**0.0131**	**0.0115**	**0.0114**	**0.0051**	**0.0018**	**0.0078**	**0.0053**	**0.0073**	**0.0079**	**0.0069**	**0.0069**
	Min	0.0038	0.0014	0.0058	0.0039	0.0055	0.0058	0.0051	0.0051	0.0033	0.0012	0.0051	0.0034	0.0048	0.0051	0.0044	0.0044
	Max	0.0151	0.0054	0.0231	0.0163	0.0215	0.0237	0.0209	0.0208	0.0083	0.0029	0.0125	0.0085	0.0117	0.0127	0.0110	0.0110
	SD	0.0034	0.0012	0.0053	0.0037	0.0050	0.0054	0.0048	0.0048	0.0013	0.0004	0.0019	0.0013	0.0018	0.0019	0.0017	0.0017
Z4	**Mean**	**0.0075**	**0.0027**	**0.0114**	**0.0080**	**0.0107**	**0.0117**	**0.0102**	**0.0102**	**0.0047**	**0.0017**	**0.0071**	**0.0050**	**0.0067**	**0.0073**	**0.0064**	**0.0063**
	Min	0.0035	0.0013	0.0054	0.0037	0.0051	0.0055	0.0048	0.0048	0.0031	0.0011	0.0048	0.0033	0.0044	0.0048	0.0042	0.0042
	Max	0.0129	0.0046	0.0197	0.0142	0.0184	0.0203	0.0180	0.0179	0.0073	0.0026	0.0111	0.0077	0.0104	0.0113	0.0098	0.0098
	SD	0.0028	0.0010	0.0043	0.0031	0.0040	0.0045	0.0040	0.0039	0.0011	0.0004	0.0017	0.0012	0.0015	0.0017	0.0015	0.0015
Z5	**Mean**	**0.0066**	**0.0028**	**0.0094**	**0.0064**	**0.0085**	**0.0093**	**0.0081**	**0.0081**	**0.0044**	**0.0019**	**0.0061**	**0.0043**	**0.0057**	**0.0061**	**0.0054**	**0.0054**
	Min	0.0034	0.0014	0.0047	0.0033	0.0043	0.0048	0.0042	0.0042	0.0031	0.0013	0.0042	0.0030	0.0039	0.0043	0.0038	0.0037
	Max	0.0108	0.0070	0.0220	0.0108	0.0138	0.0152	0.0134	0.0134	0.0066	0.0033	0.0142	0.0063	0.0084	0.0091	0.0080	0.0080
	SD	0.0022	0.0010	0.0038	0.0022	0.0028	0.0031	0.0027	0.0027	0.0009	0.0004	0.0015	0.0009	0.0012	0.0013	0.0012	0.0011
Z6	**Mean**	**0.0067**	**0.0060**	**0.0081**	**0.0055**	**0.0074**	**0.0080**	**0.0070**	**0.0070**	**0.0048**	**0.0045**	**0.0053**	**0.0038**	**0.0050**	**0.0054**	**0.0069**	**0.0069**
	Min	0.0037	0.0034	0.0042	0.0030	0.0039	0.0042	0.0037	0.0037	0.0034	0.0030	0.0037	0.0027	0.0035	0.0038	0.0034	0.0034
	Max	0.0109	0.0115	0.0194	0.0091	0.0117	0.0129	0.0114	0.0113	0.0069	0.0076	0.0132	0.0055	0.0073	0.0079	0.0047	0.0047
	SD	0.0021	0.0019	0.0032	0.0018	0.0024	0.0026	0.0022	0.0022	0.0009	0.0010	0.0013	0.0008	0.0010	0.0011	0.0010	0.0010

Table 3.7: Zonal transfer coefficient matrix of DO

		Dry period (January - April)								**Wet period (May to December)**							
		Z1	**Z2**	**Z3**	**Z4**	**Z5**	**Z6**	**IB**	**IS**	**Z1**	**Z2**	**Z3**	**Z4**	**Z5**	**Z6**	**IB**	**IS**
Z1	**Mean**	**0.0147**	**0.0051**	**0.0224**	**0.0136**	**0.0208**	**0.0217**	**0.0186**	**0.0186**	**0.0074**	**0.0026**	**0.0112**	**0.0071**	**0.0105**	**0.0111**	**0.0096**	**0.0095**
	Min	0.0051	0.0018	0.0078	0.0049	0.0073	0.0077	0.0067	0.0067	0.0043	0.0015	0.0066	0.0042	0.0062	0.0065	0.0056	0.0056
	Max	0.0329	0.0113	0.0500	0.0291	0.0464	0.0473	0.0403	0.0402	0.0142	0.0049	0.0216	0.0132	0.0201	0.0210	0.0180	0.0180
	SD	0.0083	0.0029	0.0127	0.0073	0.0117	0.0119	0.0102	0.0101	0.0023	0.0008	0.0035	0.0021	0.0032	0.0034	0.0029	0.0029
Z2	**Mean**	**0.0106**	**0.0038**	**0.0162**	**0.0106**	**0.0152**	**0.0163**	**0.0142**	**0.0142**	**0.0060**	**0.0021**	**0.0091**	**0.0059**	**0.0085**	**0.0091**	**0.0079**	**0.0079**
	Min	0.0043	0.0015	0.0065	0.0043	0.0061	0.0065	0.0057	0.0057	0.0037	0.0013	0.0056	0.0036	0.0053	0.0056	0.0049	0.0049
	Max	0.0208	0.0074	0.0319	0.0211	0.0296	0.0321	0.0281	0.0280	0.0103	0.0036	0.0157	0.0103	0.0147	0.0158	0.0137	0.0137
	SD	0.0050	0.0018	0.0077	0.0051	0.0072	0.0078	0.0068	0.0068	0.0016	0.0006	0.0025	0.0016	0.0023	0.0025	0.0022	0.0022
Z3	**Mean**	**0.0084**	**0.0030**	**0.0129**	**0.0089**	**0.0120**	**0.0131**	**0.0115**	**0.0114**	**0.0051**	**0.0018**	**0.0078**	**0.0053**	**0.0073**	**0.0079**	**0.0069**	**0.0069**
	Min	0.0038	0.0014	0.0058	0.0039	0.0055	0.0058	0.0051	0.0051	0.0033	0.0012	0.0051	0.0034	0.0048	0.0051	0.0044	0.0044
	Max	0.0151	0.0054	0.0231	0.0163	0.0215	0.0237	0.0209	0.0208	0.0083	0.0029	0.0125	0.0085	0.0117	0.0127	0.0110	0.0110
	SD	0.0034	0.0012	0.0053	0.0037	0.0050	0.0054	0.0048	0.0048	0.0013	0.0004	0.0019	0.0013	0.0018	0.0019	0.0017	0.0017
Z4	**Mean**	**0.0075**	**0.0027**	**0.0114**	**0.0080**	**0.0107**	**0.0117**	**0.0102**	**0.0102**	**0.0047**	**0.0017**	**0.0071**	**0.0050**	**0.0067**	**0.0073**	**0.0064**	**0.0063**
	Min	0.0035	0.0013	0.0054	0.0037	0.0051	0.0055	0.0048	0.0048	0.0031	0.0011	0.0048	0.0033	0.0044	0.0048	0.0042	0.0042
	Max	0.0129	0.0046	0.0197	0.0142	0.0184	0.0203	0.0180	0.0179	0.0073	0.0026	0.0111	0.0077	0.0104	0.0113	0.0098	0.0098
	SD	0.0028	0.0010	0.0043	0.0031	0.0040	0.0045	0.0040	0.0039	0.0011	0.0004	0.0017	0.0012	0.0015	0.0017	0.0015	0.0015
Z5	**Mean**	**0.0066**	**0.0028**	**0.0094**	**0.0064**	**0.0085**	**0.0093**	**0.0081**	**0.0081**	**0.0044**	**0.0019**	**0.0061**	**0.0043**	**0.0057**	**0.0061**	**0.0054**	**0.0054**
	Min	0.0034	0.0014	0.0047	0.0033	0.0043	0.0048	0.0042	0.0042	0.0031	0.0013	0.0042	0.0030	0.0039	0.0043	0.0038	0.0037
	Max	0.0108	0.0070	0.0220	0.0108	0.0138	0.0152	0.0134	0.0134	0.0066	0.0033	0.0142	0.0063	0.0084	0.0091	0.0080	0.0080
	SD	0.0022	0.0010	0.0038	0.0022	0.0028	0.0031	0.0027	0.0027	0.0009	0.0004	0.0015	0.0009	0.0012	0.0013	0.0012	0.0011
Z6	**Mean**	**0.0067**	**0.0060**	**0.0081**	**0.0055**	**0.0074**	**0.0080**	**0.0070**	**0.0070**	**0.0048**	**0.0045**	**0.0053**	**0.0038**	**0.0050**	**0.0054**	**0.0069**	**0.0069**
	Min	0.0037	0.0034	0.0042	0.0030	0.0039	0.0042	0.0037	0.0037	0.0034	0.0030	0.0037	0.0027	0.0035	0.0038	0.0034	0.0034
	Max	0.0109	0.0115	0.0194	0.0091	0.0117	0.0129	0.0114	0.0113	0.0069	0.0076	0.0132	0.0055	0.0073	0.0079	0.0047	0.0047
	SD	0.0021	0.0019	0.0032	0.0018	0.0024	0.0026	0.0022	0.0022	0.0009	0.0010	0.0013	0.0008	0.0010	0.0011	0.0010	0.0010

Chapter 4 : Evaluating Cost-effectiveness of Policies in Riverine Water Quality Management: An Integrated Hydro-economic Modelling Approach

Abstract

Urbanization and industrialization, as a result of rapid economic development, have led to the deterioration of water quality in many rivers in developing countries. Kelani River in Sri Lanka provides drinking water to Colombo and a range of market and non-market ecosystem services, but these services are threatened by deteriorating water quality. In this paper, we apply a hydro-economic model that combines a hydrological model of water quality with an economic model to evaluate policy options. The results show that the current policy of uniform industrial effluent concentration standards does not achieve the target level of ambient water quality nor account for the variability of effluent loads and abatement costs. Tradeable permits or taxes with multiple zones are the least cost policy for water quality improvements across the zones. As current institutional capabilities are being developed towards charging an emission fee, a zonal effluent tax may be easier to implement.

Key words: industrial water pollution, optimization, hydro-economic modelling, policy instrument

4.1 Introduction

In developed countries significant progress has been made to manage point source pollution (Xepapadeas, 1992, Neal et al., 2006, Shortle and Horan, 2008, Xepapadeas, 2011), in contrast, in developing countries point source pollution is becoming worse (Olmstead, 2010). It is one of the most challenging environmental externalities for the developing countries to regulate (Coria and Sterner, 2010, Olmstead, 2010), due to the rapid industrialization and urbanization of catchments and lack of investment in sanitation infrastructure (Biswas and Tortajada, 2009). In many developing countries, industrial growth has occurred before adequate regulatory frameworks were established to manage the increase in water pollution.

In numerous cases existing command and control (CAC) approaches to regulating industrial pollution have failed to maintain surface water quality. These approaches set uniform standards, but do not account for cost heterogeneity among pollution sources. Abatement costs are heterogeneous due to differences in industry type, the scale of operation and technology used. Therefore, having a uniform standard for all firms is expensive and counterproductive (Stavins, 2003). In addition, the lack of incentives to comply compounded by weaknesses in monitoring and enforcement have resulted in poor compliance by firms. Therefore, designing innovative alternative policy instruments to improve surface water quality is of paramount importance for regulatory agencies and policy makers.

The design of any environmental policy depends on two main factors: the target level of improvement in the environment; and the choice of policy instruments to achieve the target (Keohane et al., 1998). Selecting the best instruments depends on a set of competing evaluation criteria (Goulder and Parry, 2008). Among several criteria to evaluate policy instruments, there are three main categories: (1) overall efficiency or optimality which assesses the policy instrument's ability to achieve the required level of abatement that maximizes net benefits; (2) cost-effectiveness that is the ability to achieve a given abatement at least cost ; and (3) other criteria such as distributional equality, political acceptability and implementation costs (Baumol and Oates, 1988, Perman, 2003, Bennear and Stavins, 2007). The theoretical and empirical literature on the economics of water pollution suggests that properly designed and implemented market-based instrument (MBI) at least satisfy the static and dynamic efficiency criterion. Static cost efficiency requires achieving pollution reduction targets at least cost by equalizing marginal abatement costs across polluters (Baumol and Oates, 1988, Eskeland and Jimenez, 1992, Stavins, 2003). Dynamic efficiency concerns providing ongoing incentives to adopt new pollution control technologies.

Due to non–uniform mixing of water pollutants, damages are dependent on the location of the pollution source in the hydrological, social and economic landscape (Boyd, 2003, Hung and Shaw, 2005). The effect of any pollutant released into surface water is complex; it is a function of assimilative capacity of the water body (which is a function of various climatic conditions), salinity, acidity, and many other localized chemical characteristics. Therefore, the spatial configuration of polluting sources is important in designing policy instruments (McGartland, 1988, Hanley, 2007, Olmstead, 2010, Fisher-Vanden and Olmstead, 2013). Nevertheless, location specific taxes may not be practical due to the large numbers of firms and locations involved. In such cases setting up zonal taxes would be more feasible (Boyd, 2003, Olmstead, 2010).

To date the application of MBIs to manage water pollution in developing countries has been limited (Eskeland and Jimenez, 1992, O'Connor, 1999) and evaluations of their success have shown mixed results. Case studies from Malaysia, Poland and Colombia showed that effluent charges or taxes with active enforcement increased compliance with standards (Kathuria, 2006, Blackman, 2009). In addition, Chinese industries reduced emissions in response to pollution levies especially for wastewater and solid waste (Jiang and McKibbin, 2002, Wang and Wheeler, 2005). However, effluent taxes are often not set high enough to reflect the marginal social cost of emissions (Stavins, 2003).

Tradeable permits received much attention due to their attractive features such as cost efficiency, flexibility and incentives for innovation in pollution control (Lyon, 1989, Brill et al., 1984). Despite some successful cases found in the US (Nutrient Trading Program in North Carolina), Australia (Hunt River Salinity Program) and Canada (South Nation River Phosphorous Management Program), the global experience with water pollution emission trading is not extensive (Shortle, 2013). Trading can cause water quality to deteriorate in some parts of a catchment. Therefore designing a tradeable permit system needs to take the spatial impacts into account. Empirically, location-based trading ratios have been shown to be efficient in taking spatial impacts into account (Krupnick et al., 1983, Hung and Shaw, 2005, Montgomery, 1972, Fowlie and Muller, 2010)

There has been limited experimentation with tradeable permits in developing countries with some notable exceptions. For example, transitional countries such as Kazakhstan, Poland and China have introduced permit trading programs (Coria and Sterner, 2010). Given the interest of Chinese environmental authorities, recent empirical studies look at different designs of tradable permits and potential cost savings (Cao and Ikeda, 2005, Zhang et al., 2013). Lessons learned from Santiago in Chile, the first country outside the OECD to implement permit trading, show that challenges in designing a well-functioning trading program in a less developed country should not be underestimated (Coria et al., 2010, Coria and Sterner, 2010). In contrast, efficiency gains from tradeable permits can be even higher for developing countries given that there is less sunk investment in treatment facilities (Lyon, 1989).

