Title
Essays on Resource Allocation and Management, Price Volatility and Applied Nonparametrics

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Publication Date
2012

Peer reviewed|Thesis/dissertation

UNIVERSITY OF CALIFORNIA
RIVERSIDE

Essays on Resource Allocation and Management, Price Volatility and Applied Nonparametrics

A Dissertation submitted in partial satisfaction
of the requirements for the degree of

Doctor of Philosophy

in

Economics

by

Getachew Sisay Nigatu

March 2012

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Acknowledgments

First of all, I thank the almighty God for blessing me and my family with wisdom and grace.

I am indebted to my advisors and teachers for their unwavering instruction and support both during course work and throughout my doctoral research. Most especially, I would like to thank Prof. Ariel Dinar, a co-chair and an advisor for this dissertation. I was fortunate to work with him, and without him, the Nile River study would have been impossible to complete. He was kind enough to offer me the kind of supports I enriched throughout the research process. I spent a great deal of time with him, sometimes during the weekend or during holiday breaks. I have learned invaluable scholar, social and personal lessons. He was supportive in all regards, including offering a research assistantship for over two years through Water Science and Policy Center.

I would also like to thank Prof. Aman Ullah, a co-chair and an advisor for this dissertation. He was instrumental for structuring and providing an insight for price volatility and nonparametric analysis studies. I am also thankful to my advisor, Prof. Linda Fernandez, for providing the necessary support. Moreover, Prof. Richard Arnott, member of Ph.D. candidacy committee, was gracious for providing support and comment in shaping this dissertation. I would like to extend my gratitude to Prof. Jirka Šimunek for serving as committee member.

My scholar and academic success is not only the result of my school performance, but vital supports from my family and friends. I am equally indebted to my wife, Meseret Hailegiorigis, for providing love, moral support and encouragement from just right at the start of this long journey to this end. She scarifies to this success, and I have learned a lot from her strength and patience.

My families in Ethiopia also deserve a special credit for all their supports. Especially, my mother, Yeshi Mengistu, and my father, Sisay Nigatu, who are illiterates, but they sent me and my siblings to school, when schooling was not an optimal choice for them. I thank my brothers: Mekonen, Agenghu, Wondemu, Habitamu, Mengistu, Teshale and Yohannes, for their supports and for taking care of my parents while I am away from home.

I would also like to thank Ms. Eta Takele, Director, UC Cooperative Extension Riverside County. She believed in my performance, and supported my first year study. I extend my appreciation to my friends, including Dr. Abay Taddesse, Mr. Degemu Andeta, Mr. Eshetu Homa, Dr. Mesifine Adame, Mr. Getu Hunde, Dr. Getu Haile-Michael, and Mr. Kassahun Bahiru. Finally, I do appreciate those friends in Riverside, Moreno Valley, Pasadena, Los Angeles, Las Vegas, Washington DC and those in Ethiopia.

To my parents, my wife, my baby girl - Bethel Getachew, ...

ABSTRACT OF THE DISSERTATION

Essays on Resource Allocation and Management, Price Volatility and Applied Nonparametrics

by

Getachew Sisay Nigatu

Doctor of Philosophy, Graduate Program in Economics
University of California, Riverside, March 2012
Dr. Ariel Dinar, Co-Chairperson
Dr. Aman Ullah, Co-Chairperson

This dissertation is composed of three research topics. The first topic proposes an intrabasin allocate-and-trade, institution, to manage the eastern Nile River basin with the objective of increasing the overall basin's welfare through improving efficiency, equity and sustainability. By developing the Nile Environmental and Economic Optimization Model (NEEOM), we estimate the current, planned and improved welfare value. We find that a water trade institution can achieve nearly 100% of the welfare created by economically efficient allocation, and secure equivalent volumes of water compared with the status quo scheme. We estimate that riparian countries could raise about $660 million per annum for protecting and conserving the natural resources of the basin. Finally, using Global Circulation Models, we find that the institution will recover nearly all of the efficient outcomes.

The second topic is designed to study the behavior of carbon price volatility before, within and after the 2008/09 global recession using Markov Regime

Switching model. The results show that an unregulated voluntary carbon market was in high-volatile regime within, and two years before, the recession. A regulated compliance carbon market was relatively in stable and low-volatile regime for these periods, except at the end of the recession. It can be inferred that high-volatile regimes were, however, not caused by the recession *per se*. The Wald tests show that there were distinct low-and high-volatile regimes during the recession period, indicating that the recession aggravated the volatility of both voluntary and compliance markets.

The third topic is designed to study the relationship between economic growth and pollution using nonparametric econometric technique. The results indicate a partial relationship between GDP per capita and the level of PM10 pollution for low- and high-income countries. Hence, environmental policies for reducing the level of PM10 pollution have to emphasize middle-income and oil-producing high-income countries that show unprecedented increase in the level of PM10 pollution. Further, the Li and Wang test indicates that nonparametric analysis turns out to produce better results than quadratic and cubic specifications. Semiparametric models show decreasing pollution level as income rises and improve the smoothness of the relationship.

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Chapter 1

Introduction

Three research topics are covered in this dissertation. Broadly, they can be categorized as resource allocation and management; carbon price volatility with respect to the 2008/09 global recession; and application of nonparametric econometrics in environmental and resource economics research. These topics are designed to cover my major field of study, environmental and resource economics, and minor fields econometrics and development economics. Using the three topics, I try to address some challenges in environmental and resource economics, such as water resource allocation and management, carbon price, and pollution and economic development, using applied econometrics techniques.

The first topic is intended to formulate water allocation and management using economic models for the eastern Nile River Basin countries consisting of Ethiopia, Sudan and Egypt. Along with the basin-wide agreement, an intrabasin water trade based on the principle of "allocate-and-trade," is proposed for the first time to study the eastern Nile River water allocation and management. The principle of “allocate-and-trade” is tested on the grounds of basin-wide efficiency, equity and sustainability. The basic notion of “allocate-and-trade” is that, first, a basin institution, such as the Nile Basin Initiative, will assign water rights to the riparian countries, monitor and evaluate the performance of each riparian country and, then, facilitate an intrabasin water trade. By developing the Nile Environmental and Economic Optimization Model (NEEOM), the current, planned and improved welfare values from uses of the Nile River are estimated for the basin. The performance of various water rights arrangements, with and without water trade, is evaluated using the optimal allocation. The model also integrates the cost of resource degradation, and the economic impacts of climate change scenarios, that are evaluated using Global Circulation Models (GCM), with and without water trade.

The results indicate that the social planner could generate the most efficient outcome for the basin. Compared to the current economic benefit for the eastern Nile River Basin countries, $8.62 billion (in 2010 value), the social planner could generate almost 13% more benefits. If countries use the Nile River water unilaterally, the economic benefits could fall by 15% compared to the social planner’s outcome. When we introduce the institution of “allocate and trade,” the basin could achieve almost 100% of the social planner’s outcome, depending on the water rights arrangements. In addition, it is found that the new institution provides cost-effective approach for dealing with externality - resource degradation in this research. The result shows that countries could rise about $660 million to protect the resource base of the basin. Depending on the different GCM scenarios and water rights arrangements, water trade will also recover nearly all of the efficient outcomes while without trade could only recover about 64% - 99% of the efficient outcomes.

The second topic is designed to study the behavior of carbon price volatility using Markov Regime Switching (MRS) model along with Generalized Autoregressive Conditional Heteroskedasticity (GARCH) family models. The working hypothesis is to check whether there is a shift in both trend and volatility of carbon price before (pre) and within and after (post) the recent global recession. The main focus of the analysis is to compare the volatility within the 2008/09 global recession and in other periods. To understand the effect of regulation on volatility, two markets are selected: an unregulated voluntary carbon market at the Chicago Climate Exchange (CCX) and a compliance carbon market at the European Climate Exchange (ECX). Volatility is estimated for in-sample and forecasted for out-of-sample data. The probability of being at a high- or low-volatile regime is identified for the two markets. In addition, the cointegration of these carbon markets and the respective financial markets in the US and Europe are analyzed for studying the link among these markets.

The Wald Test determines that there are distinctive volatility regimes, and this further supports applying MRS models for identifying these regimes. One of the main results of this research is that the unregulated carbon market at CCX was in a high-volatile state for two years before and within the recession periods, while, except for the brief period at the end of the recession, the compliance carbon market at ECX was in a low-volatile state during the recession period. The level of volatility estimated using MRS model is lower but more stable than that of GARCH model for both markets. The parameters of cointegration indicate that the level integration among the financial and carbon markets is highly significant and strong.