An important question is, given the severity of water pollution, what has to be done to make trading programs more applicable in developing country settings. Critical features to make pollution trading work are: political commitment in implementing such schemes and work on design related issues such as realistic incentives to trade, spatial and temporal flexibility, the possibilities of reducing transaction costs, monitoring and enforcement and the rules on the allocation of permits (Coria and Sterner, 2010). The implementation of such schemes in developing country settings is a long term learning process in order to transition from CAC regulation to MBIs or a mixture of both. Some studies recommend the use of multiple or hybrid policy instruments (Bennear and Stavins, 2007, Lehmann, 2012).

This study evaluates the policy options for water quality management in Kelani River in Sri Lanka. Our focus is on organic pollution where industry is the most significant source. An empirical analysis of the application of policy instruments in a river catchment needs an integrated approach given the complexity of river dynamics, nature of pollutants and social and economic heterogeneity. The analytical framework used in this study is an integrated catchment- based hydrology model of water quality and economic model of behaviour of industrial polluters (O'Neil et al., 1983, Brill et al., 1984, Moffatt et al., 1991, Hanley and Moffatt, 1993). The calibrated catchment based hydrodynamic and water quality model is used to estimate transfer coefficients (see Chapter 3 for details). Zonal transfer coefficients give the effect of a change in pollution load from a source zone on the ambient water quality of the respective receptor zone. The abatement cost data for the economic model are based on marginal cost estimates from parametric input distance functions using firm level input and output data (Hailu and Veeman, 2000, Coelli et al., 2013) for a representative sample of water polluting firms located in the river catchment(see Chapter 2 for further details).

We analysed the cost-effectiveness of five policy options to achieve improved river water quality ranging from current concentration-based effluent standards to multiple zone system. There have been only a few studies for emerging and developing countries (Wang et al., 2004, Ning and Chang, 2007, Qin et al., 2011) that have evaluated policy instruments to control organic water pollutants. To our knowledge this is the first comprehensive analysis of policy options aimed at controlling industrial water pollution in a developing country context where the heterogeneity of abatement costs and spatial heterogeneity of water quality effects are accounted for.

The rest of the paper is organised as follows. Section 2 describes study site and water quality issues. Section 3 describes data sources used in the study. Section 4 describes the economic model. Section 5 presents and discusses results. Section 6 concludes and gives some policy implications.

4.2 Water quality of the Kelani River

Kelani River is Sri Lanka’s most economically important river. It originates in the central hills and flows to the Indian Ocean in Colombo (Figure 4.1). The river is the main source of drinking water for Colombo, provides hydropower generation, irrigation, bathing, washing and socio-cultural activities and provides a range of other ecosystem services including the removal and assimilation of sewage and industrial organic pollution.

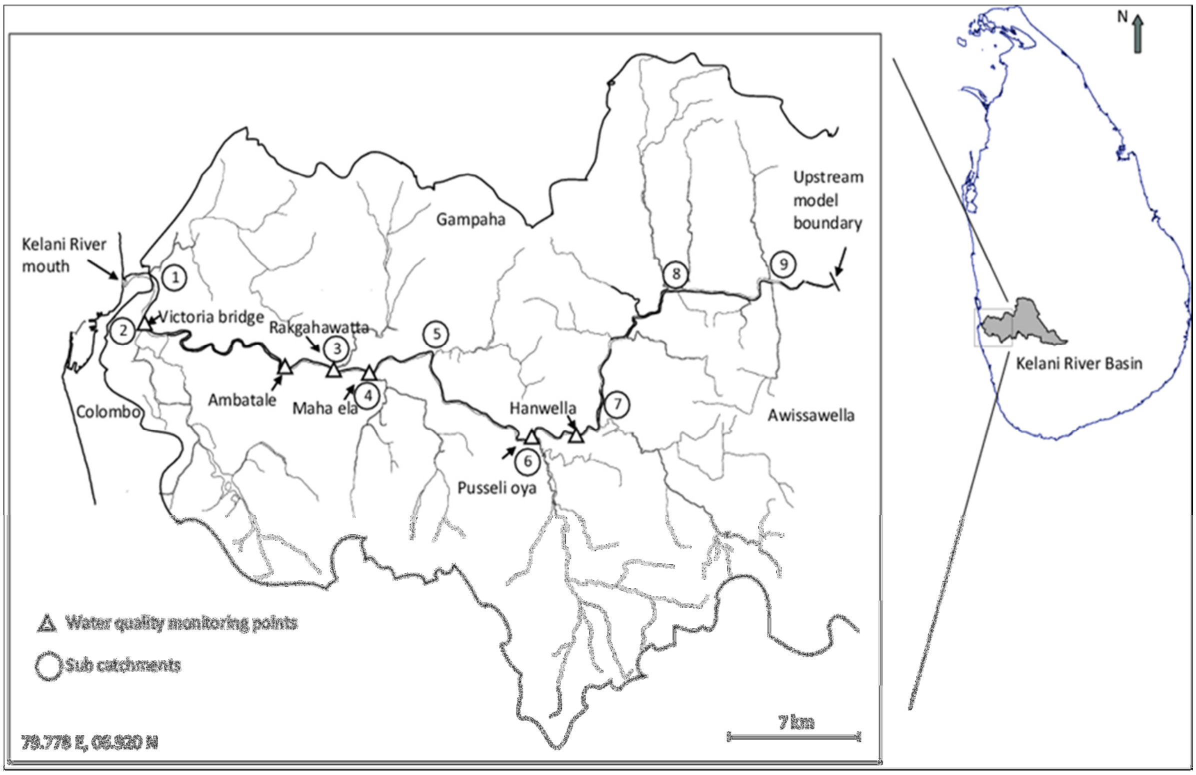
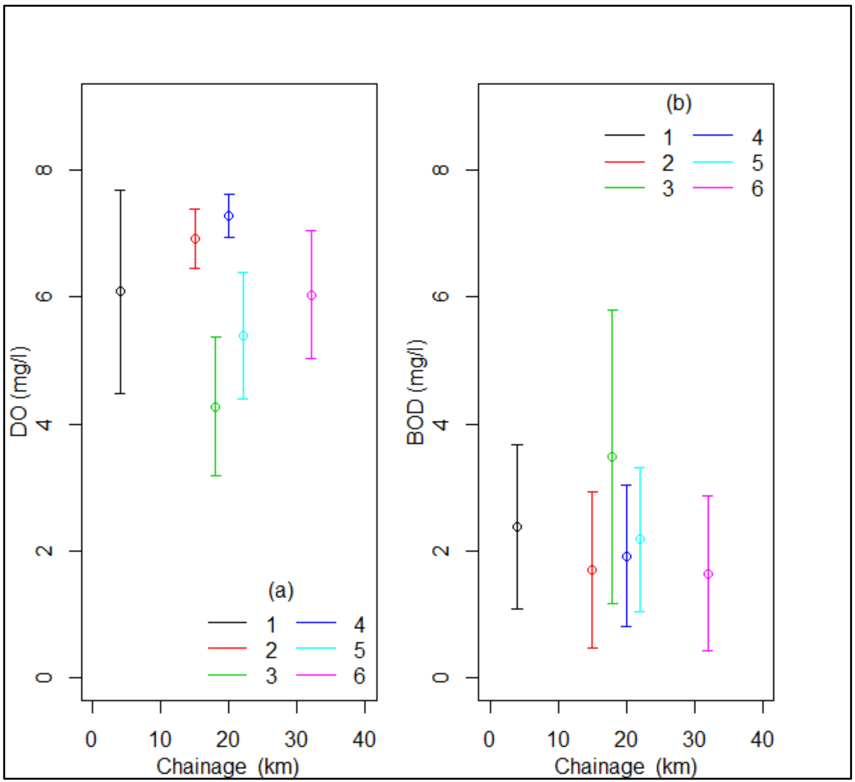


Figure 4.1: Kelani River catchment, main sub-catchments and monitoring locations

Pollutant transport in the most degraded downstream section of the river is complex and variable for four main reasons: (1) variability of monsoonal rains in the upstream mountain areas of the river and the tidal influence from downstream; (2) effluent discharge from firms and industrial parks located in the river catchment; (3) household discharges from underserved settlements and sewage outfall; and (4) pollutant discharges from nine sub catchments due to natural processes, forestry and agriculture.



1	Victoria	3	Rakgahawatte	5	Maha ela
2	Ambatale	4	Kaduwela	6	Pusseli oya

Note: “chainage” indicates distance from the river mouth, thus (1) Victoria is close to the river mouth and (6) Pusseli oya is the most upstream point.

Figure 4.2: Variation of DO and BOD in different monitoring stations

Currently the only policy specific to the Kelani is a ban on siting high polluting industries upstream of the water extraction point at Ambatale. A program to monitor water quality initiated in 2002 under the Clean River Program with the objectives of reviewing policy on locating industries and pollution standards. The review based on monitoring data found that water quality at the extraction point at Ambatale is not suitable without intensive treatment . The main pollutants are organic, coliform bacteria, and heavy metals. The industrial sources account for the largest share of organic pollution discharges in the river (Herath and Amaresekera, 2007). The river below Ambatale is of poor water quality and, as a result, the estuarine ecosystem is degraded. Figure 4.2 shows how mean DO (Dissolved Oxygen) and BOD (Biochemical Oxygen Demand) levels change in different locations of the river. Given the lack of availability of water quality data and the significance of organic pollution, we used DO as an overall indicator of water quality (Wang et al., 2003, Sánchez-Chóliz and Duarte, 2005).

The current approach to control industrial pollution in Sri Lanka is the use of CAC regulatory measures which is applied as a concentration-based effluent standard. The Central Environmental Authority (CEA) is the regulatory authority responsible for controlling pollution, which provides mandatory Environment Protection Licenses (EPL) to new business. There is strong evidence that the current approach to pollution regulation in Sri Lanka is ineffective (AECEN, 2006, Vasantha, 2008) for several reasons.

First, effluent standards regulate effluent discharge concentration, but do not restrict the total load. Second, EPL do not provide an incentive to reduce pollution as all industries are charged a uniform fee irrespective of their effluent emissions. Third, CEA has limited regulatory power and weak enforcement mechanisms. Fourth, budgetary constraints, due to a lack of a separate CEA fund, have resulted in limited resources to monitor polluters. The lack of a well-managed information system is also a hindrance to effective monitoring and enforcement.

In 2007, CEA proposed a wastewater discharge fee (WDF) program. However, its implementation presented a number of challenges due to poorly defined institutional responsibilities between agencies and lack of procedures to set and collect fees. Some of these issues are addressed by regulations resulting from the Amendment of National Environmental Act of 1980, undertaken in 2008 that eliminate legislative and regulatory constraints to earmark funds collected through discharge fee. The funds collected are expected to be used in improving the capacity of the regulatory authority to administer more complex pollution polices. Despite some improvements in institutional settings, technical and economic aspects of implementing such program have not received much attention within Sri Lanka (Vasantha, 2008).

4.3 Data

Data for the hydro-economic model is taken from three main sources (Figure 4. 3): (1) river catchment biophysical measurements; (2) industry sector costs; and (3) database of point sources.

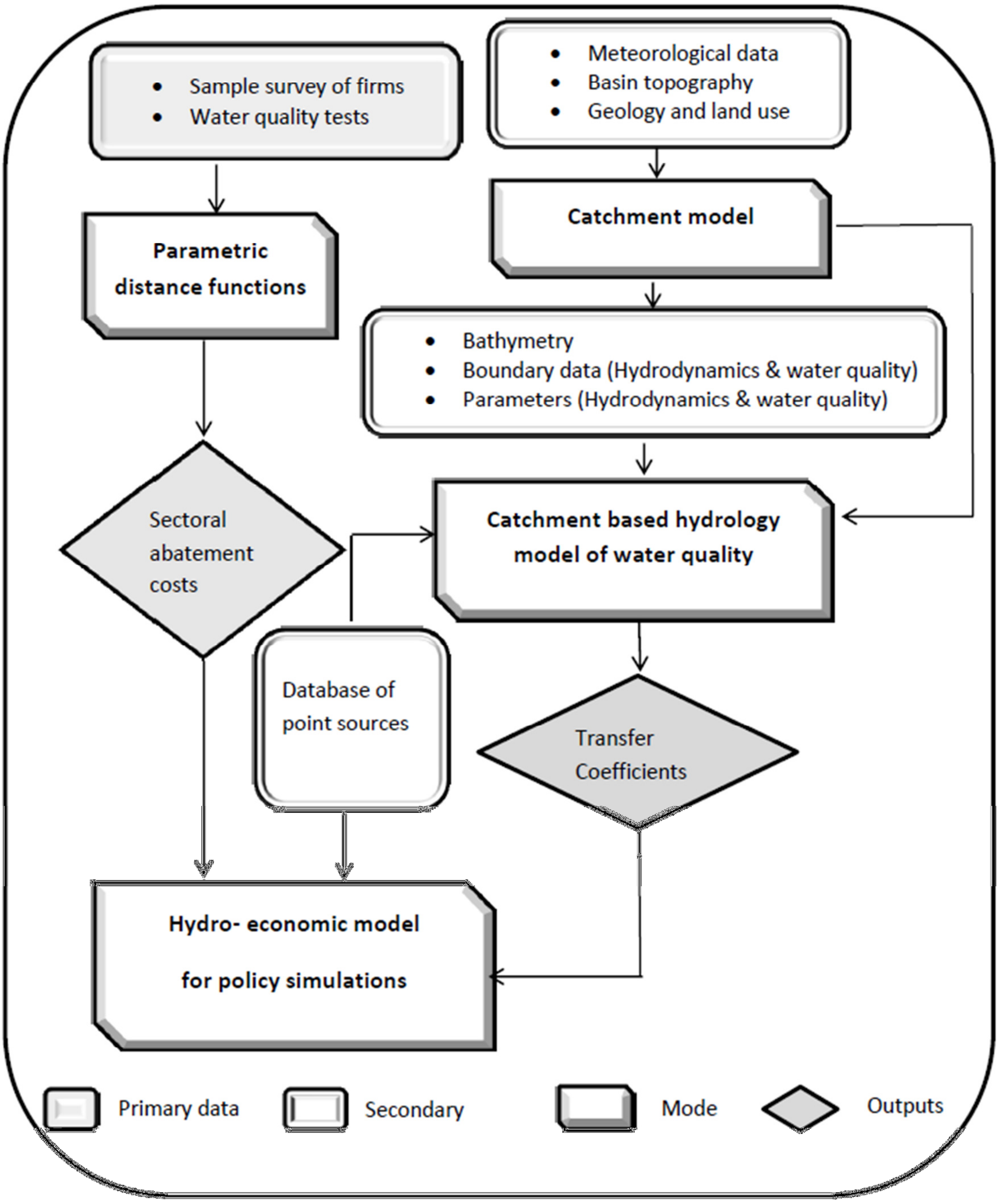


Figure 4.3: Data sources

4.3.1 River catchment biophysical measurements

Using catchment data , hydrological model of water quality can be configured to estimate each firm's contribution on ambient water quality based on its spatial location (Hanley et al., 1998, Boyd, 2003, Hung and Shaw, 2005, Hanley, 2007, Moffatt et al., 1991). The spatial effects can be described using term transfer/diffusion coefficients.

4.3.1.1 Water quality model

A catchment-based hydrological model of water quality for Kelani River was configured using the DHI MIKE (DHI, 2004) modelling tool to simulate spatial and temporal variation of hydrodynamic and water quality measures (such as DO and BOD). Specifically the catchment model (MIKE-SHE) was linked to Hydrodynamic (HD) and ECO Lab model (MIKE 21/3 Coupled model FM). Although our interest is on point sources, especially industrial pollution, we use a catchment model that accounts for all possible pollution sources. From a set of simulation experiments, we estimated the effect of point sources, on background catchment pollution that is largely due to non-point source pollution.

The catchment module[24] considered the contribution of stream flows of nine sub-catchments connected to the lower Kelani River which was captured by a hydrometric network (see Figure 4.1). The outputs from the catchment model are used as inputs for the water quality model. The coupled hydrodynamic and ECO Lab models were initialized with the observed hydrodynamic and water quality parameters from 2004. Using a triangular flexible mesh, we generated a hydrodynamic (HD) model grid for the lower Kelani River from the open ocean point[25] in Colombo to Awissawella, the upper boundary (Figure 4. 1). The model river bathymetry was generated using cross sectional depth data[26] . The HD model was forced using river discharge data (from the Department of Irrigation) for the upper boundary and water level data (Colombo tide gauge) for the open ocean boundary (see Figure 4.1). State variables for ECO Lab module, concentration of BOD, DO, coliforms, temperature and salinity were specified under initial and boundary conditions and for each point source. The biweekly water

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[24] *The Digital Elevation Model WILLMOTT, C. J., ACKLESON, S. G., DAVIS, R. E., FEDDEMA, J. J., KLINK, K. M., LEGATES, D. R., O'DONNELL, J. & ROWE, C. M. 1985. Statistics for the evaluation and comparison of models. Journal of Geophysical Research: Oceans, 90, 8995-9005. was generated combining E-TOPO and digitized 1:10,000 survey topographical maps. The geological and the land use map of the study area created using, remote sensing methods (aerial photographs) and the field explorative geological mapping as well as Google earth. The vegetation, crop cycles were assumed to be the same for the whole simulation period. Rainfall and evaporation were obtained from three meteorological stations.*

[25] *Referred to as river mouth in the Figure 4. 1*

[26] *Ten river cross sections were obtained from National Aquatic Resources Research and Development Agency (NARA), Sri Lanka*

quality data[27] were obtained from The Central Environmental Authority (CEA) and The National Water Supply and Drainage Board (NWSDB).

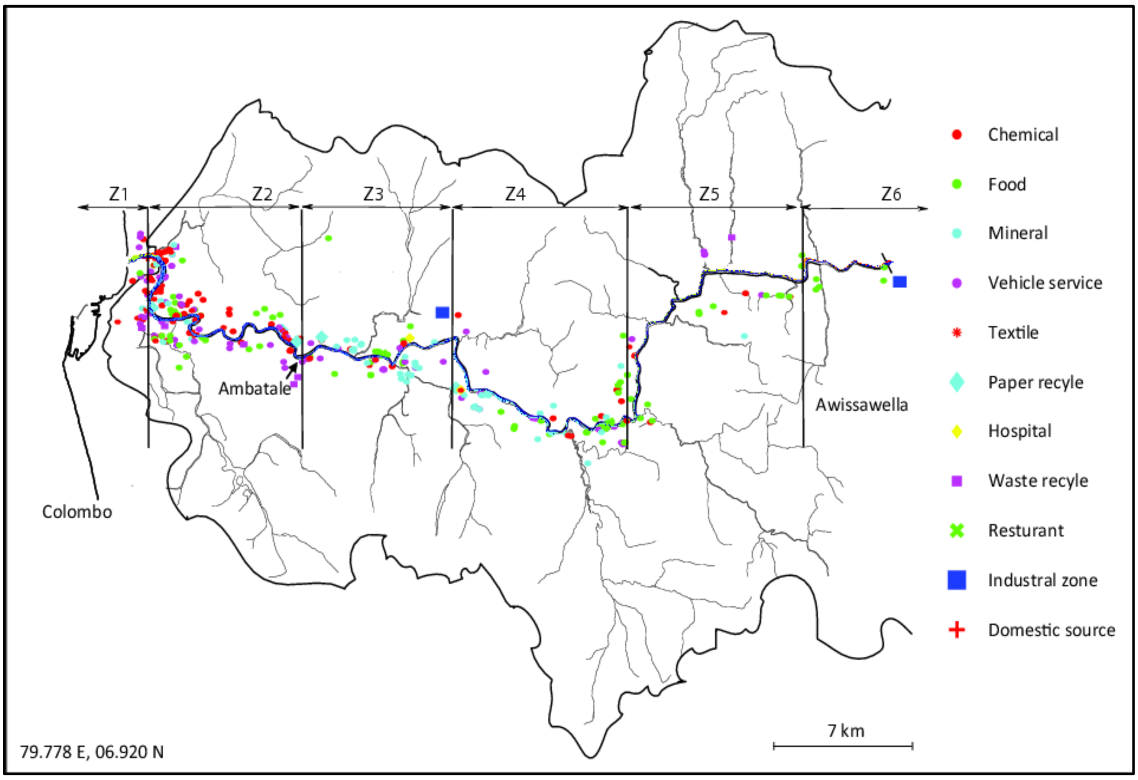

Figure 4.4: Spatial distribution of point sources and a demarcation of zones.

Point source data were from industries, households in underserved settlements and sewage outfalls near to the river. Firms located in the catchment up to 1 km from both sides of the river were selected from the CEA industrial database (see Figure 4.4). Pollution loads from firms were estimated based on type of industry, water usage, availability of treatment facility (see Table 4.1). Actual data on wastewater discharge from the two main industrial parks (Biyagama and Seethawaka) were collected from the CEA. The pollution loads from the parks were calculated assuming that they are complying with the existing concentration standards for BOD.

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[27] *The dataset of water quality along few monitoring points of the lower Kelani River has been collected under the Clean Rivers programme.*

Table 4.1: Daily pollution loads from point sources

Point sources	Number of establishments	Pollution load (BOD Kg/day)
Individual firms	323	3,703
Industrial parks	2	750
Underserved settlements	3,177	2,170
Sewage outlet	1	5,011
Total		11,634

Pollution loads from the households in underserved settlements[28] on the river bank were based on average water consumption and the standard concentration of BOD in domestic waste. Data[29] on the sewage outfall located at Mutwal (located within the model domain) was also collected. The sewage outfall was considered as a point source in our hydrology model.

The baseline model runs were carried out for 8 years stating from 2004. Using the refined statistical index of model performance[30] (Willmott et al., 2012), we validated the baseline model. The river hydrodynamic outputs were validated against measured water levels[31] and with achieved skill level of 0.9. The overall model performance for water quality predictions in relation to DO and BOD levels were 0.49 and 0.46 indicating reasonably good model fit.

Since the catchment is heavily industrialised, it was not practical to estimate transfer coefficients for all firms and industrial parks. Therefore, based on hydrodynamic, water quality variations and the purpose of river water use, we divided the lower Kelani River into 6 main zones. The zoning approach has been used by environmental regulators to reduce the transaction and administrative cost of managing water pollution where zones are defined on the basis of areas with similar pollution dispersion characteristics (Hung and Shaw, 2005, Yang et al., 2011). The experimental simulations to estimate

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[28] *Using data from population Census collected by the Department of Census and Statistics DCS 2012. Census of Population and Housing. Colombo: Department of Census and Statistics, Sri Lanka., Sri Lanka*

[29] *ADB Technical Assistance Consultant's Report 2009 on Sri Lanka: Assessing Colombo Municipality Wastewater Systems.(Financed by the Technical Assistance Special Fund) prepared by Lanka Hydraulic Institute Ltd, Colombo, Sri Lanka).*

[30] The index value varies from -1 to 1 where -1 indicates poor model performance while 1 indicates the perfect performance.

[31] *Data on water levels of the river was obtained from the Department of Irrigation, Sri Lanka*

zonal transfer coefficients (ZTC) were conducted for two years (2009-2010) excluding the pollution loads from each zone while maintaining all other inputs and parameters same. The ZTC describes the effect of unit pollutant released in a particular zone on surface water quality with respect to the receiving zone of the river (Boyd, 2003). Since the water quality of the river is comparatively poor during low flow conditions (during dry period), in this paper, we use estimates for dry period. The values reported in the Table 4.2 represent the improvement in ambient DO level of a receiving zone (mg/l) with respect to reduction of 100kg of BOD per day in a particular zone.

Table 4.2: Matrix of zonal transfer coefficients

		Dry period (January - April)							
		Z1	**Z2**	**Z3**	**Z4**	**Z5**	**Z6**	**IB***	**IS***
Z1	**Mean**	**0.0020**	**0.0011**	**0.0069**	**0.0063**	**0.0031**	**0.0068**	**0.004**	**0.0066**
	Min	0.0004	0.0003	0.0022	0.0021	0.0007	0.002	0.001	0.0021
	Max	0.0062	0.0029	0.0164	0.0144	0.0093	0.0161	0.0112	0.016
	SD	0.0017	0.0008	0.0043	0.0037	0.0025	0.0042	0.003	0.0041
Z2	**Mean**	**0.0044**	**0.0018**	**0.0087**	**0.0070**	**0.0064**	**0.0088**	**0.0074**	**0.0083**
	Min	0.001	0.0005	0.0027	0.0024	0.0015	0.0027	0.0019	0.0027
	Max	0.0111	0.0043	0.0196	0.015	0.0161	0.0201	0.0184	0.0184
	SD	0.0031	0.0012	0.0052	0.0039	0.0045	0.0054	0.0051	0.0049
Z3	**Mean**	**0.0045**	**0.0018**	**0.0086**	**0.0069**	**0.0066**	**0.0088**	**0.0076**	**0.0081**
	Min	0.0013	0.0006	0.003	0.0026	0.002	0.003	0.0023	0.0029
	Max	0.0101	0.0039	0.0181	0.0139	0.0146	0.0183	0.0168	0.0167
	SD	0.0027	0.001	0.0047	0.0035	0.0039	0.0048	0.0045	0.0043
Z4	**Mean**	**0.0043**	**0.0017**	**0.0081**	**0.0066**	**0.0063**	**0.0083**	**0.0073**	**0.0077**
	Min	0.0014	0.0006	0.003	0.0026	0.0021	0.0031	0.0024	0.003
	Max	0.0091	0.0035	0.0164	0.0127	0.013	0.0164	0.0151	0.015
	SD	0.0024	0.0009	0.0041	0.0031	0.0034	0.0042	0.004	0.0037
Z5	**Mean**	**0.0038**	**0.0015**	**0.0071**	**0.0057**	**0.0055**	**0.0074**	**0.0071**	**0.0066**
	Min	0.0015	0.0006	0.003	0.0026	0.0021	0.0032	0.003	0.0028
	Max	0.0072	0.0028	0.0133	0.0104	0.0103	0.0141	0.0131	0.0121
	SD	0.0018	0.0007	0.0032	0.0024	0.0025	0.003	0.0031	0.0029
Z6	**Mean**	**0.0035**	**0.0017**	**0.0063**	**0.0051**	**0.0049**	**0.0065**	**0.0063**	**0.0058**
	Min	0.0015	0.0007	0.0027	0.0024	0.002	0.003	0.0028	0.0026
	Max	0.0065	0.0033	0.0116	0.009	0.0089	0.012	0.0113	0.0104
	SD	0.0016	0.0008	0.0027	0.002	0.0021	0.0025	0.0026	0.0024

IB – Biyagama industrial park located in Z3 and IS- Seethwaka industrial park located in Z6

4.3.2 Industry sector costs

We estimated industry level marginal abatement costs using data collected from our survey of representative sample of water polluting firms (74) located in the River catchment[32]. Production and administrative managers were interviewed in 2013 to

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[32] *There are 324 medium and large scale water polluting firms and two main industrial parks located within 1 km of the lower river catchment. We used CEA database of industries in the Western Province as the frame to*

complete a formal questionnaire (See Appendix 1). The Firm level data on input and output quantities, cost of inputs and revenues, wastewater volumes related to 2012 (Table 4.3). In addition, waste water samples were collected from the firms where the recent water quality data were not available

Table 4.3: Descriptive statistics of variables[33] used in the estimation ('000s)

	Variable	Unit	Mean	Standard deviation
Inputs	Raw materials	US$	1936.74	11700.00
	Labour	US$	96.21	267.83
	Power	US$	65.48	284.48
	Service and maintenance	US$	42.74	204.44
	Treatment cost	US$	3.02	6.09
Output	Total sales	US$	4700.36	17900.00
Undesirable outputs	BOD load	Kg	3.78	15.67
	COD load	Kg	6.74	26.87
	TSS load	Kg	3.33	19.39

Two common approaches to estimate abatement costs include cost functions and the use of distance functions, the later has been more widely used due to its lower information requirements for example , information on pollution regulations and input prices are not required to estimate distance functions (Lee et al., 2002, Lee, 2005, Hailu, 2013) . Distance functions parameterize environmental technology in multi input and multi-output setting including undesirable outputs. A few studies have calculated shadow prices using distance functions in developing and emerging country context (Murty and Kumar, 2003, Murty et al., 2006, Murty et al., 2007, Van Ha et al., 2008, Mandal, 2010, Xu et al., 2010, Dutta and Narayanan, 2011)

We employed parametric input distance functions with the use of input and output data of firms including water pollutants as undesirable outputs. The use of parametric input distance functions was justified on four counts: 1) In the presence of undesirable outputs, an input-based efficiency measure is easy to interpret as it represents the

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select water polluting firms located in the catchment and also to select representative sample of firms to conduct the primary survey.

[33] *All the values in the table are reported in annual terms*

proportional change in inputs with both desirable and undesirable outputs held constant (Hailu and Veeman, 2000, Murty et al., 2006); (2) Input based efficiency is more appropriate as most firms have more control over inputs than outputs; (3) parametric distance function estimations using linear programming allow simple imposition of economic constraints and are differentiable (which is an important feature for estimation of shadow prices) ; and (4) Shadow price estimates using input distance functions do not depend on the choice of a direction vector as it is the case of directional distance functions (Zhou et al., 2014).

We estimated a translog input distance frontier by linear programming (Hailu and Veeman, 2000, Murty and Kumar, 2002, Coelli et al., 2013). Using the behavioural assumption of cost minimization and the duality between the cost function and input distance function, shadow prices of water pollutants were derived. The calculated shadow prices with respect to a particular pollutant can be defined as the marginal cost of abatement (MAC) for BOD. Table 4.4 reports shadow prices for each industry.