The final topic focuses on the application of nonparametric econometric techniques in the area of environment and development economics. The main purpose of this paper is to examine whether or not there is a systematic relationship between environmental pollution and economic development using environmental Kuznets curve (EKC) hypothesis. The data used in the analysis includes average level of Particulate Matter (PM10) pollution, GDP per capita, coal consumption per capita, trade openness and urban population for 160 countries for the period 1991-2005. In addition, parametric and semiparametric specifications are estimated and the performance of these specifications is tested against the nonparametric model.

The nonparametric regression result partially supports the EKC hypothesis for low- and high-income countries. For low-income countries, the level of pollution initially surges but after reaching a certain threshold income level, around $500 GDP per capita, the level of pollution falls. For high income countries, the level of pollution demises as the level of income rises. For the middle income countries, a decrease in the level of pollution for lower-middle income countries is followed by unprecedented increase in the level of pollution for higher-middle income countries that produce petroleum products. In addition, a significance test indicates the superiority of the nonparametric regression over the parametric and semiparametric specifications.

Chapter 2

The Welfare Value of Allocate-and-Trade: Addressing Efficiency, Equity and Externality in the Eastern Nile River Basin

2.1 Introduction

The process of allocating water from international water-bodies (such as rivers, lakes and aquifers) that are shared by two or more riparian countries usually focuses on reaching a basin-wide agreement (treaty) (Dinar and Wolf, 1994). The allocation could also be the result of factors such as colonial and Cold War legacies, property rights issues, national interests, prior uses and political and diplomatic influences (Elhance, 1999). In addition, managing an international water body that does not have a basin-wide agreement is a difficult task (Dinar, 2004). In the meantime, international water law is particularly vague and narrow in mediating water conflicts (Kilgour and Dinar, 1995; United Nations, 1997).[1]

A typical river basin that does not have basin-wide agreements on water allocation and basin management is the Nile River (Allan, 2009). Accordingly, Nile River water allocations are based on political dominance, military strength and financial superiority, with little or no regard for efficient allocation of the resource (Elhance, 1999; Waterbury, 2002; Allan, 2009). These factors lead to unsustainable outcomes in an era of rapid population growth, apparent climate change, massive soil erosion, extensive agricultural practices and increasing energy demand (Martens, 2011; Allan, 1994; Arsano and Tamrat, 2005). The current state of water allocation is predominately governed by the 1959 bilateral agreement between two of the upstream countries out of eleven riparian countries (Waterbury, 2002), as shown in Figure 2.1.

The main argument of the paper is that a mere basin-wide agreement is not a viable strategy for Nile River water allocation. This is because riparian countries differ in economic strength, political power and hydrologic and climatic position (Just and Netanyahu, 1998; Martens, 2011). In addition, some characteristics such as high rainfall variability over time and across subregions, low and negative

[1]I would to thank Prof. Ariel Dinar for his extensive and constructive comments. This paper benefited from feedback and comments by Franklin Fisher, Paul Block, Mac Kirby, Richard Arnott, Linda Fernandez, John Joyce, Daene McKinney, John Waterberry, and Frank Ward. I am grateful for the help provided by these individuals. The feedback from the participants of UCOWAR 2011 in Boulder, CO, is also appreciated. This research is supported by the *Water Science and Policy Center (WSPC)* at UCR, and this paper is reproduced as WSPC working paper (Nigatu and Dinar, 2011).

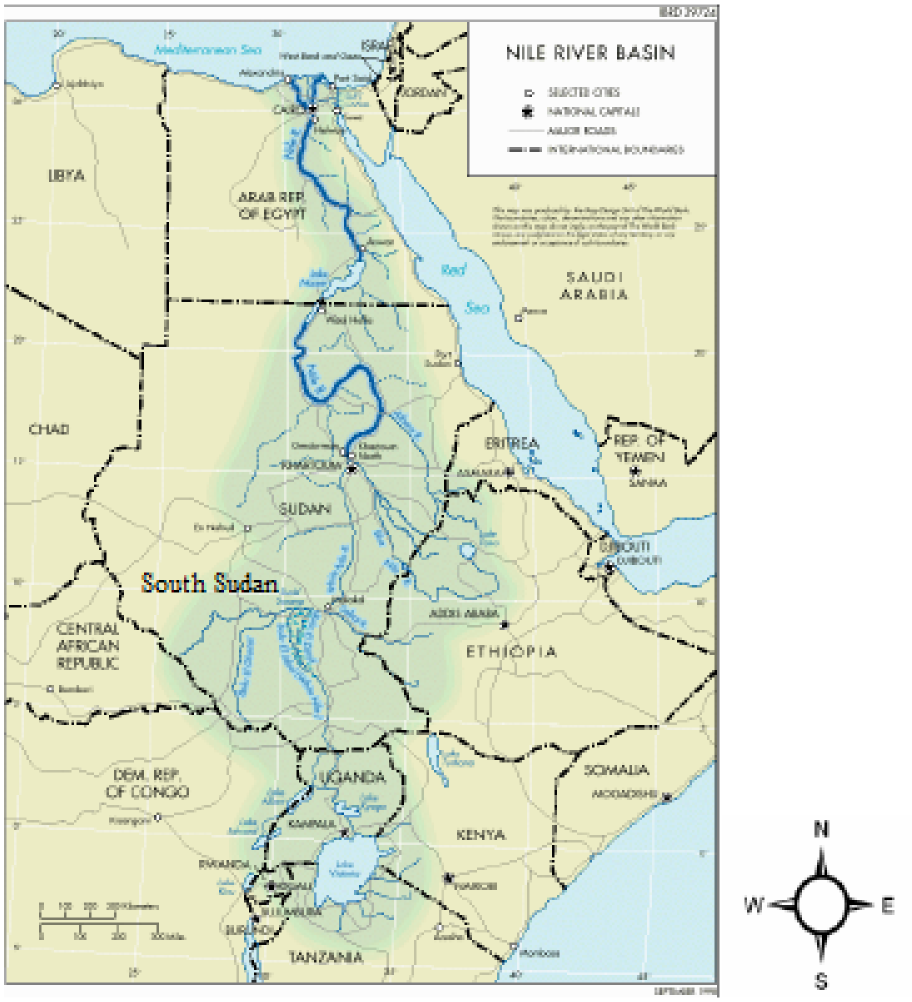

Figure 2.1: The Nile River Basin

economic growth in some riparian countries, and the desirability of short-term actions over long-term water-related needs, make basin-wide agreement on Nile River water allocation and management a difficult task (Waterbury, 2002; Dinar, 2004).

Along with the basin-wide agreement, an intrabasin water trade based on the principle of "allocate-and-trade," is proposed for the first time to study the Nile River allocation for eastern Nile Basin riparian countries consisting of Ethiopia, Sudan and Egypt, shown in Figure 2.1. The principle of "allocate-and-trade" will be tested on the grounds of basin-wide efficiency, equity and environmental sustainability that can be enacted with agreement at the country level. The basic notion of "allocate-and-trade" is that, first, a basin or a regional institution will assign water rights to the riparian countries, monitor and evaluate the performance of each riparian country and, then, facilitate an intrabasin water trade.[2] We design the intended water trade in an analogy to the emission (carbon) market in which a similar shift in the area of water, where the principles are essentially the same, is long overdue (Olmstead and Stavins, 2008).

Like for any other economic good, water trade has the potential of allocating water to areas where it produces the highest economic return (Saliba and Bush, 1987). Market-related policy instruments, if well designed and implemented, encourage economic agents to undertake conservation and protection efforts and accommodate changing patterns in society's demand (Easter et al., 1998). Studies show that the problem of burgeoning water scarcity and deteriorating water quality could be solved if water is properly treated as an economic good (Sunding, 2000). In a regional setting, water markets are also used to promote economic development and political stability (Whittington et al., 1995), increase income

[2]A possible basin-wide institution could be the Nile Basin Initiative (NBI) that is already in place and leads various development programs on the Nile basin. According to the mission statement stated on its website, NBI is "an inter-governmental organization dedicated to equitable and sustainable management and development of the shared water resources of the Nile Basin (NBI, 2012)." It runs by a secretariat, which is assigned each year from the member state. The entire Nile Basin River System consists of eleven countries: Ethiopia, Sudan, Egypt, South Sudan, Kenya, Eritrea, Uganda, Tanzania, Burundi, Rwanda, and Democratic Republic of Congo, as shown in Figure 2.1. This research is based on the 2010 data, so Sudan in the research represents both the South Sudan (the new country) and Sudan (North).

and crop yield (Meinzen-Dick, 1998) and improve income distribution (Saliba and Bush, 1987).