Table 4.4: Marginal abatement costs of BOD

Industry	BOD (US$/ kg)		
	Median	Mean	Standard deviation
Chemical	16.57	43.26	57.51
Food	1.83	13.20	28.42
Beverages	0.001	60.11	134.36
Livestock farms	0.82	40.37	88.22
Vehicle service	2.51	12.85	21.62
Textile and leather	3.86	26.65	68.39
Mineral	18.4	42.30	57.32
Waste recycling	0.51	5.76	9.40
Total	3.02	25.48	57.74

We also simulated firm level marginal and total abatement costs for each level of BOD from their current level of effluents (Simonovic and Fahmy) to the different levels covering 85 percent of total abatement, assuming firm level efficiency remains the same. The individual level abatement cost curves were used to estimate industry level abatement cost curves and abatement coefficients. These abatement coefficients were used in the optimization analysis to estimate total abatement costs. Figure 4.5 shows the abatement cost curves drawn using the industry level coefficients for 324 firms drawn from the eight industries. Annual abatement is shown in ‘000 kgs and the cost values are presented on a logarithmic scale. The curves show wide variation of abatement costs.

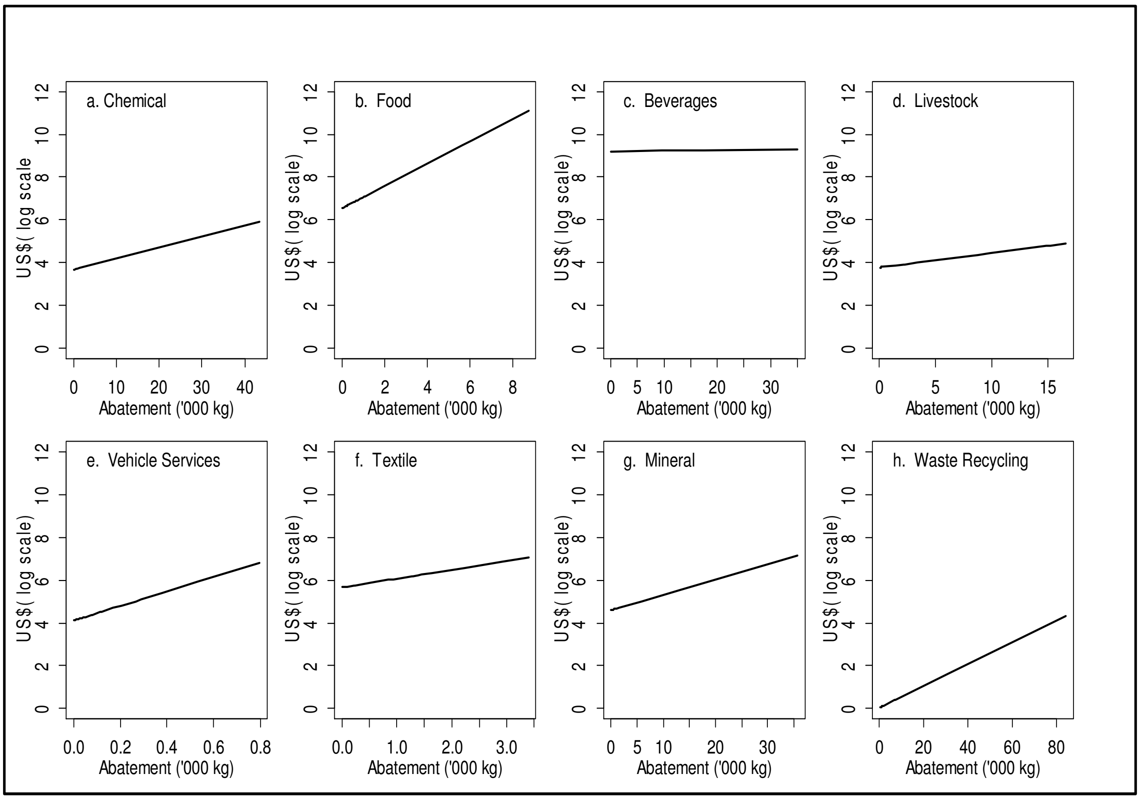

Figure 4.5: Abatement cost curves for industries

The abatement cost estimates for industrial parks that possess common wastewater treatment (CWT) facilities were computed using information on wastewater charges levied by the Board of Investment (Sado et al.) on firms located in these parks. Only maintenance cost of common treatment facilities was considered as the fixed cost is not paid by individual industries. Table 4.5 shows the calculated cost for treatment of 1kg of BOD by each CWT facility located in the industrial parks.

Table 4.5: Calculation of variable abatement cost for industrial parks

Industrial Park	Wastewater volume (cm^3/ day	BOD load initial (kg)	BOD load final (kg)	BOD load treated	Total charge (US$) /day	Recovery rate (%)	Total maintenance cost (UD$)	Unit BOD cost (US$/kg)
Biyagama	15,000	3000	450	2550	1500	64	2343.75	0.92
Seethawaka	10,000	2000	300	1700	1000	74	1351.35	0.79

The current charge by the BOI on firms is SLRs[34] 12 per cm^3 of wastewater. Assuming 1US$=120 SLRs. The total charge per day from all firms within the Biyagama industrial park is (12/120) x15,000= US$1500. Likewise, the total charge by Seethtwaka industrial park is US$1000. We calculated the initial BOD load using wastewater volumes and the pre-treatment concentration standard for BOD which is 200mg/l. For example, initial BOD load for Biyagama is (200x15,000/1000000) kg . As we know the final concentration of BOD in treated water, final BOD load could be calculated as (30x15,000/1000000) kg for Biyagama. Using the information on the recovery rate of the maintenance cost of the central treatment plant from the charges, we calculated the total maintenance cost per day for each industrial park. With the use of BOD load information, we calculated the unit cost of BOD treated by the CWT facilities (Table 4.5). In addition, individual cost of treatment per average firm (SLRs 18/ per cm3 of wastewater) located in industrial parks to meet pre-treatment standards was also used to calculate total abatement costs for the industrial parks.

4.3.3 Firms and industrial parks

Firm data come from the CEA database of industries in the Western province (Appendix 2). There were 324 water polluting firms that come under high and medium level of pollution categories and two major industrial parks. Firm level pollution loads[35] were calculated using standard BOD concentration level of each industry (for firms without any treatment facility) and wastewater volume for each firm. Firms with treatment facilities were assumed to comply with current BOD concentration standards (30 mg/l) and their loads were calculated by multiplying concentration standards with wastewater volumes.

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[34] *Sri Lankan Rupees*

[35] *The analysis of our sample survey data revealed that the firms with treatment facilities have higher compliance rates. Therefore, for the firms who were not surveyed, were considered as complying firms if they possess a treatment facility.*

4.4 Hydro-economic model

Use of hydro-economic models to manage river catchments integrates hydrological, engineering, environmental and economic aspects to determine efficient and cost effective management decisions (Heinz et al., 2007). Such an integrated approach is needed to make socially optimal policy decisions. These models operationalize economic concepts by including them at the centre of water resource management (Harou et al., 2009). Despite the widespread use of hydro-economic models to manage different aspects of water resources, application of such models to simulate policy options to control wastewater pollution is limited. The European Union Water Framework Directive for nitrate pollution management led to a number of key studies (Gömann et al., 2005, Aftab et al., 2007, Peña-Haro et al., 2009, Cools et al., 2011) and a smaller number of studies addressed BOD emissions (Moffatt et al., 1991, Hanley and Moffatt, 1993, Hanley et al., 1998). There are few studies on emerging countries such as Taiwan (Ning and Chang, 2007, Wang et al., 2004, Qin et al., 2011).

The hydro-economic model combines the hydrology model of water quality with an economic model of firms' behaviour. Estimated zonal transfer coefficients from the hydrology model of water quality (described in section 4.3.1.1.), used as inputs to our economic optimization model.

4.4.1 Economic optimization model

The policy options considered in cost-effectiveness analysis were: (1) current effluent concentration standard; (2) uniform emission cuts from all the sources; (3) emission tax or permit system; (4) zonal (single-zone) system; and (5) multiple zone system.

Among the range of policy instruments, (1), (2) and (3) only focuses on emission reductions but are not linked to ambient water quality targets. Policy option (1) and (2) are two types of command and control policies and (3) represent the least cost solution: an option to benchmark with (1) and (2) that do not account for spatial considerations. In contrast, option (4) and (5) consider spatial effects of configuration of pollution sources on ambient river water quality representing single to multiple zones approach.

Policy options without spatial consideration

The regulator's main objective is to minimize the total abatement cost (c_i) for firms subject to the total abatement target. The objective function of the regulator can be written as :

$$Min \sum_{i=1}^{p} c_i \ (x_i) \ = \ \sum_{k=1}^{K} \sum_{j=1}^{J} \sum_{i \in p_{kj}} c_{kji}(x_{kji}) \tag{4.1}$$

Firms are denoted by i =1,2, ... p ; x_i is the abatement of firm i and c_i is the cost of abatement for firm i; the industrial sectors that firms belong to are denoted by j =1,2, ... J; River zones are denoted as k =1, 2, ... K. p_{kj} is a set of firms in zone k in industry j. x_{kji} is the level of abatement of firm i belongs to industry j and zone k. c_{kji} is the corresponding abatement cost for firm i that belongs to industry j and zone k.

Costs are minimised subject to the following set of constraints:

$$\sum_{k=1}^{K} \sum_{j=1}^{J} \sum_{i \in p_{kj}} (x_{kji}) \geq TR \tag{4.2}$$

TR is the constraint that specifies total abatement target from all firms; and firm's abatement level is allowed to range from zero up to the current emission level:

$$0 \leq \ (x_{kji}) \leq (x_{kji}^{0}) \tag{4.3}$$

The cost-effective allocation of abatement is such that marginal abatement costs be equalized across firms: $c'_i = \lambda$, where λ (lagrangian multiplier) is a constant which is equal to the shadow value of the emission reduction target. Therefore, the optimal permit price/ tax rate would be equal to the shadow value (λ).

Policy options with spatial heterogeneity

The objective is to minimize the total cost of abatement for firms as shown in Eq. (4.1) while achieving targeted improvement in ambient DO levels:

$$\sum_{k=1}^{K}\sum_{j=1}^{J}\sum_{i\in p_{kj}}(x_{kji}).(d_{kh}) \geq \Delta D_h \qquad (4.4)$$

The constraint $\Delta D_h$is the target improvement in ambient DO level in the zone *h* that is the difference between the target and the observed mean DO level of the zone *h*. d_{kh} is the transfer coefficient of zone *k* with respect to the zone h; the receptor zones are denoted by *h*=1,2,....*K.*

The first order condition under single / multiple zone system that provide cost-effective allocation of emissions is : $c'_i = \lambda_h * d_{kh}$, where the marginal abatement cost weighted by corresponding zonal transfer coefficients provide the shadow value for each zone λ_h. The optimal zonal tax (t_k) or permit price for given DO target is equal to the shadow value for each zone. The total tax revenue (T_{kji}) can be represented by

$$T_{kji=}t_k \,.\, x_{kji} \qquad (4.5)$$

4.5 Results

4.5.1 Current effluent concertation standard

Our evaluation of current regulation is based on the current concentration standard of BOD (30mg/l) on effluents released by the firms to the River. Assuming fully compliance of all firms and using sectoral level abatement cost coefficients, we computed the aggregate abatement cost (US$ 1,726,489 per annum) for firms to reduce their emissions to reach the required uniform concertation level. The abatement cost is comparatively low for the firms with bigger levels of initial emissions x^0_{kji}.

Using information of transfer coefficients, we link current regulations to ambient water quality (DO concentration levels). The potential improvement in DO levels from the current level for each zone is computed (Table 4.6) assuming all firms comply fully. The current level of DO shows what has been achieved with a given compliance level.

The last column of the Table 4.6 shows the DO levels that would occur if all firms comply with the current effluent standard.

What came out from the evaluation of current regulation is that the aggregate cost would be higher if all firms comply with effluent standard. In order to achieve DO levels with fully compliance, 63 percent of current total BOD load need to be reduced. Linking the regulation with currently observed ambient DO levels, it shows that the current effluent regulation does not achieve the potential gains in improvement of DO levels (see Table 4.6) due to poor compliance[36].

Table 4.6: DO level under current uniform regulation with 100% compliance

Zone	Monitoring location*	Current mean DO level ** (mg/l)	Possible improvement in DO level	Expected DO level (mg/l)
Z1	Vicotria	6.100	0.153	6.253
Z2	Ambatale	6.880	0.198	7.078
Z3	Rakgahawatte	4.300	0.196	4.496
Z4	Pusselioya	6.000	0.185	6.185
Z5	Hanwella	6.900	0.162	7.062
Z6	Seethawaka	6.870	0.146	7.016

**One monitoring location was selected from each zone to indicate water quality*
*** Average concentration of DO from 2008-2011*

In addition, the current regulation is based on BOD concentrations, not loads. Therefore, relatively small scale firms with a lower effluent loads and large scale firms with a large load of effluents face the same concentration standard. This is especially true for the industrial parks even with full compliance; their emission loads are considerably high and have bigger influence on ambient DO level, than dispersed individual firms (see Table 4.2 on transfer coefficient values for industrial parks).

4.5.2 Uniform emission cuts

Here, we evaluate the cost of uniform emission cuts assuming each firm reduces a uniform percentage of emissions (Figure 4.6). The costs are calculated under two

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[36] *The compliance rate to the current regulatory standard of BOD is about 35 perc cent.*

scenarios (1) firms can reduce their emissions from current level to zero (abatement potential is 100%); (2) firms can reduce their emissions from current level to 20 percent (abatement potential is 80%). The second scenario is more practical as 100% abatement can be very costly or may not be possible with available technologies to treat wastewater.

The Figure 4.6 shows changes in total cost in both scenarios and also the cost corresponding to 63 per cent reduction of emission load. The aggregate costs are increasing in both cases with the increase the level of emission cut.

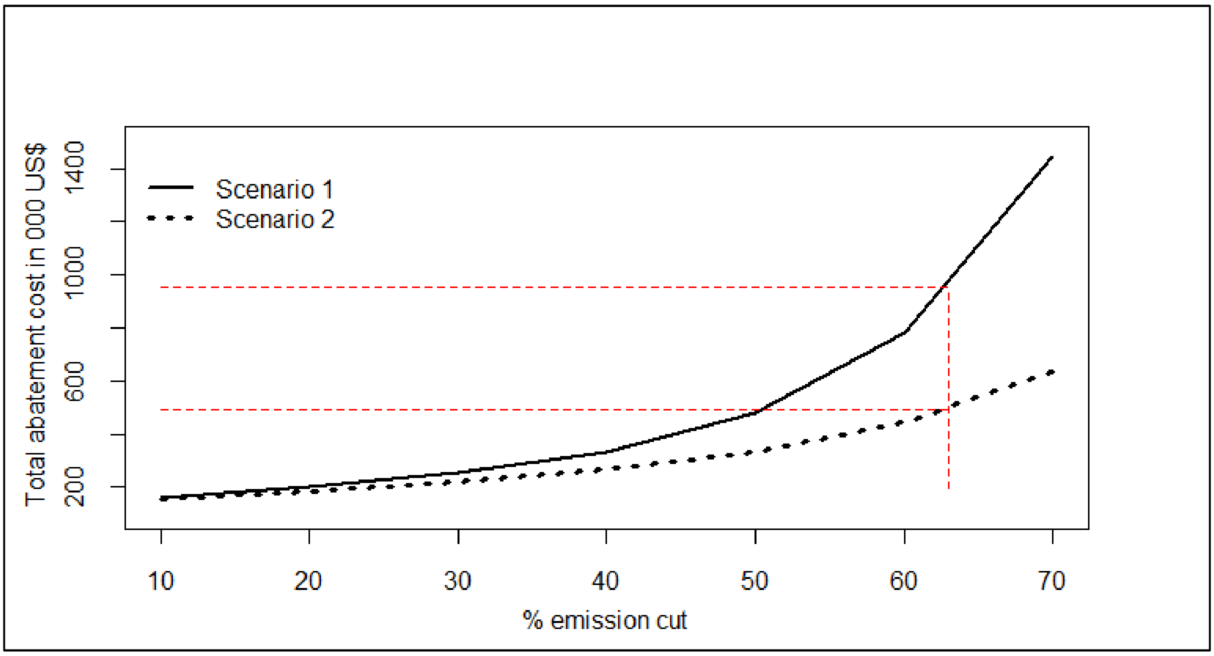


Figure 4.6: Total abatement cost under different emission cuts

4.5.3 Emission permit and taxes

We conducted an optimization analysis using nonlinear programming techniques to find the lowest aggregated cost for industries if a permit or tax is introduced based on emission load. The aim is to minimize the aggregate abatement cost (see, Eq. (4.1)) while achieving target levels of aggregate abatement (Eq. (4.2)). As mentioned above in section 5.2, both scenarios were considered.