In practice, formal and informal water markets exist in Australia, Chile, India, Mexico, Pakistan, Spain and the United States (Easter et al., 1998). Analytically, water markets are designed to address a wide variety of economic and ecological issues (Dinar and Wolf, 1994; Becker, 1996; Aytemiz, 2001; Bhaduri and Barbier, 2008). For the Nile River in particular, the potential benefits of establishing regional water markets have been considered for a long time (The Economist, 1992; Wu, 2000). Whittington et al. (1995) underscored that trading water rights would be the single most notable innovation that could be introduced in a new agreement on Nile water. In addition, Abate (1994) suggested the higher economic value of trading water among the eastern and northern regions of the Nile. Introducing a water market and evaluating its welfare value are, however, relatively new approaches in the Nile River basin.

The existing literature advocating for water trade in an international basin context has focused mainly on physical feasibility (Matete and Hassan, 2005). In addition, environmental externalities and climate change have been given less emphasis (Easter et al., 1998). The threat of climate change, for instance, requires the development of water institutions and policies that are sufficiently flexible, adaptive, and robust (Adler, 2008). This is because climate change could result in unprecedented environmental challenges, such as altering mean annual river flow by up to 70% in some rivers (Kilgour and Dinar, 1995). For the Nile River in Ethiopia which contributes about 85% of the basin's water, climate change is characterized by low adaptability and decreased runoff (Dinar and Wolf, 1994; FAO, 1997). Moreover, the resource degradation (soil erosion), which originates in the upstream country, Ethiopia, could affect all riparian countries through siltation of reservoirs, clogging the irrigation canals and reducing agricultural productivity (Longin et al., 2005; Arsano and Tamrat, 2005).

The main research question is whether or not Pareto improvements can be achieved through designing new allocation mechanisms. Is it possible to establish a water market, along with basin-wide agreement, that is efficient in allocating the resource among riparian countries? How can countries sharing the river distribute costs to conserve the resource base and prepare for climate change? Finally, how can a regional institution be designed to help attain these objectives?

The remainder of the paper is developed as follows. The following section discusses the Theoretical Framework and verifies related propositions. Section 3 presents the proposed empirical model. The Data and Parameter section provides the source of data and information and review of the main parameters. The research findings are discussed in the Results and Discussion section. Finally, a Conclusion summarizes the main results of the paper and identifies directions for future research.

2.2 Theoretical Framework

The theoretical analysis starts with specifying the social planner's problem of allocating a scarce resource among the riparian countries who share it.[3] Then, it introduces the proposed "allocate-and-trade" and a mechanism to deal with externality problems.

2.2.1 Properties of the Social Planner Allocation

From its theoretical formulation, the social planner's problem helps identify the characteristics of the social welfare function and welfare allocation. This is because every Pareto-efficient allocation is a social welfare optimum when the allocation is formulated, based on social welfare weights (Mas-Colell et al., 1995). The shadow values from efficient allocation can be used to assign these weights that can assist in identifying river water sharing schemes among riparian countries and evaluating the performance of the baseline allocation scheme. Based on the above premises, proposition 1 can be conceptualized as

Proposition 1. *The social planner will assign social welfare weights for riparian countries based on their efficiency, which are different from the weights in the baseline (status quo) allocation. As a result, the social welfare function that attaches these social welfare weights produces higher basin welfare than those in the baseline allocation scheme.*

[3]In this research a social planner could be a basin or a regional Nile organization, such as NBI, that is given a mandate to optimally allocate the Nile River water for riparian countries that could generate higher marginal benefit for each additional resource. In this case, the basin's overall benefit is the main objective, and assigning water rights arrangement is not the ultimate goal of the social planner.

Let represent the social welfare function using $W(u_1(.), ..., u_n(.)) = \sum_i \pi_i u_i(D_i)$, where $i = 1, ..., n$ is a riparian country; D_i is water demand; and π_i is a social welfare weight (where $\sum_i \pi_i = 1$ and $\pi_i \geq 0$). Again, let assume that the social planner is only constrained by the available resource, S_i, from k tributaries such that $\sum_k S_{ik} = S_i$.

If the social welfare function has desirable characteristics, such as being concave, continuous and monotonic, then there are some choices of weights, π_i^*, that maximize the social welfare and provide efficient resource allocation, D_i^*, (Varian, 1992). To identify the social welfare weights, the maximization problem, Z, can be formulated as

$$Max\ Z_{(D_i)} = \sum_i \pi_i u_i(D_i) + [\sum_i \mu_i(S_i - D_i)], \tag{2.1}$$

where μ_i is multiplier for the resource constraint.

Using the assumptions that guarantee an interior solution, $D_i^* > 0$, the first-order condition with respect to allocation, D_i, becomes

$$\pi_i u_i'(D_i^*) = \mu_i, \text{for all } i. \tag{2.2}$$

We adapt the implication from the First Fundamental Theorem of Welfare Economics that every competitive equilibrium allocation can attain efficiency in the social planner's problem. The relevant results of a competitive equilibrium are its allocation, D_i^*, and a positive price, P, that clears the competitive market.

The competitive equilibrium can be written as

$$Max\ Z_{(D_i)} = \sum_i u_i(D_i) + [\sum_i \lambda_i P(S_i - D_i)]. \tag{2.3}$$

The first-order condition for the competitive equilibrium with respect to allocation, D_i, can be identified as

$$u_i'(D_i^*) = P\lambda_i, \text{for all } i, \tag{2.4}$$

where λ_i is shadow value of the resource.

After rearranging Eq. (2.2) and Eq. (2.4), the social welfare weight can be assigned for each riparian country using $\pi_i^* = 1/\lambda_i$, provided that the multiplier for the resource constraint, μ_i, must be equal to the competitive price, P (Varian, 1992). This weight provides the "first-best" water allocation scheme among riparian countries. If the social planner assigns higher social weight to a riparian country, then the country generates higher economic benefit. Therefore, the social planner's allocation, D_i^*, provides the highest welfare value for the basin. In this particular case, however, the benefit comes at the expense of lower marginal social welfare due to an inverse relationship between social weight and shadow value.

Moreover, since $\lambda_i > 0$, every riparian country has its own stake in the social welfare, and the stake may vary among riparian countries, depending on their efficiency, which can arise from economies of scale. Overall, this allocation would lead to the participation of all riparian countries in using the resource. Thus, the outcome of the social planner is different from the baseline allocation in that it promotes basin-wide participation. □

2.2.2 Allocate-and-Trade

The efficiency of introducing "allocate-and-trade" can be evaluated with the help of the social planner's welfare outcome. The next proposition helps identifying the level of efficiency after the concept is introduced in the analysis.

Proposition 2. *A basin-wide "allocate-and-trade" can help recover a more significant portion of the social planner's efficiency than without trade, provided that water rights arrangements are specified a priori. This is also true in dealing with externalities in which "allocate-and-trade" provides the necessary incentive to reduce (eliminate) the impact of externalities.*

The starting point for this analysis is the social welfare function used in the social planner's problem, Eq (2.1). The principle of "allocate-and-trade" can be integrated with the objective function through the concept of excess demand, ED_i: the difference between total demand, D_i, and initial water rights, $\bar{W}^i$.[4]

With the introduction of a price that clears excess demand, P^{ED}, and average unit cost of resource degradation, c_i, the maximization problem becomes

[4]When countries plan to use the resource, they incur costs, such as construction costs. These costs are similar for all countries that face international trade. These costs may not affect the basic analysis of identifying optimality or evaluating the intrabasin water trade.

$$Max\ Z_{(D_i)} = \sum_i [\pi_i u_i(D_i) - c_i D_i] + \sum_i P^{ED}(ED_i) + [\sum_i \mu_i (S_i - D_i)]. \quad (2.5)$$

Substituting $\sum_i (ED_i) = \sum_i (D_i - \bar{W}^i)$ in Eq. (2.5) and deriving and rearranging the first-order condition with respect to allocation, D_i, yields

$$\pi_i u_i'(D_i^*) + P^{ED} = \mu_i + c_i. \quad (2.6)$$

For "allocate-but-no-trade" case (without-trade case), excess demand is not considered a limiting factor in the maximization problem as shown below

$$Max\ Z_{(D_i)} = \sum_i [\pi_i u_i(D_i) - c_i D_i] + [\sum_i \mu_i (\bar{W}^i - D_i)]. \quad (2.7)$$

Deriving and rearranging the first-order condition with respect to allocation, D_i, becomes

$$\pi_i u_i'(D_i^{**}) = \mu_i + c_i. \quad (2.8)$$

The marginal value of water in the case of "allocate-and-trade" [LHS of Eq. (2.6)] is higher than without trade [LHS of Eq. (2.8)], provided that both cases face the same shadow value, $\mu_i + c_i$. Since the volume of water available in the basin and the resource degradation associated with the available water remains the same in both with- and without-trade cases, the basin faces the same shadow value in both cases. The shadow value can be identified through adding scarcity value, μ_i, and externality cost, c_i, as displayed using P^* in Figure 2.2.