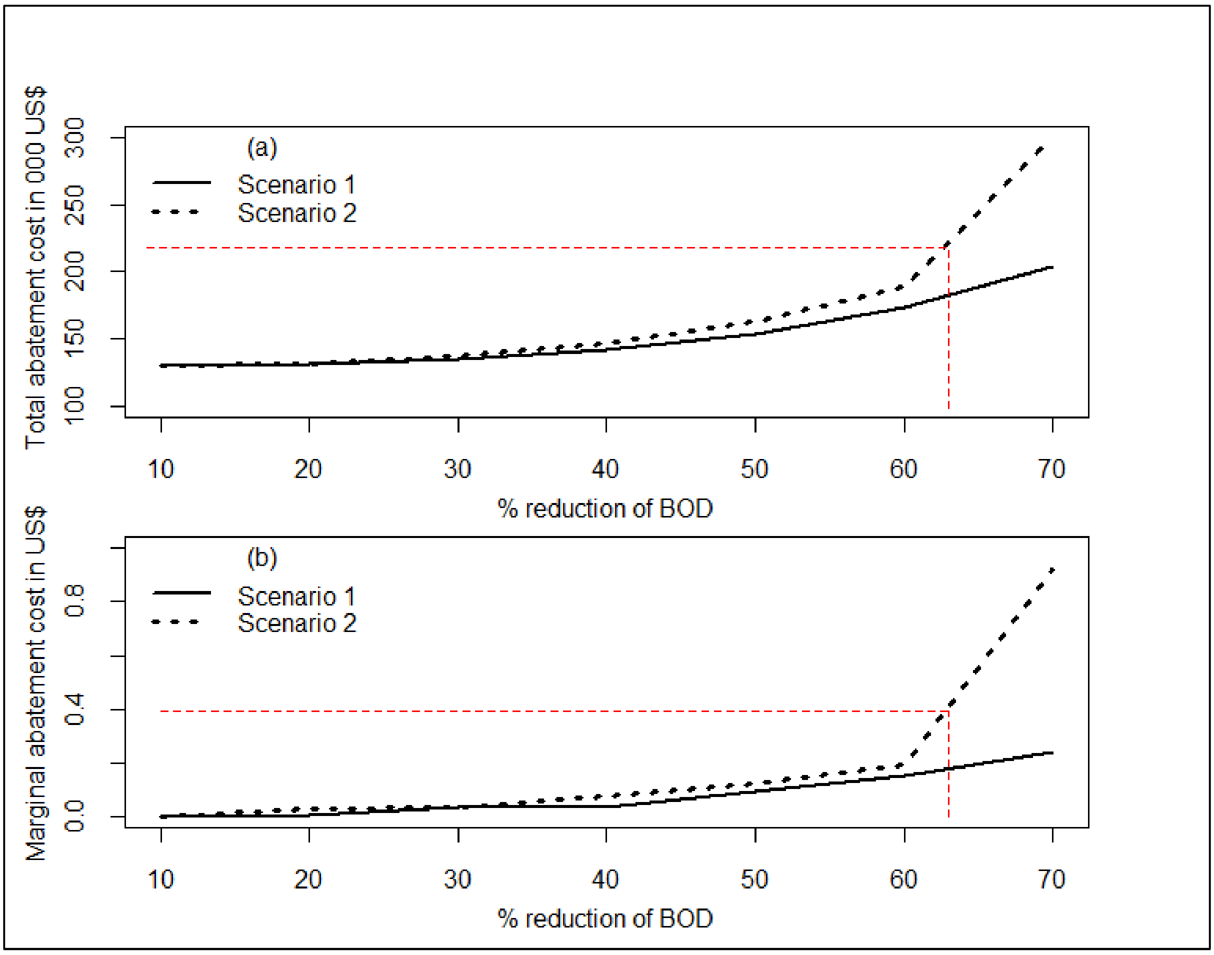


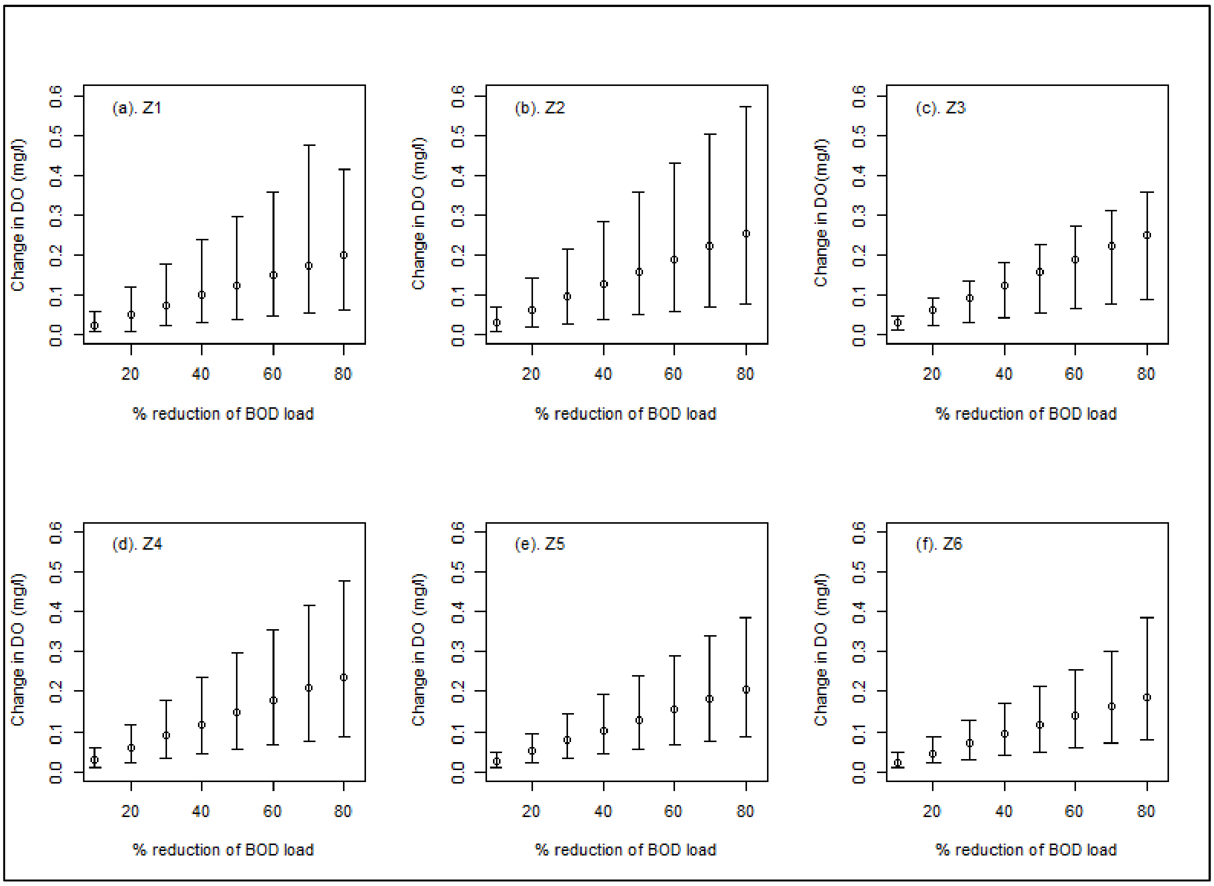
Figure 4.7: Total and marginal abatement costs for different level of emission cuts

The analysis of the results of emission permit/tax system reveals that the cost of reducing emission loads increases gradually at the margin and, beyond 60 percent reduction range, the curves get steeper (Figure 4.7 (a) and (b)). The marginal cost of achieving 63 per cent reduction is US$ 0.39 /kg. If an emission tax is introduced, the total tax revenue gained by the regulator per year would be equal to US$ 361,347.

4.5.4 Zonal **system**

The spatial variability of pollution sources adds more complexity to designing policy instruments (Tietenberg, 1995). The zonal approaches tend to provide the middle ground between simple emission based policies to administratively complex source specific instruments (Tietenberg, 1995, Cao and Ikeda, 2005). Zonal systems try to address the spatial variability by dividing the control region into a specific number of zones, thereby reducing transaction cost to the regulators as all the pollution sources within a specified zone have similar transfer coefficients. These systems attempt to lower the vulnerability of creation of hotspots by limiting the trades only within zones as long as the ambient water quality standard is achieved at the receptor zone (Tietenburg, 2010, Tietenberg, 1995).

Figure 4.8 shows the effect of BOD load reductions on ambient DO levels in 6 zones (see Figure 4.3 for details on zones). The point identified on each bar shows the change in DO based on mean transfer coefficients with respect to per cent reduction of BOD load. The lower and upper ends of the bar show change in DO levels from lower to upper bounds on the transfer coefficients (Table 4.2).



Note: The point identified on each bar indicates the change in DO based on mean transfer coefficients. The lower and upper ends of the bar show change in DO levels from lower to upper bounds on the transfer coefficients

Figure 4.8: Effect of BOD load reductions on ambient DO levels for each zone

Zone 2, the drinking water extraction point is the most responsive to BOD abatement followed by Z3 and Z4. The corresponding elasticities[37] of DO with respect to BOD abatement for Z2, Z3 and Z4 are 0.053, O.052 and 0.049. The Z6, upstream end of the

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[37] *Percentage DO change was calculated assuming the baseline mean DO level of all zones as 6mg/l*

river has lowest influence as expected, where the river discharge rate is high. Z1 is the lowest end of the river, which has comparatively lower impact due to the tidal influence from the sea.

If regulator wants to introduce a permit system based on ambient water quality (DO levels), the objective is to minimize the total cost of abatement of firms and industrial parks which depends on each firms' level of abatement (Eq. 4.1). The Eq. (4.4) sets the target improvement in DO level $(\Delta D_h\ )$ for zone *h*. The role of transfer coefficient (d_{kh}) in the equation is describing the effect of BOD load reduction on ambient DO level. Under this system, focus is on improvement of ambient water quality in one zone (receptor), while trading is allowed only within zones. In some cases, regulator picks up the worst-case receptor assuming that improvement in such zone would bring improvement in the other zones.

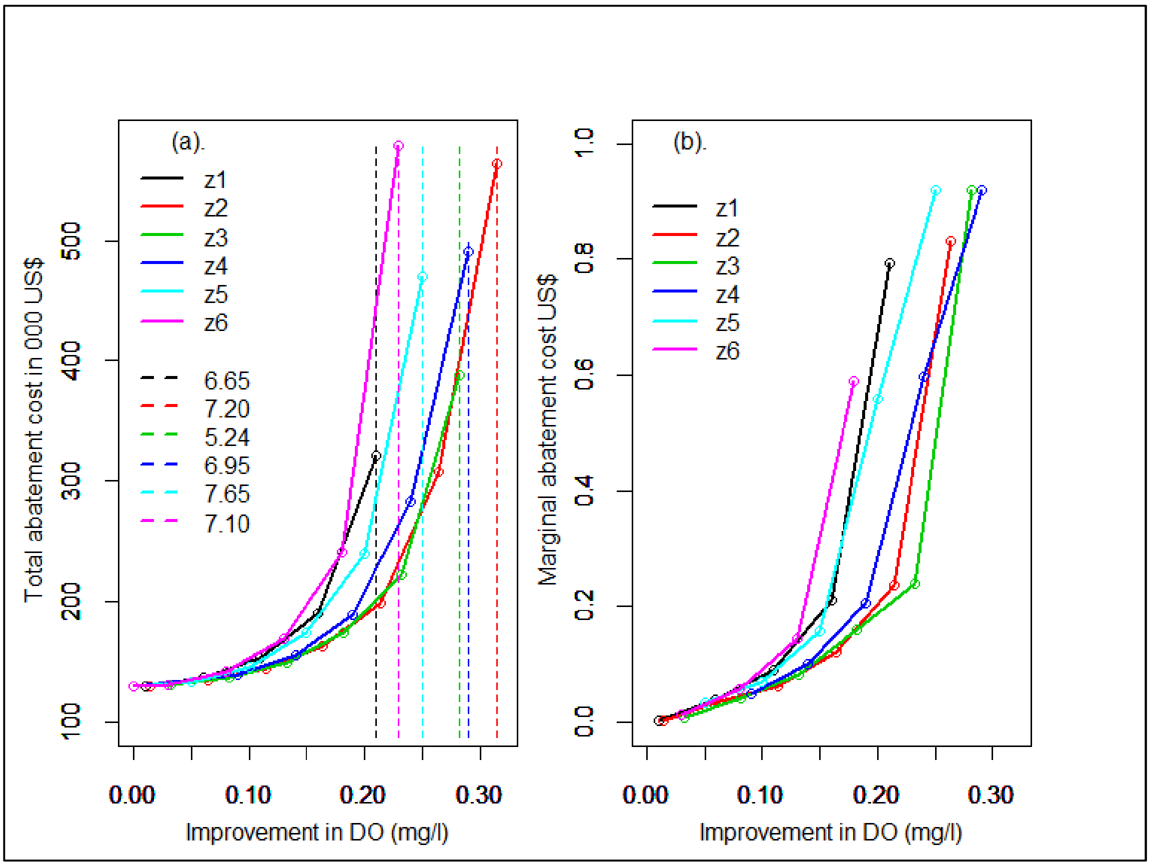

Figure 4.9: Total and marginal cost of abatement with respect to the improvement in ambient DO levels under zonal system

In this study, given the importance of water quality of all the zones, the optimization analysis carried out for each zone separately to look at the optimal increase in DO level in each zone and relevant abatement cost and marginal costs are shown in Figure 4.9. Figure 4.9(a) shows how total abatement cost changes with the different levels of DO improvements (mg/l) in ambient water quality for each zone. The abatement cost curves increase gradually and then get steeper with further improvement of DO levels. All the zones follow similar pattern. Z6 which is the first upstream zone in the lower catchment shows highest abatement cost followed by Z1 and Z5. Z2 and Z3 show comparatively lower cost initially; however, beyond 0.28mg/l costs rise steeply.

We calculated the maximum possible improvement in DO levels that could be obtained with the reduction of BOD loads from each zone from the current level (based on observation data available in monitoring points of each zone). The vertical dotted lines in Figure 4.9(a) show the maximum possible improvement of DO levels obtained by reducing industrial emissions.

The Figure 4.9 (b) shows the marginal cost for each zone at each level of improvement of DO. The marginal costs of improving the DO level is increasing implying that greater improvement in DO need greater reduction on BOD loads. However, the marginal costs vary for each zone and depend on: (1) location of the zone in the river catchment which is reflected in the transfer coefficient; (2) current observed mean DO levels at the monitoring point of each zone; and (3) current water quality target of the each zone. If overall target of DO level is 7 mg/l, which can be achieved easily in some zones that are relatively clean, but beyond 7mg/l , marginal costs are very high for these zones. If the level of DO improvement only considered without current DO levels, Z6 has the highest marginal cost followed by Z1, Z5, Z4, Z2 and Z3.

It is important to note that the improvement of DO level in Z2 (where water extraction point is located) to a considerable level (beyond 7mg/l) at lower cost is possible with reduction of industrial emissions. The maximum possible DO level that can be achieved at Z2 is 7.2mg/l (see Figure 4.9). As Z2 is the most important zone in terms of water quality, the regulator would implement a zonal system focusing on improvement in DO levels at Z2. Currently, the National Water Supply and Drainage Board (NWSDB), Sri

Lanka is treating water (conventional treatment) before releasing water into the public water supply. The additional cost spend from simple treatment to conventional treatment is about US$ 1.13 million per annum. Assuming other water quality parameters at required standard, improvement in DO level at least for 7 mg/l would save additional cost for cost water treatment (due to switching from simple to conventional treatment).

Z1 is very close to the marine sewage outfall (Mutwal). Therefore, further improvement of water quality of the Z1 and the estuary can be achieved, by redirecting the outfall further out to sea. The only possible way to further improve Z3 and Z5 is addressing the non-point source pollution from sub catchments. Given availability data, this is beyond our research; however, implementing best management practices in agriculture, awareness programs among communities and restrictions on fertilizer and pesticides use could reduce pollution from non-point sources.

4.5.5 Multiple zone system

Riverine zones are connected to each other and in the non-tidal reaches the movement of river is unidirectional. Analysing zones separately does not account for the hydrological links between zones and possible positive externalities due to cleaning up one zone on the other zones (Howe, 1994). Under multiple zone system, the trading is allowed among zones ; transfer coefficients among zones were used as trading ratios(Hung and Shaw, 2005). We undertook an optimization analysis to minimize cost while simultaneously achieving the targeted level of DO improvement for all the zones. Multiple zone permit systems allow polluting firms to utilise their own knowledge on their costs and trade can be more effective in approximating the cost effective solution (Howe, 1994). This approach can be implemented with different levels of DO targets for each zone. The objective function in this analysis is to minimize the total aggregate cost (Eq. (4.1) while achieving simultaneous improvement in DO levels for all the zones at different targets (Eq 4.5). Therefore, 6 constraints were set using target level of improvement for each receptor zone. We also analysed the costs while setting target improvement of each zone into a same level (For example 0.25 and 0.20). The results are reported in Table 4.8 under 2nd and 3rd scenarios.

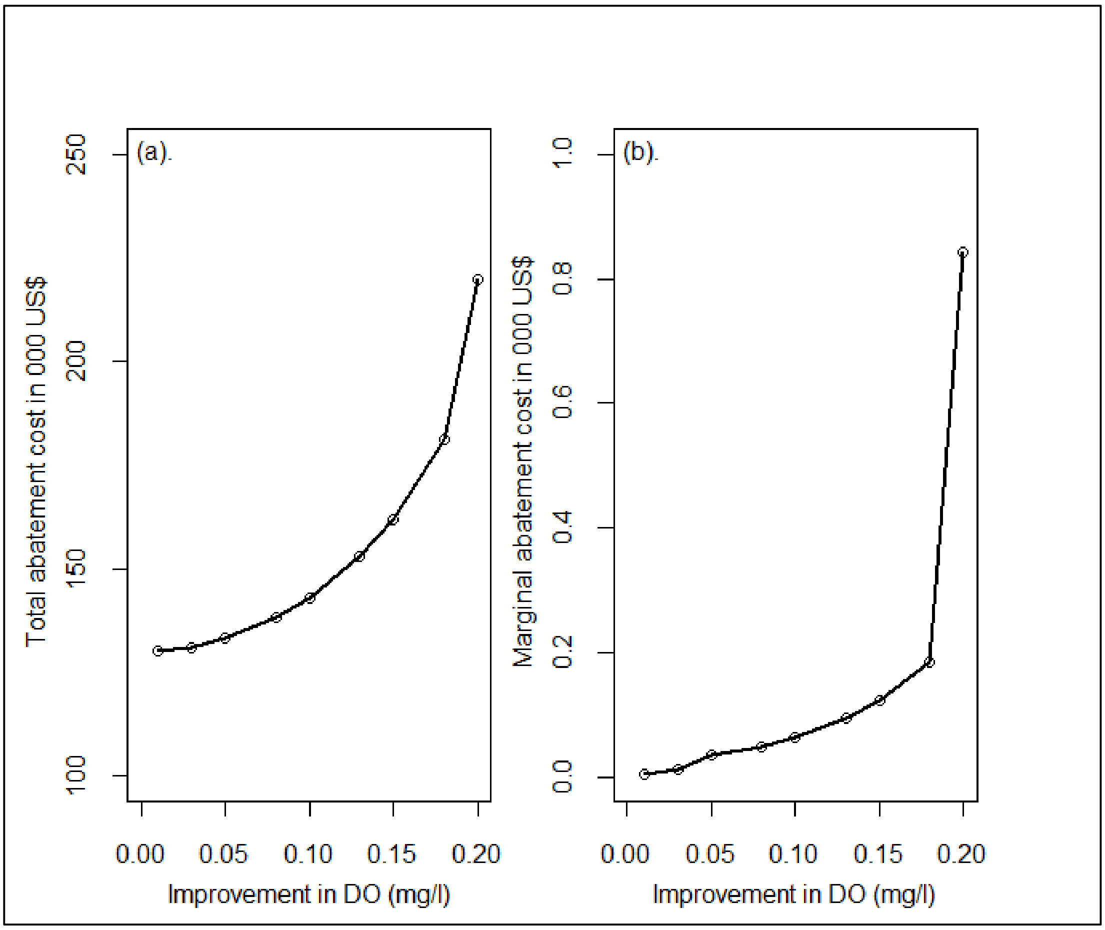

Figure 4.10: Abatement cost and marginal costs under multiple zone analysis

The abatement costs curves follow the similar pattern as in the case of zonal (single-zone) analysis (Figure 4.10 (a)). The main difference observed include that the overall cost is comparatively low with the same levels of improvement in all the zones. We also analysed the overall marginal cost under multiple zone analysis as shown in Figure 4.10 (b). The zonal marginal costs are lower than the case of zonal analysis up to the improved DO level 0.15mg/l. However, marginal abatement costs for further improvement are rapidly increasing under multiple zone system and higher than the marginal costs for zonal system. This is mainly due to simultaneous improvement is targeted in all the zones under multiple system and improving some zones are costlier than others.

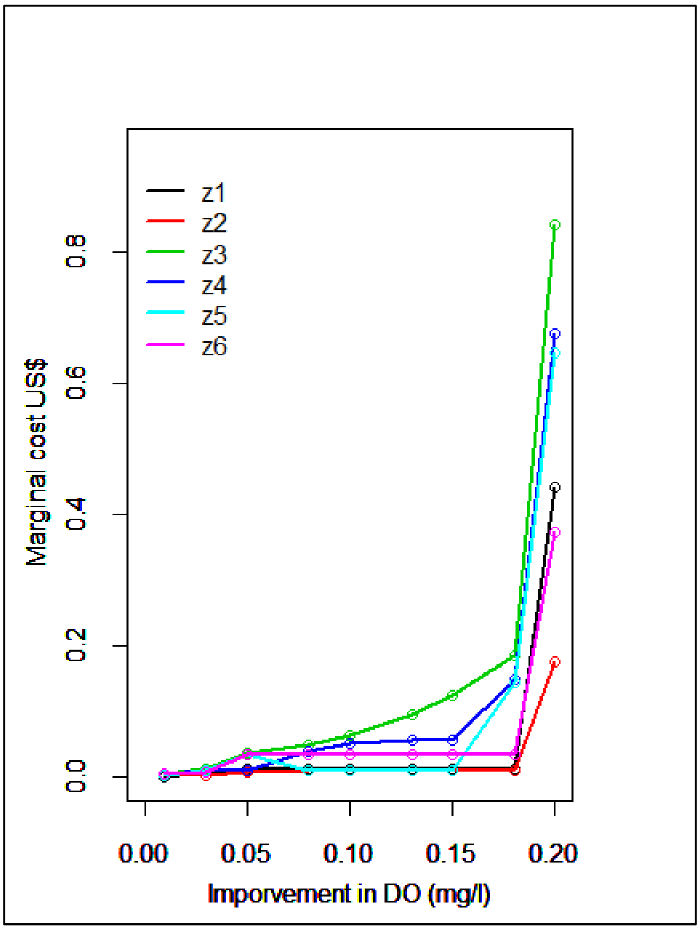

Figure 4.11: Marginal cost under multiple zone analysis

The zonal marginal costs under multiple zone analysis are shown in the Figure 4.11. These zone-specific marginal costs can be used in designing zonal tax or permit values. According to theory, taxes and tradeable permits provide the same cost savings under perfect information with no transaction costs. In real situations, the choice between a tax and tradeable permit depends on uncertainty of information and other considerations. However, design and implementation challenges in less developed country settings, an emission tax differentiated by zones would be a preferred policy once the administrative costs are accounted.

4.5.6 Comparison of policy options

Our aim in this analysis is to look at cost effective instruments while maintaining improved river ambient water quality. The first three policy options that do not account for spatial heterogeneity of pollution sources are reported in Table 4.7 with corresponding cost values. The comparison was made considering the same level of

BOD load reduction (63%) as in the case of current effluent concentration standards. We also report the corresponding improvement in ambient DO levels of the river for these policy options.

Table 4.7: Cost comparison of policy options that do not account for spatial effects

Policy options	Cost ('000 US$) per annum	Cost as a % of total cost of production*	Improvement in DO level (mg/l)
(1) Current effluent regulation	1,726	0.254	0.14-0.15
(2) Uniform emission cuts	931	0.136	0.14-0.20
(3) Emission permits	202	0.029	0.15 - 0.19

**This is a rough estimation based on mean cost of production of a firm calculated using sample survey.*

The cost comparison of the policy options (4) and (5) that consider spatial heterogeneity of firms are reported in Table 8, under three scenarios: (1) maximum possible improvement in DO level of each zone under zonal system and corresponding cost for same level of improvements under multiple zone system; (2) maximum possible improvement under zonal system and multiple zonal system; (3) uniform level of improvement (0.2 mg/l) across all the zones under both systems.

Among evaluated policy options that do not consider spatial variations, current regulation on effluent standards is the most expensive policy if all the firms fully comply (Table 4.7). Even with such cost, maximum possible improvement in DO levels would be 0.153mg/l. The cheapest option would be the use of emission permits. However, this option does not bring required level of DO improvements in all the zones.

Given the importance of water quality in certain zones, considering spatial heterogeneity is a must. Zonal system can offer low cost solution if the water quality concerns are only for one zone (Table 4.8). For example if water quality of the zone 2 where extraction of water is only the concern, the cost of improvement in zone 2 would be less compared to multiple zone system.

However, water quality of most of the zones is important due to various water uses. Having analysed the trade-offs between cost and improvement in river water quality, targeting improvement in all the zones under multiple zone system appears cost effective generating considerable improvement in water quality (Table 4.8).

Table 4.8: Cost comparison of policy options with spatial heterogeneity

		(4) Zonal system			(5) Multiple zone system		
	Zone	DO change (mg/l)	DO level (mg/l)	Cost ('000 US$)	DO change (mg/l)	DO level (mg/l)	Cost ('000 US$)
1	1	0.19	**6.29**	369	0.19	**6.29**	
	2	0.3	**7.18**	446	0.3	**7.18**	
	3	0.25	**4.55**	431	0.25	**4.55**	
	4	0.2	**6.2**	491	0.2	**6.2**	
	5	0.2	**7.1**	380	0.2	**7.1**	
	6	0.19	**7.06**	636	0.19	**7.06**	
				2,752			656
2	1	0.19	**6.29**	369	0.25	**6.35**	
	2	0.3	**7.18**	446	0.25	**7.13**	
	3	0.25	**4.55**	431	0.25	**4.55**	
	4	0.2	**6.2**	491	0.25	**6.25**	
	5	0.2	**7.1**	380	0.25	**7.15**	
	6	0.19	**7.06**	636	0.25	**7.12**	
				2,752			431
3	1	0.19	**6.29**	369	0.2	**6.3**	
	2	0.2	**7.08**	186	0.2	**7.08**	
	3	0.2	**4.5**	217	0.2	**4.5**	
	4	0.2	**6.2**	199	0.2	**6.2**	
	5	0.2	**7.1**	370	0.2	**7.1**	
	6	0.19	**7.06**	636	0.2	**7.07**	
				1,977			217

In order to put cost figures in perspective, we reported total abatements cost as a percentage of the total cost of production (Table 4.7) of firms using mean cost of production of the sample data. This shows that overall cost to industries to reduce their emissions is 0.25 per cent in the case of current regulations. With other instruments that does not consider spatial effects the cost is even less. Compared to the government spending on the water treatment, private and public health costs associated with poor water quality and losses of ecosystem services, overall cost to industries is very low. Being a developing country, government takes the burden of providing clean water, health service and other infrastructure services at reasonable

cost; industry also has a role to play to internalize the negative externalities due to by-product of their production process.
This is why the regulator’s role in choosing policies is very important. For example, under current regulations, small firms face higher marginal abatement costs while large scale firms have lower marginal abatement costs due to economies of scale in pollution abatement. On the other hand, the current policy suffers from inadequate monitoring and enforcement that leads to non-compliance.

4.6 Conclusions and Policy implications

Using an integrated hydro-economic model, we evaluated five policy options ranging from the current effluent concentration standard approach to complex multiple zone approach to manage organic water pollution during dry season in the Kelani River. Our integrated model incorporates spatial variability of pollution sources estimated from a hydrology model of water quality and sectoral level marginal costs obtained from estimated parametric input distance functions. We undertook a series of optimization analyses with an aim of minimizing aggregate abatement costs while achieving various water quality targets based on policy options.

Our analysis shows that the current policy of allowing uniform effluent concentration standard does not achieve river ambient water quality targets and does not account for the variability effluent loads or abatement costs. Even if it could be implemented effectively, the current effluent standard is expensive compared to alternative potential policy options. Nevertheless, the overall cost to the industries to achieve required improvements in river water quality is not very high under current regulations compared the government spending on water treatment and public health and loss of ecosystem services . However, selecting the right policy, designing and implementation with monitoring and enforcement are challenging due to poor institutional capacities and inadequacy of data.