The social welfare is measured by the economic surplus, or the area under the marginal benefits curve. The social welfare from trade, represented by area AP^*B, is larger than without trade, area aP^*b. In other words, trade can create an incentive among riparian countries to use resources for economic activity as it produces more basin welfare. An important feature of this analysis is that the gap between with- and without-trade welfare gain for each additional volume of water decreases as water becomes abundant.

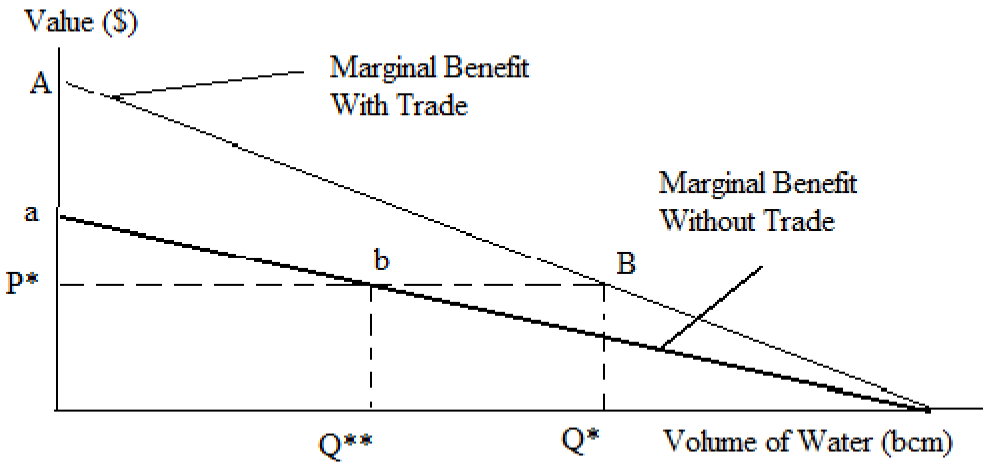

Figure 2.2: The Welfare Value of the Basin With- and Without-Trade Cases

The value of excess demand is non-positive, $\sum_i P^{ED}(ED_i) \leq \ 0$: zero in most cases, but near zero in some cases (Varian, 1992). Therefore, the welfare value from trade is exactly equal to the value of the social planner's welfare in most cases in which the value of excess demand exactly equals zero. In some exceptional cases, when the value of excess demand is less than zero, the welfare value from trade is less than the social planner's outcome, but higher than the case of without trade.

Therefore, trade can help recover all or nearly all of the social planner's welfare, as implied in proposition 2.

The cost of resource degradation is equated with the monetary value that riparian countries allocate to protect the resource base (abatement). Therefore, the level of abatement depends on the amount of resource used by riparian countries and represented by $c_i D_i^*$, where $D_i^* = \{Q^*\ ,\ Q^{**}\}$. As shown in Figure 2.2, more resource can be allocated through trade, Q^*, than without trade, Q^{**}. This implies that trade results in more abatement since $c_i Q^* > c_i Q^{**}$. □

2.2.3 Externality within the Social Planner's Problem

In the above case, the average unit cost of externality, c_i, is exogenously determined by calculating the economic loss caused by resource degradation. In the next proposition, a theoretical foundation that helps to endogenously determine the externality cost is presented.

Proposition 3. *The externality cost can be endogenously determined by including the externality-generating activity within the social welfare function. In this case, the geographic position of the externality-generating activity affects the welfare of the riparian countries to different extents.*

Two separate analytical formulations are presented to conceptualize unidirectional and multi-directional externality.[5]

[5] In this paper, the resource degradation (soil erosion) which originates in Ethiopia could affect all riparian countries through siltation behind the dams, clogging the irrigation canals and reducing agricultural productivity (Longin et al., 2005).

2.2.3.1 Unidirectional Externality: externality that affects only one riparian country

Assume that there is one upstream, (henceforth "US"), and one downstream, (henceforth "DS"), riparian country in the basin. The externality-generating activity, e, originates from the upstream riparian country, and it could affect only the downstream riparian country. Welfare is represented by using $u^i(D_i, e^i)$, for $i = \{US,\ DS\}$, with $e^{US} = 0$ and $e^{DS} = e$. Moreover, the abatement and damage cost associated with the externality are specified using $A(e)$ and $M(e)$, respectively. The upstream riparian country maximizes $u^{US}(D_{US}) - A(e)$, whereas the downstream riparian country maximizes $u^{DS}(D_{DS}, e) - M(e)$. If there is no basin-wide agreement between the two riparian countries, the competitive equilibrium abatement cost, $A(e)$, for the upstream riparian country is at the point where the marginal abatement cost is zero, $A^{'}(e) = 0$, or at point $e^{'}$, as shown in Figure 2.3. The downstream riparian country maximizes the net welfare by accounting for the damage cost at the point where $(u^{DS})' = M'(e)$. Then, the marginal benefit of controlling damage must equal the marginal damage cost.

The Pareto-efficient externality level can be identified by maximizing the social welfare function formulated as

$$Max\ Z_{(e)} = \ [u^{US}(D_{US}) + u^{DS}(D_{DS}, e) - A(e) - M(e)]. \qquad (2.9)$$

Using the assumptions that guarantee an interior solution, $e^* > 0$, and deriving and rearranging the first-order condition with respect to the externality-generating activity, e, the social efficient level would be attained when

$$\underbrace{(u^{DS})^{'}(e^*)\ - A^{'}(e^*)}_{Net\ Marginal\ Benefit(MB)} \quad = \quad \underbrace{M^{'}(e^*).}_{Marginal\ Damage\ Cost(MC)} \tag{2.10}$$

The social efficient level of externality is determined by taking account of the upstream riparian country's impact on the downstream riparian country, as identified in Eq. (2.10). The social efficiency requires that the basin's net marginal benefit equals the downstream riparian country's marginal damage cost, as represented at point e^* in Figure 2.3. As Mas-Colell et al. (1995) pointed out, for non-zero abatement cost, optimality does not require a complete elimination of (negative) externality; there is always a certain level of externality in socially efficient allocation schemes. As long as the externality does not affect the upstream riparian country, it may not have an incentive to keep a lower level of externality. Therefore, the downstream riparian country needs to compensate the upstream riparian country by an amount τ per unit of externality, in which the demand for externality control equals the supply at the socially optimal level of externality, e^* (Hanley et al., 1997). Thus, the solution leads to endogenously determining the externality cost. This victim pays principle is also known in the literature as payment for environmental services (Pagiola, 2008). □

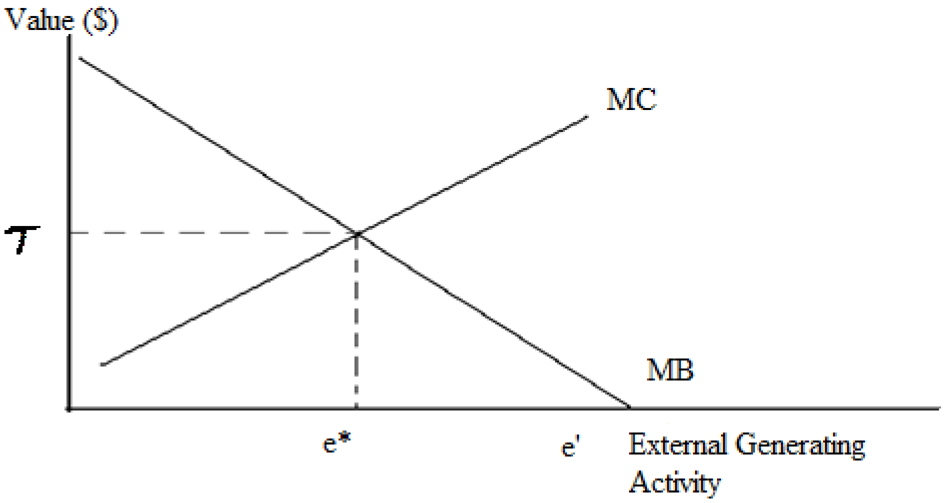

Figure 2.3: Socially Efficient and Competitive Equilibrium Level of Externality

2.2.3.2 Multi-directional Externality: externality that affects both riparian countries

In this situation, the externality-generating activity is endogenized in each riparian country's benefit, $u^i(D_i, e)$, and social welfare, $W(u_i, e)$, functions. The competitive equilibrium results remain similar with the above case. Maximizing the social welfare function can be represented using

$$Max\ Z_{(e)} = \ [u^{US}(D_{US}, e) + u^{DS}(D_{DS}, e)]. \tag{2.11}$$

Deriving and rearranging the first-order condition with respect to externality-generating activity, e, yields

$$\underbrace{u^{US\ \prime}(e^*)}_{Marginal\ Benefit(MB)} \quad = \quad \underbrace{-u^{DS\ \prime}(e^*).}_{Marginal\ Damage\ Cost(MC)} \tag{2.12}$$

The comparative equilibrium level of externality, $e^{'}$, occurs at the point where the marginal benefit (MB) to the upstream country for an additional unit of externality-generating activity, $u^{US}\,'(e^{*})$, is zero, as shown in Figure 2.3. At this point, the upstream riparian country imposes maximum externality until its marginal benefit from additional externality-generating activity is zero. As specified in Eq. (2.12), under efficient condition, however, the level of externality is adjusted to the point where the marginal benefit to the upstream country for an additional unit of externality-generating activity equals its marginal damage cost to the downstream country, e^{*}, in Figure 2.3.

The above analysis also facilitates a solution for the externality problem, depending on the availability of regional institution and framework for basin-wide agreement. The main objective in any solution framework is to restore the efficient level of externality, e^{*}, based on the marginal benefit and cost for riparian countries. For instance, a Pigouvian tax, τ, is exactly equal to the amount that the downstream riparian country would be willing to pay to the upstream riparian country to reduce the externality from $e^{'}$ to e^{*}, as shown in Figure 2.3. □

2.3 Empirical Model

Existing Nile River studies did not include environmental damages, such as soil erosion in the Ethiopian highlands and siltation in Sudan and Egypt water reservoirs, which threaten the carrying capacity and environmental sustainability of Nile waterways (reservoirs and canals) (Longin et al., 2005). In addition, climate change scenarios were not studied in line with the basin's welfare, but rather their effect on Nile River flow (such as IPCC (2001); Conway (2005); Kim and Kaluarachchi (2009)).

We formulated Nile Environmental and Economic Optimization Model (NEEOM) with the objective of maximizing the net economic value of allocating Nile River water for irrigation and hydropower sectors, taking into account resource degradation and various climate change scenarios, and the possibility of introducing basin-wide water trade via "allocate-and-trade." The two sectors consume the lion's share of the water in the basin. Domestic and industrial water uses, which account for about 13%, 3.3% and less than 1% of water use in Egypt, Sudan and Ethiopia, respectively, are not part of the analysis (FAO, 2010).

2.3.1 Objective Function

The general objective function is formulated with the following specification

$$\frac{\sum_d \sum_t \beta_{dt}(D_{dt}^{IR})^{(\alpha_{dt}+1)}}{\alpha_{dt}+1} + \sum_d \sum_t P_{dt}^{HP}(kWh_{dt}) + \sum_d \sum_t P_{dt}^{ED}(ED_{dt}) - c\sum_d \sum_t [(D_{dt}^{IR}) + (D_{dt}^{HP})] \tag{2.13}$$

where,

d = demand district,

t = month ($t = 1, ..., 12$),

β_{dt} = coefficient of inverse demand function,

α_{dt} = exponent of inverse demand function for demand elasticity,

D_{dt}^{IR} = irrigation water demand (m^3 per month),

D_{dt}^{HP} = hydropower water demand (m^3 per month),

kWh_{dt} = amount of electricity produced (kilowatt-hour, kWh),

P_{dt}^{HP} = net unit price of electricity ($ per kWh),

ED_{dt} = excess water demand (m^3 per month) ,

P_{dt}^{ED} = the shadow price of excess demand ($ per m^3)and

c = average unit cost of resource degradation ($ per m^3).

The first and second component are designed to take into account the economic benefit of using Nile water for irrigation and hydropower sector, respectively. The third component introduces intrabasin trade and the last component takes into account the cost of resource degradation, as specified in 2.2.2 or Nigatu and Dinar (2011).

2.3.2 Constraints

The main constraints in the optimization model are mass balance, hydropower production, irrigation and allocation constraints.

2.3.2.1 Mass Balance Constraint

$$ST_{d,t+1} = (1 - \gamma_{dt}^{ST})ST_{dt} + WI_{dt} - D_{dt}^{IR} - D_{dt}^{HP} - WO_{dt}, \tag{2.14}$$

with its bound

$$ST_{dt}^{MIN} \leq ST_{dt} \leq ST_{dt}^{MAX}, \tag{2.15}$$

and continuity condition

$$WI_{dt} = WO_{d-1,t} + r^{IR}(D^{IR}_{d-1,t}) + r^{HP}(D^{HP}_{d-1,t}), \tag{2.16}$$

where,

$d - 1$ = the previous demand district,

$t + 1$ = the following month,

$ST_{d,t+1}$ = volume of water stored in a reservoir at the beginning of the following month (m^3),

ST_{dt} = volume of water stored in a reservoir at the beginning month (m^3),

WI_{dt}= volume of water inflow to a reservoir (m^3 per month),

WO_{dt}= volume of water outflow to the next reservoir (m^3 per month),

ST^{MIN}_{dt} = minimum volume of water stored in a reservoir (m^3),

ST^{MAX}_{dt} = maximum capacity of water stored in a reservoir (m^3),

γ^{ST}_{dt} = share of stored water lost due to evaporation,

r^{IR} = share of return flow after water is used for irrigation and

r^{HP} = share of return flow after water is used for hydropower.

2.3.2.2 Hydropower Production Constraints

$$kWh_{dt} = \rho \; D^{HP}_{dt} \; H_{dt} \; \eta_{dt}, \text{ and} \tag{2.17}$$

$$kWh_{dt} \leq kWh^{MAX}_{dt}, \tag{2.18}$$

where,

kWh_{dt} = amount of electricity produced (kilowatt-hour, kWh),

kWh_{dt}^{MAX} = maximum installed hydropower capacity,

H_{dt} = the structural height associated with the dam (meter),

η_{dt} = the technical efficiency of the power plant and

ρ = a conversion factor for water flow in generating hydropower.

2.3.2.3 Irrigation Constraints

$$D_{dt}^{IR} = CWR_{dt}\ L_{dt}\ \mu_{dt},\ \text{and} \tag{2.19}$$

$$L_{dt} \leq L_{dt}^{MAX}, \tag{2.20}$$

where,

CWR_{dt} = crop water requirement (m^3/hectare/year),

μ_{dt} = intensity of land use,

L_{dt} = amount of land for irrigation (hectare) and

L_{dt}^{MAX} = the maximum irrigation potential land (hectare).

2.3.2.4 Allocation Constraints

These constraints come into the model through balancing the total water demanded for the economic activities and supplied through various water allocation arrangement scenarios. Four scenarios are identified and explained in detail.

Scenario 1. Baseline Allocation Of all the dialogues and conflicts surrounding the Nile River, the most prominent is the 1959 bilateral agreement signed between two downstream countries (Sudan and Egypt) (Waterbury, 2002). Leaving the detailed hydro-politics aside, the baseline (status quo) allocation can be used as a first reference point for calculating the economic value of the Nile River.[6]

$$\sum_d \sum_t |_{Su}(D_{dt}^{IR} + D_{dt}^{HP}) \leq 25\% \text{ or } 18.5 \text{ bcm for Sudan and} \quad (2.21)$$

$$\sum_d \sum_t |_{Eg}(D_{dt}^{IR} + D_{dt}^{HP}) \leq 75\% \text{ or } 55.5 \text{ bcm for Egypt,}$$

where,

Su and Eg stand for Sudan and Egypt, respectively.

Scenario 2. Unilateral Allocation This allocation literally means that a country uses the Nile River according to its natural flow without considering its immediate or distant neighbors.[7] This allocation is a prevalent strategy pursued by riparian countries because of the lack of a basin-wide water allocation treaty (Wu and Whittington, 2006). NEEOM is designed to address unilateral allocation based on the following specifications

[6] 1 billion cubic meters (bcm) = 810,373 acre-feet, or 1 acre-foot = 1234 cubic meters (cm). The baseline allocation is based on the Nile River water that reaches the Aswan High Dam.