Introducing emission permits or tax based on wastewater discharge (loads) without considering spatial effects would be the cheapest compared to current regulations given the cost and compliance considerations. Some background work is on-going in order to improve current institutional capabilities to implement a tax or fee based on effluent discharge, which is expected to be feasible in the near future. However, with discharge fees, the impacts due to spatial distribution of pollution sources and variation of zonal river quality are not considered. Therefore, emission charges may not assure the improvement needed in ambient water quality of different zones.

Given the variability of river water use and water quality in different zones, accounting spatial heterogeneity is required to make sure to achieve the water quality targets of zones. The zonal system accounting for both cost heterogeneity and the spatial distribution suggests that an ambient DO level of 7 mg/l can be achieved with some realistic reduction of industrial BOD loads. However, this is possible with only some zones and the cost varies with each zone. Out of 6 Zones, 3 Zones could be improved to achieve DO level of 7mg/l. Most importantly Zone 2, where drinking water extraction takes place, can be improved with lower marginal cost compared to other zones. Such improvement of DO would save about US$ 1.13 million per annum, not having to undertake intensive treatment assuming other water quality parameters remain acceptable range. However, implementing the zonal system becomes expensive if simultaneous improvement of water quality of more than one zone is considered.

Implementing multiple zone system that accounts for externalities due to simultaneous improvement in other zones would be the least cost option if improvements of multiple zones are concerned. Therefore, implementing tradeable permits under multiple zone system would be the best policy option for controlling organic water pollution of the lower Kelani River. There are some promising features that would help to gain potential cost savings with an implementation of permit system such as large number of potential traders, cost heterogeneity among polluting firms and, relatively less fixed waste treatment capital in place. However, given the design and implementation challenges being a developing country, transitioning from current regulatory system to tradeable permits would be a step-wise long term process. Therefore, the environmental authority would aim at implementing a zonal tax. The marginal cost for each zone corresponding to required improvement in DO level, under multiple zone system can be used as a zonal tax rate. The tax revenue gained from the zonal tax can be used in improving the institutional capabilities. Once the capabilities are developed and required systems are in place, policy makers would try to pilot a multiple zone trading system. Then the estimated transfer coefficients can be used as trading ratios.

Overall, this study provides planners and policy makers with a framework and deeper numerical insights on selecting policies in a context of a developing country with a rapidly industrializing catchment in order to increase social welfare by incorporating abatement cost and spatial heterogeneities.

Further studies are needed with more emphasis on implementation issues and transaction costs which is beyond our research. In this study, our focus was mainly on controlling organic pollution due to industries. However, it is clear that industries and domestic sources account for only a small percentage of overall emissions where emission comes from catchments due to natural and non-point sources higher. Therefore, further improvement of highly polluted zones needs to focus on catchment pollution from non-point sources as well.

Chapter 5 : Conclusions

5.1 Introduction

Poor river water quality is a major issue worldwide due to point and non-point source pollution. Advanced economies have made progress in managing point source pollution, but non-point source pollution remains a challenge. However, developing and emerging economies are facing the challenge of controlling the point sources due to rapid industrialization and urbanization. Poor water quality brings adverse effects on the economy, in terms of human health and reduced ecosystems services. Existing command-and-control (CAC) regulations to manage water pollution in these countries have struggled to adapt to the scale of the pollution problems brought by industrialization. As a result policy makers and environmental regulators are exploring new policy instruments to manage river water quality.

The overall objective of this thesis was to investigate the choice of policy instruments to manage an economically and ecologically important river, the Kelani in Sri Lanka. The evaluation of policy instruments was based on a cost-effectiveness analysis of water quality targets. The key research findings and policy implications are presented below, followed by an overview of research contribution and significance of the findings. The chapter concludes with limitations and directions for future research.

5.2 Research questions, findings and policy implications

5.2.1 Research question 1

What are the abatement costs for firms located in the river catchment under current command-and-control regulations that specify effluent concentration standards?

This research question is investigated in Chapter 2. Here we used firm specific input and output data including undesirable outputs to estimate abatement costs under current effluent regulations. Employing multi-input and multi-output translog production technology, we estimated marginal abatement costs as shadow prices of effluents and the technical efficiency of firms belonging to eight industries. We also extended our analysis to compute total abatement cost for firms under the given level of compliance. Further, we estimated total abatement costs under different policy scenarios, related to simultaneous reduction in concentration of three water pollutants including current regulatory standards.

Key findings

The three main findings are: (1) estimates on shadow prices show a wide variation among firm- specific marginal abatements costs due to differences between industrial sectors, scale of operation and the degree of compliance with effluent concentration standards; (2) the analysis of policy scenarios with simultaneous reduction of concentration levels of three pollutants reveals that the abatement costs are comparatively high under current effluent standards; and (3) firm specific efficiency measures are negatively correlated with the degree of compliance to effluent standards; implying that there is no incentives to comply.

Policy implications

Chapter 2 provides an understanding on impact of current command-and-control policy on firms in terms of costs and incentives to control effluents. The results have two main policy implications: (1) prevalence of cost heterogeneity in abatement costs among firms and; (2) firms lack incentives to comply with current effluent standards. Both of these points strongly suggest that current regulations are not effective and there is a need to consider new policy instruments. Further, lack of information on firms’ abatement cost functions is one of the main constraints faced by the regulators. Therefore, the marginal abatement costs estimated in this chapter can be used as basis for designing new policy instruments and estimating the likely cost savings form alternative policies.

5.2.2 Research question 2

What are the impacts on ambient river water quality due to the spatial distribution of pollution sources on the river catchment?

This research question is addressed in the Chapter 3. Due to the non-uniform mixing feature, the severity of ambient water pollutants depends on the location of pollution sources in the hydrological, economic and social landscape. Water quality models can describe spatial aspects of pollution sources on ambient water quality. A catchment based water quality model was developed by integrating a catchment model with a hydrology model of water quality. Using model simulations, this chapter examines the marginal effect of pollution sources at locations along the river on ambient water quality across all locations.

Key findings

Three major findings came out of this chapter: (1) it measured the contribution of point sources on ambient water quality of the river given the background non-point source pollution; (2) a strategy to manage lower Kelani River by zoning is proposed; (3) the water quality model is used to estimate zonal pollution transfer coefficients.

Policy implications

The findings of this chapter contribute to policy in three ways: First, the estimates of contribution of pollution sources on ambient water quality provide an understanding of impact due to industrial and domestic sources on background catchment pollution. This information provides a first estimate of the determinants of lower catchment pollution measured as DO and BOD. It also provides an understanding to what extent the water quality improvements can be gained by reducing industrial and domestic effluents. This implies an important policy message that controlling point sources would help in improving river water quality to a certain extent in many zones at reasonable cost ; however, controlling non-point sources is also important to achieve long term water quality improvement throughout the lower Kelani River.

Second, the chapter suggests a practical and economical way of managing the lower Kelani River with the introduction of zoning. Zoning would help to reduce the transaction cost of managing pollution sources while spatial heterogeneity is taken into account. Further, zoning strategy would be a useful tool in designing and implementation of policy instruments that have spatial considerations. For example, this information is useful in designing policy options where maintaining water quality of certain zones is extremely important, notably, the drinking water extraction zone.

Third, the zonal transfer coefficients estimated measure the marginal effects on ambient water quality of a receiving zone due to a change of 100kg in BOD load in another zone. Regulators and policy makers can use transfer coefficients in three ways: First, new industries should be located along the river in a way that minimizes the pollution effects in sensitive zones. Second, transfer coefficients can be used to calculate the effect of each pollution source on ambient water quality. The regulators can use such information to set priorities for regulating zones and pollution sources. For example, the contribution of industrial parks to poor water quality seems high even with compliance to current regulations. Third, the transfer coefficients also provide valuable inputs to design cost-effective socially optimal policy designs. For example, the zonal transfer coefficients can be used as trading ratios in designing trading system of effluent permits among zones.

5.2.3 Research question 3

What is the optimal policy mix to manage industrial water pollution in Kelani River?

The third research question is addressed in Chapter 4. The hydro-economic model combined a hydrology model of water quality with an economic optimization model of a cost minimizing firms. The model incorporated spatial variability of pollution sources on ambient water quality, from transfer coefficients obtained from the water quality model (described in Chapter 3) and abatement costs from parametric input distance functions estimated by linear programming (described in Chapter 2). Five policy options were evaluated ranging from current effluent standards to complex multiple zone system to control industrial water pollution.

Key findings

The main finding of this chapter reflects the main finding of the thesis as outputs of Chapter 2 (abatement costs) and outputs of Chapter 3 (transfer coefficients) are combined together in a model to evaluate policy options. The findings reveal that current policy on effluent concentration standards is not only expensive compared to alternative policy instruments but also does not achieve the ambient water quality standards nor account for the variability of effluent loads and abatement costs. Taxes or permits based on emission loads came out as low cost option, but does not account for spatial variability thereby fail to achieve ambient water quality targets in all zones. Among the policy instruments that account for spatial heterogeneity, multiple zone system stands out as the cost- effective option if water quality improvement of more than one zone is concerned.

Policy implications

Our analysis shows that the current effluent regulation is expensive if all firms comply. Moreover, even with full compliance, current regulations fail to achieve river water quality targets. Therefore, the regulator needs to consider alternative policy instruments.

The variability of water quality and the differences in water use across zones means that cost-effective policy instruments must account for the spatial distribution of firms and social costs of pollution. Multiple zone system that accounts for externalities due to simultaneous improvement in all six zones is the least cost option. Regulator can implement a permit or tax system under a multiple zone approach. There are some promising features in terms of implementing a tradeable permit system such as a large number of potential traders, cost heterogeneity among firms and the lack of investment in waste water treatment infrastructure. However, being a less developed country with design and implementation challenges and lack of experience, transitioning from current command-and-control system to permit trading would be a long term process. Nevertheless, the current institutional capabilities are being developed towards charging an emission fee/ tax. Therefore, the regulator could aim at implementing a tax differentiated by zones under multiple zone system. The revenue gained from the zonal tax system could be used in improving institutional capabilities. Once the experience gained from the zonal tax system and improved institutional capabilities is in place, the regulator could pilot transition to a permit trading scheme.

The contribution of this thesis to the literature is the evaluation of range of policy options to address river pollution within the constraints of a developing country. These include the complexity of tropical river, limited institutional capacity and limited data. In particular this thesis provides one of the first empirical evaluations of zonal based policies in a developing country.

5.3 Study limitations and future research directions

In this thesis, we analysed the cost-effectiveness of several policy options. However, we did not incorporate the transaction costs associated with any of these options due to a lack of data availability. Incorporating transaction cost may provide full costs associated with policies which can influence the policy choice. Despite the fact that studies incorporating transaction costs in policy making in water pollution control is limited, future studies should make an attempt to incorporate transactions costs

In this thesis, our main focus was on industrial pollution and we used dissolved oxygen (DO) as the main indicator of water quality. However, water quality is measured by several parameters such as heavy metals, coliforms, salinity and nutrients. Heavy metals are also an issue, given the absence of data specific to each sources prevented us modelling them. Our model incorporated salinity and coliform levels as well; however, poor availability of data on domestic sources prevented us analysis of coliforms. The communities live in the underserved settlements of the lower catchment that do not have access to clean water and sanitation, utilize river water for multiple day-to-day uses. Detailed studies on health impacts of river water quality on such poor urban communities would be beneficial in terms improving river water quality and human welfare.

Studies on river catchment with detailed data on land use would also helpful to get holistic understanding of non-point sources. It is important to build a long term comprehensive databases with monitoring data in systematic manner and covering more locations along the river. If such data set is transparent and publically available further research would have been done to develop overall water quality index for different river zones.

The river estuary is an important ecosystem which has also been negatively affected due to poor water quality of the river. Studies on non-market valuation would also provide useful inputs in planning and managing river water quality.

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Appendix 1 : Questionnaire

Questionnaire number						**Date**							
EPL number(if available)													

Survey of firm located in Kelani river catchment in Sri Lanka -2013

1. Geographical location of the company
2. Identification information
3. Raw materials
4. Fuel and other utilities
5. Cost of non – industrial services purchased
6. Other expenses

7. Other income

8. Employment and Labour cost

9. Fixed Assets

10. Products and by-products

11. Current waste treatment facility

12-17 Abatement expenditure for water pollution control

Enumerators Name		**Signature**		**Date completed**	
Supervisors Name		**Signature**		**Data completed**	

1. Geographical location of the company

1	Province			6	Name of the industrial location	
2	District			7	Address of the head office	
3	Divisional Secretary’s Division					
4	Grama Nidladhari Division			8	If company has many branches, name them	
5	industrial location	I	Industrial Zone/ Estate			
		II	Other			

2. Identification information

1	Name of the company							6	Name of the respondent	
2	Description of the industry							7	Designation	
3	Main products/services							8	Contact number	
4	Industrial code							9	Fax number	
5	Type of ownership	I	Domestic	II	Foreign	III	Joint	10	Email address	
6	Sector	I	Government	II	Private			11	Postal address (if different form head office address)	
		III	Board of	IV	Corporation					
		V	Government Department							

3. Raw materials purchased in 2012

	Description of Raw materials	Unit of measurement	Purchased in last month		Purchased in year 2012	
			Quantity	Value (Rs'000)	Quantity	Value (Rs'000)
	I	II	III	IV	V	VI
1						
2						
3						
4						
5						
6						
7						
8	Semi-Finished Goods					

4. Fuel and other utilities purchased in 2012

	Fuel	Unit of measurement	Quantity	Value (Rs'000)		Other utilities	Unit of measurement	Quantity	Value (Rs'000)
	I	II	III	IV		I	II	III	IV
1	Firewood				9	Electricity purchased			
2	Coal and Charcoal				10	Electricity generated			
3	Petrol				11	Electricity used			
4	Diesel oil				12	Water from supply board			
5	Furnace oil				13	Water from wells			
6	Gas				14	Water from water bodies			
7	Other fuel								

5. Cost of non-industrial services purchased in 2012

	Item	Cost (Rs.'000)
		I
1	Communication (includes telephone, postage, fax, email and internet)	
2	Advertising	
3	Transport services	
4	Accounting services	

6. Other expenses in 2012

	Item	Expenditure (Rs'000) I
1	Work done by others on material supplied by the industrial undertakings	
2	Repair and maintenance for buildings	
3	Repair and maintenance for plant and machinery	
4	Repair and maintenance pollution control equipment	
5	Repair and maintenance for other fixed assets	
6	Rent/ leased payments (building, plant , machinery and other fixed assets)	
7	Insurance chargers	
8	Interest paid	
9	Other non-operating expenditure	

7. Other income in 2012

	Item	Expenditure (Rs'000) I
1	Income from services- work done for others on material supplied by them	
2	Value of electricity generated and sold	
3	Value of own construction	
4	Rent received from buildings, plant, machinery and other fixed assets	
5	Interest received	

8. Employment and labour in 2012

	Employment category	Full time (number of workers)	Part time (number of workers)	Total salary paid	Other contributions EPF and ETF (Rs'000)	Bonuses and allowances (Rs'000)	Staff welfare expenses (Rs '000)
		I	II	III	IV	V	VI
1	Skilled operatives						
2	Unskilled operatives						
3	Managerial/ Administrative						
4	Technical/ Supervisory						
5	Clerical						
6	Working proprietors and Active partners						
7	Unpaid family workers						