[7] In this scenario, it is assumed that riparian countries will implement projects that are currently on the drawing board, such as, the Blue Nile sub-basin and Baro sub-basin multipurpose projects in Ethiopia, the New Valley Projects in Egypt and the Upper Atbara and Merowe projects in Sudan. First, Ethiopia unilaterally decides water allocation for its existing and planned water demand projects, then Sudan and, finally, Egypt. 98.5 bcm of Nile water is used for this and the other scenarios, taken from the Global Runoff Data Centre (GRDC, 2010).

$$\sum_d \sum_t |_{Et}(D_{dt}^{IR} + D_{dt}^{HP}) \leq \sum_k \sum_t |_{Et} S_{kt} \text{ for Ethiopia,}$$
$$\sum_d \sum_t |_{Su}(D_{dt}^{IR} + D_{dt}^{HP}) \leq \sum_k \sum_t |_{Su} S_{kt} \text{ for Sudan and} \quad (2.22)$$
$$\sum_d \sum_t |_{Eg}(D_{dt}^{IR} + D_{dt}^{HP}) \leq \sum_k \sum_t |_{Eg} S_{kt} \text{ for Egypt,}$$

where,

Et = Ethiopia,

k = Nile River tributaries,

S_{kt} = volume of water supplied (m^3 per month),

$\sum_k \sum_t |_{Et} S_{kt}$ = total volume of water supplied to Ethiopia from Nile River tributaries, namely Atbara, Blue Nile and Sobat (m^3 per month),

$\sum_k \sum_t |_{Su} S_{kt}$ = total volume of water supplied to Sudan from White Nile, and Atbara, Blue Nile and Sobat sub-basin after water is diverted in Ethiopia (m^3 per month) and

$\sum_k \sum_t |_{Eg} S_{kt}$ = total volume of water supplied to Egypt (m^3 per month)

$=\sum_k \sum_t |_{Su} S_{kt} - [\sum_d \sum_t |_{Su}(D_{dt}^{IR} + D_{dt}^{HP})]$.

This allocation is sometimes supported by upstream riparian countries, such as Ethiopia, that claim the adoption of "absolute territorial sovereignty" water rights in managing trans-boundary rivers (Dinar and Wolf, 1994). A similar approach was adopted by Turkey, the upstream riparian, to the Euphrates-Tigris river in its discussion with Syria and Iraq (Kibaroglu and Ünver, 2000).

Scenario 3. Social Planner or Efficient Allocation As specified in the theoretical model, the social planner provides an efficient allocation of Nile River water. That means that any other intervention could lead to a welfare value that is inferior to the social planner's outcome. Consequently, efficiency from the social planner's outcome can be used as a yardstick by which the performance of other allocation schemes can be evaluated. In this scenario, Nile water that generates the maximum economic benefit is allocated optimally for economic activities regardless of where they are located. This specification can be presented using

$$\sum_d \sum_t (D_{dt}^{IR} + D_{dt}^{HP}) \leq \sum_k \sum_t S_{kt}. \tag{2.23}$$

The crucial element of resource allocation that cannot be warranted through efficient allocation is the issue of equity: fairness in the distribution of income or resources. In the case of a common-pool resource such as the Nile River that crosses international boundaries and sovereign nations, efficiency alone cannot stand as the primary objective for allocating and managing resources. Therefore, an intrabasin "allocate-and-trade" is introduced to attain efficiency, address equity and maintain environmental sustainability.

Scenario 4. Allocate-and-Trade The principle behind this arrangement is that water could be used for the economic sectors that generate the highest economic benefit. The third component of Eq. (2.13), through the value of excess demand, $\sum_d \sum_t P^{ED}(ED_{dt})$, introduces an intrabasin "allocate-and-trade," or a water trade (henceforth "trade") that attaches a positive price, as specified in proposition 2. This helps in identifying the condition when water is transferred to a riparian country with a higher marginal benefit. At the same time, a buyer riparian country is willing to compensate a seller riparian country that has a lower shadow value of water. The excess demand constraint becomes

$$\sum_d \sum_t ED_{dt} = \sum_d \sum_t (D_{dt}^{IR} + D_{dt}^{HP}) - \sum_i \bar{W}^i, \tag{2.24}$$

with the following additional condition for supply bound

$$\sum_i \bar{W}^i \leq \sum_k \sum_t S_{kt}, \tag{2.25}$$

where,

$\bar{W}^i$ = initial water rights.

2.4 Data and Parameters

This section presents the source of data and information and review of the main parameters used in solving the optimization model.

2.4.1 Data Sources

The United Nations Food and Agricultural Organization (FAO, 1997; Allen et al., 1998) and the World Bank Development Indicator Database (The World Bank, 2009) are the main sources of agricultural (including crop water requirement, area coverage, potential irrigated land), hydrological and economic data.

Hydropower price data is taken from The World Bank (2007) for Ethiopia and Sudan and from Egyptian Electricity Holding Company (2009) for Egypt. The Global Runoff Data Center (GRDC) provides the Nile River flow data at a stream gauging station (GRDC, 2010). Kirby et al. (2010) furnished additional Nile River flow, its seasonal variability, evapotranspiration, and current Nile River water use. The Global Energy Observatory is the main source for hydropower data (for capacity, dam characteristics and reservoir volume) (GEO, 2010). Block and Strzepek (2010) provided information about proposed projects in Ethiopia.

2.4.2 Price Elasticity of Water Demand

Literature on the price elasticity of water for different demand sectors in each country and district is extremely scant. In addition, determining the exact elasticity value is a data (primary data) intensive task, and it is beyond the scope of this paper. He et al. (2006) estimated -0.2 for the price elasticity of irrigation water demand in Egypt; Green (2003) and Nauges and Whittington (2010) found price elasticity for water in the range of -0.1 to -0.2 and -0.3 to -0.6, respectively. Following Fisher et al. (2005), who suggest using low-elasticity values for water use in the Middle East, we use -0.2 for the price elasticity of irrigation water demand.

2.4.3 Crop Water Requirements and Intensity of Land Use

The Food and Agricultural Organization of the United Nations (FAO) has developed the CROPWAT software (Allen et al., 1998). For each crop, it calculates the monthly water requirement for irrigated agriculture based on climate, rainfall, soil and wind. In this paper, basic water requirement and intensity of land use data is used for analyzing irrigation water demand as shown in Table 2.1.

Table 2.1: Irrigation Potential, Water Requirement and Intensity of Land Use in the Eastern Nile Basin

Riparian Country	2009 total irrigated land in million hectare	Irrigation potential in million hectare	% of land use	Intensity of Land Use in%	Gross Irrigation Water Requirement in m^3/hectare/year
Ethiopia	0.02	2.22	0.90	116	9,000
Sudan	1.95	2.75	71.0	87	14,000
Egypt	3.25	4.42	73.5	167	13,000

Source: FAO (1997).

2.4.4 Average Unit Cost of Resource Degradation

An estimation of the total cost of resource degradation (soil erosion in Ethiopia and siltation in Sudan and Egypt) in relation to agriculture is given in Table 2.2. It is based on some previous studies, available data and informed assumptions.[8] In Ethiopia alone, the cost of soil degradation is estimated to be around 2 to 3% of the agricultural GDP (Bewket and Teferi, 2009). 2% of the agricultural GDP loss is assumed for estimating the total resource degradation cost. Dividing the

[8]The capacity to generate hydropower is also constrained by siltation behind dams. The major cause of siltation is soil erosion in the Ethiopian highlands, which contributes about 85% of Nile River water (Martens, 2011). Some factors that cause soil erosion are underdeveloped agricultural practices, poor soil and water management policies and deforestation. Hence, in dealing with soil erosion in the Nile basin, appropriate policies and practices should focus on the agricultural sector. That is why the estimated average unit cost of resource degradation only takes into account agricultural sector GDP loss. Before the construction of various dams along the Nile River, Sudanese and Egyptian farmers were benefiting from fertile soil brought by erosion. Currently, reservoirs, constructed in the Nile basin, block the eroded fertile soil and suffer from sediment deposition (Longin et al., 2005).

basin's annual economic loss due to resource degradation (0.745 billion US$) by annual eastern Nile River flow (around 80 bcm) results in the average unit cost of resource degradation, which is around $0.009 per cubic meter of Nile water.

Table 2.2: Estimating Economic Loss from Soil Degradation in the Eastern Nile Basin

Riparian Country	GDP[a] in 2009 billion US$	% of[a] Agri. sector in GDP	Estimated[b] % loss of Agri. GDP	% of[c] country's economy in the Basin	Estimated total GDP loss due to soil erosion in billion US$	% of the total loss
Ethiopia	33.9	43.8	2	11.7	0.035	4.7
Sudan	54.2	32.6	2	84.0	0.297	39.8
Egypt	188.0	13.1	2	84.0	0.414	55.5
Basin					0.745	

Sources: [a] CIA (2009), [b] Bewket and Teferi (2009), [c] FAO (1997).

2.4.5 Climate Change

The two most crucial climate parameters that shape basin hydrology are runoff and reservoir evaporation, specified using Eq. (2.14) and Eq. (2.16), respectively. These parameters are the by-products of temperature, precipitation, soil type, land biomass (vegetation) and pollution level. The values of these parameters are calculated by General Circulation Models (GCM) used to simulate climate scenarios (IPCC, 2001). The variations among various GCM models are also large, especially in predicting precipitation. Some models anticipate an increase in the annual runoff of Nile River and others anticipate a decrease (IPCC, 2001; Conway, 2005; Kim and Kaluarachchi, 2009). For this paper, Kim and Kaluarachchi's (2009) model is selected, because the simulation is performed based on 6 GCM models, as shown in Table 2.3.

Table 2.3: Parameters for Climate Change Scenarios in Eastern Nile Basin for 2050s

GCM	PET % Change	Q % Change
CCSR	9	80
CGCM	11	-14
CSIRO	14	-32
ECHAM	17	64
GFDL	1	-13
HADCM	19	-11

GCM Global Climatic Model or General Circulation Model;
CCSR Center for Climate System Research;
CGCM Canadian Global Coupled Model 2;
CSIRO Commonwealth Scientific and Industrial Research;
ECHAM European Centre Hamburg Model 4;
GFDL Geophysical Fluid Dynamics Laboratory's Rhomboidal 30 truncation;
HADCM Hadley Centers Climate Model 3;
PET potential evapo-transpiration; Q runoff

Sources: Kim and Kaluarachchi (2009)

Climate change is a forecasted and/or simulated phenomenon that would presumably happen in the future. Apparently, the value of the net benefit is discounted to reflect the present value of the basin's welfare. For the present value estimation, we adapt a discount rate of 4% from the Nile River basin study used by Jeuland (2010).

2.4.6 Water Right Arrangements

We propose five water rights arrangements (WRA) to initiate water trade, based on suggestions from Nile River experts, historical facts, past and present hydro-politics and experience from other river basins, as shown in Table 2.4. From Whittington et al. (1995) and Beaumont (2000), we identify WRA I and WRA IV, respectively. The United Nations Convention *Article 5* helps formulate WRA II (United Nations, 1997). Using the Middle East perspective discussed in Fisher et al. (2005), WRA III and WRA V are formulated. Except for WRA II, Sudan and Egypt share 25% and 75% of the downstream portion of Nile water, respectively, as formulated in the 1959 bilateral agreement (Waterbury, 2002).

Table 2.4: Proposed WRA of Nile River Water among Eastern Nile Riparian Countries, in %

Riparian	WRA				
Country	I	II	III	IV	V
Ethiopia	12.2	33.3	40.0	50.0	60.0
Sudan	22.0	33.3	15.0	12.5	10.0
Egypt	65.8	33.3	45.0	37.5	30.0
Basin	100.0	100.0	100.0	100.0	100.0

2.5 Results and Discussion

NEEOM uses a nonlinear programming approach in optimizing the eastern Nile River. The optimization model is written and solved using General Algebraic Modeling System (GAMS) software NLP (Non Linear Programming) solver. The model's setup is similar to the approach used by McKinney and Savitsky (2006). The model performs an annual dynamics only because interannual dynamics will not change the results as there is no dynamic parameter that changes over annum that affects the objective function. The mean annual runoff, calculated using the last 50 years of Nile River flow data, is used as the main input for the economic activities. The main decision variables are "irrigation water released," "land irrigated," "hydropower water released," "electricity generated" and "volume of water traded." The results from the optimization model are presented in four broad sections: efficiency, equity, resource degradation and climate change.

2.5.1 Welfare Values and Efficiency

The allocation constraints, identified using Scenarios 1-4, are used as the basis for analyzing the results from the optimization models.

2.5.1.1 Scenario 1. Baseline Allocation

For Scenario 1 through 3, a reduced form objective function is used, as shown below

$$\frac{\sum_{dt} \beta_{dt} * (D_{dt}^{IR})^{(\alpha_{dt}+1)}}{\alpha_{dt}+1} + \sum_{dt} P_{dt}^{HP} * kWh_{dt}. \tag{2.26}$$

The baseline allocation can be used as a calibration because its welfare values are estimated based on facts on the ground. The optimization results confirm that Egypt uses the volume of water specified in the 1959 bilateral treaty, as shown in Table 2.5. Sudan uses more water than the volume assigned in the treaty. Although the treaty did not explicitly allocate water for Ethiopia, it uses almost 3.9 bcm of water from the Nile River.

The economic benefit for the basin from the baseline allocation is \$8.62 billion.[9] The shadow values indicate that allocating additional water to Egypt would result in a higher economic benefit, *ceteris paribus*. For Sudan, however, the shadow value of additional water is negligible.

Table 2.5: The Results of the Optimization Models for Different Allocation Scenarios

Scenario	Riparian Countries	Nile River Water bcm	% share	Net Benefit Billion US\$/annum	Shadow Value US\$/cm
Baseline	Ethiopia	3.9	4.0	0.38	-
	Sudan	27.3	28.2	2.67	0
	Egypt	65.5	67.7	5.57	0.544
	Basin	96.7	100.0	8.62	0
Unilateral					
	Ethiopia	36.1	36.6	2.75	0
	Sudan	29.3	29.7	2.92	0
	Egypt	33.2	33.7	2.79	1.070
	Basin	98.5	100.0	8.46	0.017
Social Planner	Ethiopia	22.3	22.6	2.05	-
	Sudan	15.9	16.1	2.42	-
	Egypt	60.3	61.3	5.23	-
	Basin	98.5	100.0	9.71	0.584

[9] Price and shadow value per cubic meter of water, and net benefit and welfare value per annum are expressed in 2010 US\$, unless otherwise stated.

2.5.1.2 Scenario 2. Unilateral Allocation

The result from the unilateral allocation shows that the welfare value for the basin could reach $8.46 billion. The benefit from this allocation is 2% less than the the baseline allocation. As expected, the unilateral allocation does not represent a Pareto improvement compared with the baseline allocation. The share of the economic pie for Ethiopia and Sudan from unilateral allocation is bigger than in the baseline allocation, but it is smaller for Egypt. As expected, Ethiopia could use a significant portion, 36.6%, or 36.1 bcm, of Nile water.

The shadow value of water reveals that Egypt is the only riparian with a positive value. That means that both Ethiopia and Sudan would be able to meet their water demand through unilateral allocation, and more water does not provide an extra economic benefit for both riparian countries, *ceteris paribus*.[10]

2.5.1.3 Scenario 3. Social Planner's Allocation

Based on efficiency and maximizing the basin's welfare, the social planner could allocate 22.3 bcm, 15.9 bcm and 60.3 bcm of water to Ethiopia, Sudan and Egypt, respectively, as shown in Table 2.5. For Egypt, the social planner's water allocation is higher than the unilateral allocation. This is because Egypt uses Nile water more efficiently than other riparian countries. The economies of scale, through accumulated experience and technological advancement, is the main source of efficiency in Egypt. In another efficiency condition, there is no economic

[10]As explained in the unilateral allocation, we deal with intrabasin allocation and the information for potential land is collected from FAO (1997), as shown in Table 2.1. If Ethiopia and Sudan divert the Nile water away from the Nile basin, their shadow values would be positive.

benefit from generating hydropower in Sudan. Hence, allocating water for a sector or to a riparian country that could use the Nile water more efficiently increases the economic pie of the region. The optimization result confirms the efficiency condition of using water in a place where it could generate the highest welfare benefits for the basin.

There is a significant basin's welfare improvement from the social planner's outcome compared with the baseline and unilateral allocations. In addition to the highest welfare gain of $9.71 billion, the efficient allocation results in the highest shadow value of water for the basin compared with other scenarios. An extra cubic meter of water could increase the overall welfare of the basin by $0.584. Hence, the efficient outcome can assist in designing appropriate policy. The next section introduces water trade after assigning water rights arrangements.

2.5.1.4 Scenario 4. Allocate-and-Trade

This section begins with analyzing the welfare value of different water rights arrangements, as proposed in Table 2.4, but without introducing water trade. The efficient welfare value of $9.71 billion can be used to evaluate the economic performance of the proposed water rights arrangements. Among the water rights arrangements, WRA I results in the maximum welfare benefit of $9.53 billion, which is nearly 2% lower than the efficient outcome, as shown in Table 2.6. Even though there will be an improvement in the economic benefit for Ethiopia (from $1.35 billion for WRA I to the maximum $2.75 billion for WRA III) as it gets more water, the economic benefits for the downstream countries decline considerably.

For instance, if Egypt is assigned the smallest share of the Nile River water, WRA V, Egypt's economic benefit could reaches the lowest level of $2.71 billion.