9. Depreciation of Fixed Assets in 2012

		Total value(Rs.) I	Rate II	Depreciation (Rs.) III
1	Land			
2	Buildings			
3	Plant & Machinery			
4	Transport equipment			
5	Computer equipment			
6	Pollution control equipment			
7	Others			

10. Products/services and by-products in 2012

	Description of commodities produced	Unit of measurement	Production capacity	Total products moved out of the establishment in 2012		Of which exports in 2012 Quantity
				Quantity	Value (at Producers Price) Rs'000	
		I	II	III	IV	V
1						
2						
3						
4						
5						
6						
7						
8						
9						
10	Semi-Finished Goods					
11	By- products					
12	Water pollutants					
13	Solid waste					
14	Air pollutants					
15	Any other					

11. Current waste treatment facility

	Yes/ No	a. Company owned b. Central facility	Capacity	Unit of measurement	Amount reused after treatment	Annualized capital investment	Cost of maintenance	Cost of testing	Any other cost
	I	II	III	IV	V	VI	VII	VIII	IX
Solid waste									
Waste water									
Smoke									
Any other									

12. How do you dispose water discharge after the production process?

I	Dispose directly to the Kelani river
II	Dispose to a canal which is connected to the river
III	Dispose treated waste water directly to the river
IV	Dispose treated waste water to canal which is connected to the river
v	Mention if any other

13. Any problems with existing treatment plant?

14. Any new plans and innovative ways to reduce water pollution in the coming years
For example, use of cleaner production technologies

15. What do you think about existing regulations of waste water disposal?

16. According to your opinion why companies are not complying with existing regulation?

17. Any ideas/ suggestions to improve existing regulation or new methods such as a tax or permit system?

18. Future abatement expenditure for water pollution control [38]

Options to reduce emissions	Level of emission to be reduced at each step	Expenditure (Rs)			
		6 months I	1 year II	2 years III	3 Years IV
1. Improve existing treatment plant					
	25-50%				
	50- 75%				
2. Invest on new treatment plant					
	25-50%				
	50- 75%				
3. Changing input mix					
	25-50%				
	50- 75%				
3. Changing the production process[39]					
	25-50%				
	50- 75%				

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[38] For the companies which do not possess current treatment facilities

[39] By changing the production technology for example adopting cleaner technology

19. Water quality measures available

Before EPL(Date)		After EPL(Date)	
BOD		BOD	
COD		COD	
TSS		TSS	

20. If firm does not have any treatment or needs changes to the existing facility, fill the following details

Capital cost for proposed treatment facility	Capacity	Estimated life time	Annual operational cost	Name of the service provider

21. Any remarks about waste treatment facility and observations

Appendix 2 : Water polluting firms in the Kelani River catchment

Firm number	Industry	zone	Pollution category	BOD concentration (mg/l)	BOD load (kg/day)
1	2	2	1	303	0.48
2	3	3	1	12	96
3	1	3	1	12	0.001
4	5	3	1	15	0.03
5	7	3	1	15.2	0.02
6	8	3	1	560	0.9
7	5	3	1	65	0.1
8	4	4	1	855	0.21
9	1	4	1	22	0.11
10	1	2	1	22	0.18
11	1	2	1	22	0.07
12	5	2	1	25	0.03
13	2	2	1	21	0.03
14	1	2	1	150	0.87
15	7	2	1	20	1.81
16	7	2	1	8.2	0.03
17	1	2	1	160	0.17
18	6	2	1	2400	2.56
19	7	2	1	15.2	0.97
20	5	2	1	58	0.33
21	1	2	1	150	0.03
22	5	2	1	26	0.14
23	6	2	1	15	0.02
24	5	2	1	15	0.08
25	1	2	1	22	0.07
26	8	2	2	1000	2.67
27	2	4	1	20	0.02
28	1	1	1	18	0.2
29	7	3	2	12	0.01
30	7	3	2	1	0.001
31	7	3	2	12	0.01
32	2	2	2	326	0.09
33	5	2	1	59	0.22
34	1	2	1	45	4.32
35	5	3	1	65	0.04
36	5	2	2	29	0.31
37	4	4	2	1800	0.1
38	2	4	2	325	0.8
39	5	4	2	168	0.13
40	7	4	2	1	0.001
41	5	3	2	1	0.001
42	5	3	2	117	0.79
43	2	3	1	700	16.8

Industry type

1	Chemical
2	Food
3	Beverages
4	Livestock
5	Vehicle service
6	Textile & leather
7	Mineral
8	Waste recycling
9	Industrial park 1
10	Industrial park 2

Pollution category

1	High
2	Medium

44	7	1	1	1	0.001
45	5	3	1	1.7	0.001
46	5	1	1	11	0.06
47	8	2	1	30	20
48	6	3	1	30	0.58
49	5	3	1	43	0.07
50	5	3	2	117	0.11
51	6	2	1	400	3.81
52	6	2	1	2400	4.48
53	6	1	1	500	8
54	2	2	1	303	2.83
55	2	2	1	14	0.13
56	4	2	1	579	0.31
57	1	2	1	30	9.6
58	5	4	1	10	0.02
59	6	1	1	31	6.14
60	4	3	1	303	0.87
61	5	2	1	9	0.05
62	3	4	1	5	48
63	7	2	1	2	2.13
64	7	3	1	22	0.02
65	7	3	2	64	0.2
66	4	4	2	4500	0.4
67	4	3	2	4210	6.06
68	7	4	1	17	0.13
69	2	3	2	326	0.47
70	2	3	2	675	0.99
71	5	1	2	117	2.18
72	5	1	1	26	0.11
73	7	3	1	1	0.001
74	1	1	1	22	0.01
75	7	3	2	1	0.001
76	6	1	1	200	0.001
77	6	5	1	200	0.03
78	2	4	2	326	0.001
79	2	5	2	171	0.36
80	2	6	2	326	0.17
81	2	4	2	134	2.26
82	4	5	2	4210	0.27
83	4	5	2	733	0.29
84	7	4	2	12	0.001
85	1	4	1	12	0.05
86	1	5	1	173	2.53
87	7	5	1	10	3.02
88	8	5	1	20000	1.07
89	4	5	2	1687	0.69
90	2	2	1	87.71	0.97
91	2	5	1	136.2	1.51
92	8	2	1	972.66	1.55
93	2	2	2	623.37	0.59

94	6	2	1	169.67	0.17
95	5	2	1	49.96	0.14
96	4	4	1	412.29	26.8
97	1	3	1	73.67	0.69
98	2	2	2	623.37	0.59
99	6	4	1	109.23	2.28
100	5	4	1	49.95	0.14
101	6	3	2	776.32	2.44
102	5	5	1	49.95	0.14
103	4	4	2	1687	0.69
104	1	2	1	42.42	0.001
105	2	4	2	358.9	0.34
106	1	2	1	42.42	0.4
107	7	4	2	38.69	0.21
108	7	4	2	22.28	0.12
109	5	5	1	49.95	0.14
110	5	2	1	32.16	0.09
111	8	4	1	360.52	0.58
112	7	4	1	9.46	1.76
113	4	5	2	1687	0.69
114	1	1	1	27.3	0.26
115	5	4	1	28.76	0.08
116	5	2	1	28.76	0.08
117	2	2	1	152.35	1.69
118	7	3	2	22.28	0.12
119	2	2	1	236.64	2.62
120	5	2	1	28.76	0.08
121	7	3	1	9.45	1.76
122	5	2	2	131.6	0.56
123	7	3	2	38.7	0.21
124	2	5	2	623	0.59
125	5	2	1	32.16	0.09
126	2	4	2	174	2.94
127	1	1	1	27	0.25
128	1	2	1	73.67	0.69
129	4	4	2	1687	0.69
130	7	4	2	38.69	0.21
131	2	4	2	623.4	0.59
132	2	2	2	302.24	5.11
133	5	1	2	131.6	0.56
134	1	2	1	42.41	0.4
135	5	4	2	75.76	0.32
136	7	4	2	22.27	0.12
137	7	4	2	14.35	0.08
138	5	4	1	32.16	0.09
139	1	2	1	27.31	0.26
140	4	5	1	368.71	23.97
141	6	5	1	109.23	3.5
142	2	2	2	623.37	0.59
143	7	3	1	14.68	2.73

144	7	3	1	9.45	1.76
145	5	2	1	49.95	0.14
146	4	4	2	1687	0.69
147	2	4	1	640.41	41.63
148	1	2	1	73.67	0.69
149	8	2	2	1178.61	2.14
150	7	2	1	5.44	0.02
151	8	2	1	972.66	3.06
152	6	4	1	109.23	0.04
153	6	4	1	109.23	0.6
154	1	2	1	42.41	0.88
155	5	4	2	131.6	0.73
156	7	3	2	14.34	36.18
157	8	4	1	320	19.27
158	5	2	2	131.6	0.56
159	6	2	2	776.32	2.44
160	4	4	2	971.27	0.4
161	7	4	2	14.34	0.08
162	6	2	1	189.73	3.95
163	7	4	2	14.34	0.08
164	3	3	1	10.37	26.17
165	5	2	2	84.72	0.36
166	7	3	1	14.66	2.73
167	6	5	1	109.23	0.26
168	8	2	1	360.52	0.58
169	4	4	2	1687	0.69
170	6	3	2	776.328	2.44
171	5	4	1	49.95	0.14
172	1	2	1	42.42	0.4
173	2	5	1	236.64	2.62
174	4	3	2	1687	0.69
175	5	3	2	84.72	0.36
176	7	3	1	14.68	2.73
177	1	2	1	42.41	0.4
178	2	1	1	237.37	15.43
179	7	2	2	38.69	0.21
180	7	4	2	22.28	0.12
181	1	4	2	194	1.81
182	7	3	2	22.27	0.12
183	7	3	2	38.69	0.21
184	7	4	2	22.28	0.12
185	2	3	2	623.37	0.59
186	7	4	2	14.34	0.08
187	3	4	1	6.67	0.06
188	5	4	1	28.76	0.08
189	7	2	1	5.44	1.01
190	7	4	1	49.95	0.14
191	8	2	1	694.97	231.66
192	5	1	2	131.6	0.56
193	6	2	2	446.96	1.41

194	7	4	2	22.27	0.12
195	5	5	2	48.77	0.21
196	2	2	1	18.01	45.45
197	5	1	2	131.6	1.46
198	2	2	1	87.71	0.82
199	1	4	1	42.42	0.23
200	7	4	2	38.69	97.63
201	3	6	1	10.37	0.67
202	4	2	1	640.41	5.99
203	1	1	1	640.41	119.12
204	7	2	1	5.44	0.02
205	5	2	1	49.95	1.04
206	6	5	1	294.7	0.12
207	4	3	2	1687	9.34
208	7	4	2	1687	15.77
209	1	4	1	27.3	1.77
210	4	2	1	412.3	3.85
211	8	2	1	257.59	85.86
212	5	2	1	49.95	0.14
213	5	1	1	18.52	0.05
214	5	4	2	131.6	0.56
215	6	2	1	189.73	3.95
216	5	1	1	18.15	0.05
217	2	2	2	623.37	0.59
218	2	3	1	42.53	1.74
219	7	2	2	14.34	0.08
220	1	2	1	73.673	0.01
221	8	2	1	257.6	85.87
222	7	4	2	14.34	0.08
223	2	4	2	1687	0.69
224	8	3	1	320	11.91
225	5	2	1	49.95	0.14
226	6	2	1	109.23	0.02
227	7	3	2	38.69	0.21
228	5	1	2	131.6	0.56
229	6	1	1	294.7	6.14
230	5	4	2	131.6	0.56
231	6	1	1	169.67	3.54
232	8	2	2	1316	5.57
233	1	2	1	27.3	0.26
234	1	4	1	42.41	0.4
235	7	3	1	14.68	2.73
236	2	4	2	623.37	0.59
237	7	3	1	22.27	4.14
238	1	3	1	73.67	0.69
239	6	2	2	776.33	2.44
240	1	1	1	42.41	0.4
241	4	5	2	1687	0.69
242	1	4	1	42.42	0.4
243	1	5	1	73.67	0.69

244	4	5	2	1687	0.69
245	2	5	2	623.37	0.59
246	5	4	1	49.95	0.14
247	2	2	1	10.37	0.13
248	2	2	1	18.01	45.45
249	4	4	2	1687	0.69
250	5	1	1	28.76	0.08
251	4	2	1	640.41	41.63
252	1	2	1	73.67	0.69
253	1	2	1	27.3	0.26
254	2	4	2	623.37	0.59
255	1	2	1	73.67	0.69
256	1	2	1	73.67	0.69
257	4	5	1	412.29	26.8
258	5	2	2	131.6	0.56
259	7	3	1	9.45	1.76
260	5	2	1	49.95	0.14
261	7	3	1	9.45	1.76
262	5	2	1	18.52	0.001
263	6	2	1	109.23	2.28
264	7	4	1	5.45	1.01
265	6	5	2	776.32	2.44
266	7	2	1	9.45	1.76
267	1	2	1	42.41	0.4
268	5	2	1	28.76	0.08
269	2	4	1	114.74	1.94
270	4	6	1	640.41	41.63
271	6	2	1	446.96	9.31
272	5	3	1	18.52	0.05
273	4	4	2	1687	0.69
274	1	2	1	42.42	0.4
275	2	2	1	152.35	1.69
276	7	3	1	8.45	0.001
277	1	2	1	27.3	0.26
278	1	3	1	42.41	0.001
279	6	2	2	776.33	2.44
280	7	3	2	22.27	0.12
281	4	2	1	368.71	23.97
282	1	2	1	42.41	0.4
283	2	2	2	623.37	0.59
284	4	4	1	623.37	40.52
285	4	2	1	18.01	45.45
286	5	3	1	32.16	0.09
287	5	2	2	131.6	0.56
288	6	2	2	446.96	1.41
289	4	4	2	1086	0.45
290	1	2	1	42.42	0.4
291	2	2	1	87.71	0.97
292	6	2	2	446.96	1.41
293	2	5	1	368.71	23.97

294	1	2	1	27.31	0.26
295	5	5	2	131.6	0.56
296	5	1	2	131.6	0.56
297	5	2	1	28.78	0.08
298	3	4	1	10.37	26.17
299	1	2	1	42.42	0.4
300	1	4	1	27.31	0.26
301	1	2	1	73.67	0.69
302	6	2	2	776.33	2.44
303	5	2	2	131.6	0.56
304	4	4	1	640.41	41.63
305	4	6	2	1086.08	0.45
306	1	2	1	42.42	0.4
307	7	4	1	14.68	2.73
308	6	2	2	776.33	2.44
309	1	2	1	27.31	0.26
310	7	3	2	22.27	0.12
311	6	2	1	169.67	0.62
312	4	6	2	1687	0.69
313	1	2	1	42.42	0.4
314	8	1	2	1000	0.96
315	5	1	2	117	0.18
316	7	2	2	20.78	0.01
317	7	2	1	7	0.02
318	5	5	2	345	0.46
319	6	2	2	102	0.03
320	5	2	1	60	0.03
321	2	3	2	326	0.63
322	5	2	2	14	0.02
323	7	4	2	12	0.001
324	3	3	1	250	2000
325	9	6	1	30	450
326	10	3	1	30	300