Table 2.6: The Results of the Optimization Model for Different WRA Without Trade

Riparian Country	WRA I	II	III	IV	V
	Volume of Nile Water Assigned, in bcm				
Ethiopia	12.1	32.8	39.4	49.2	59.1
Sudan	21.7	32.8	14.8	12.3	9.8
Egypt	64.8	32.8	44.3	36.9	29.5
Basin	98.5	98.5	98.5	98.5	98.5
	Volume of Nile Water Used, in bcm				
Ethiopia	12.1	32.8	36.3	35.7	35.2
Sudan	21.7	28.7	14.8	12.3	9.8
Egypt	64.8	32.8	44.3	36.9	29.5
Basin	98.5	94.3	95.4	84.9	74.6
	Net Benefit, in Billion US$ per annum				
Ethiopia	1.35	2.58	2.75	2.72	2.68
Sudan	2.69	2.91	2.33	2.13	1.89
Egypt	5.49	2.95	4.03	3.43	2.71
Basin	9.53	8.44	9.11	8.28	7.28
	% of the Social Planner's Welfare Recovered				
Basin	98.1	86.9	93.8	85.3	75.0

Note: Some variations are due to rounding.

In addition, as the basin institution assigns a lesser volume of water to the downstream riparian countries, the shadow values of water for these countries rises substantially, as shown in Figure 2.4. For the upstream riparian country, the shadow value reaches zero once Ethiopia gets 36.6% or more of water rights. This is because Ethiopia only demands around 36.1 bcm of Nile water for existing and planned projects along the Nile Basin. If Ethiopia and Sudan divert the Nile water away from the Nile basin, their shadow values and economic benefits will be higher than what is shown here. Hence, any water rights arrangement beyond this level would result in a zero shadow value, as indicated in Figure 2.4. The variation in the shadow value of water suggests the possibility of improving the welfare of the basin through trade.

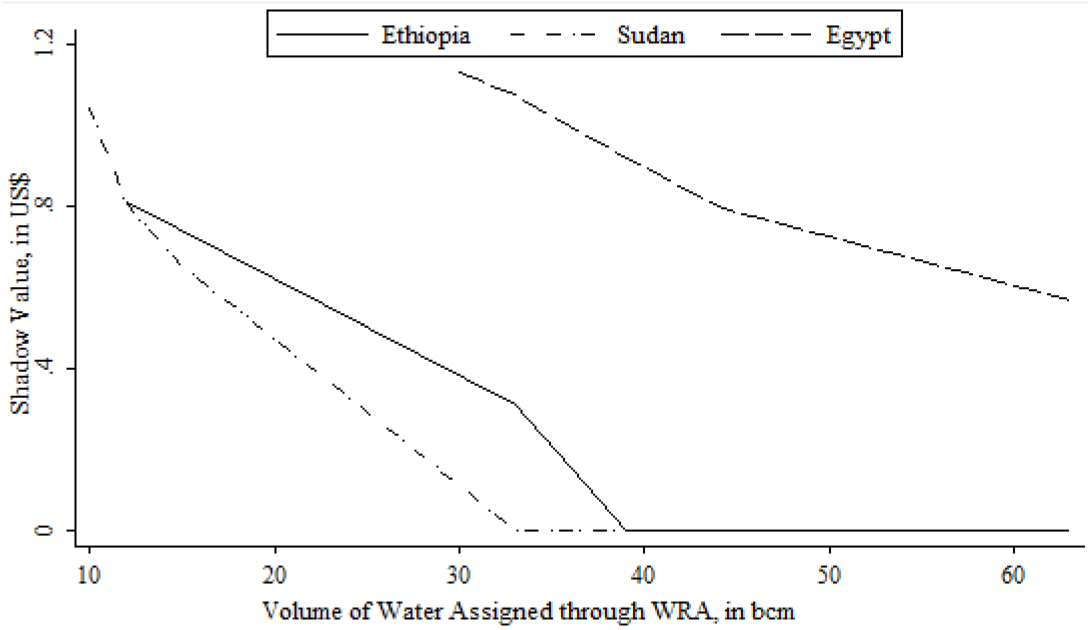

Figure 2.4: The Shadow Values of Nile River Water for Different WRA

In order to evaluate the potential Pareto improvement, a water trade is introduced, along with a variety of initial water rights arrangements. A reduced form objective function is now formulated as

$$\frac{\sum_d \sum_t \beta_{dt}(D_{dt}^{IR})^{(\alpha_{dt}+1)}}{\alpha_{dt}+1} + \sum_d \sum_t P_{dt}^{HP}(kWh_{dt}) + \sum_d \sum_t P_{dt}^{ED}(ED_{dt}). \quad (2.27)$$

The economic benefit from trade can be analyzed in two perspectives: with- and without-transfer payment, as shown in Table 2.7.[11] As expected, the transfer payment does not change the welfare value at the basin level; it redistributes economic benefits among riparian countries. In the case of trade scenario, there are water rights arrangements that could result in the welfare value for the basin that is equivalent to the efficient outcome, as shown in Table 2.7.

The shadow value of water helps design the transfer payment among riparian countries. As shown in Table 2.7, an individual country's economic benefit varies with- and without-transfer payment scenarios. Ethiopia is a net recipient of the transfer payment, as it gets more volume of water through the water rights arrangement. The maximum transfer payment could reach \$3.82 billion in the case of WRA V. This payment comes from the sale of 6 bcm and 30 bcm of water to Sudan and Egypt, respectively, at an average shadow price of \$0.104 per cubic meter of water, as shown in Figure 2.5. On the other hand, Sudan and Egypt become a net payer of the transfer, as they get a lesser volume of water. This is also supported by economic theory that the shadow value for additional water

[11] Riparian countries could arrange a variety of payment mechanism, such as a direct payment for the use of water, as in the case of this paper, or an indirect payment through providing other comparable services or products for water use.

Table 2.7: The Results of the Optimization Model for Basin-wide "Allocate-and-Trade" for Different WRA

Scenarios	Riparian Country	WRA I	II	III	IV	V
		Volume of Nile Water Used, in bcm				
	Ethiopia	21.4	18.3	19.9	21.7	22.3
	Sudan	12.3	15.3	16.1	15.9	16.0
	Egypt	64.8	64.8	62.4	60.8	60.1
	Basin	98.5	98.5	98.5	98.5	98.5
		Net Benefit, in Billion US$ per Annum				
With Trade only						
	Ethiopia	1.99	1.76	1.89	2.02	2.06
	Sudan	2.26	2.44	2.44	2.43	2.42
	Egypt	5.43	5.47	5.37	5.26	5.23
	Basin	9.68	9.67	9.70	9.71	9.71
With Trade and Transfer Payment						
	Ethiopia	1.41	3.01	3.13	2.83	3.16
	Sudan	2.73	3.25	2.44	2.43	2.42
	Egypt	5.54	3.41	4.13	4.44	4.13
	Basin	9.68	9.67	9.70	9.71	9.71
		Pattern of Trade				
	Ethiopia	buyer	seller	seller	seller	seller
	Sudan	seller	seller	buyer	buyer	buyer
	Egypt	-	buyer	buyer	buyer	buyer
		% of the Social Planner's Welfare Recovered				
	Basin	99.6	99.6	99.9	100.0	100.0

Note: Some variations are due to rounding.

increases as the downstream riparians get a lesser volume of water, as revealed in Figure 2.4.

As explained earlier, because of the comparative advantage of Egypt for using Nile water more efficiently than the other riparian countries, it will benefit from buying more water, provided that the water rights arrangement is strictly enforced and transfer payment system incurs negligible transaction costs. When Ethiopia is assigned a lower volume of water (for instance WRA I), it becomes a buyer of water. Since the marginal benefit for each additional unit of water in Ethiopia is the highest among the riparian countries for WRA I, Ethiopia will purchase water from Sudan which has a relatively lower opportunity cost of water than Egypt. For WRA II, both Ethiopia and Sudan are net sellers, while Egypt is a net buyer of water, as displayed in Table 2.7.

The potential Pareto improvement from both with and without trade in reference to the efficient outcome is shown in Table 2.6 and Table 2.7. Theoretically, as long as there is a well-defined water rights agreement, water trade takes care of the ultimate allocation and equates the net benefit of all water rights arrangements. In this case, the change in the mix of economic sectors in the optimization results and transfer of water from one country to another generate slightly different results among water rights arrangements.

Finally, as a regional institution assigns a greater volume of water to the upstream riparian country, trade will ultimately help recover nearly all of the efficiency, as claimed in proposition 2. For instance, for the Egalitarian allocation identified using the UN Convention (WRA II), trade can help recover about 99.6% of the efficiency, whereas without-trade scenario recovers about 86.9% of the efficient outcome. Therefore, assigning water rights without-trade agreement makes the basin worse off in terms of welfare. This can be explained through the fundamental implication of economic theory that water rights alone do not help attain efficiency. It can be inferred that water rights and water trade could help attain efficient level of economic outcome.

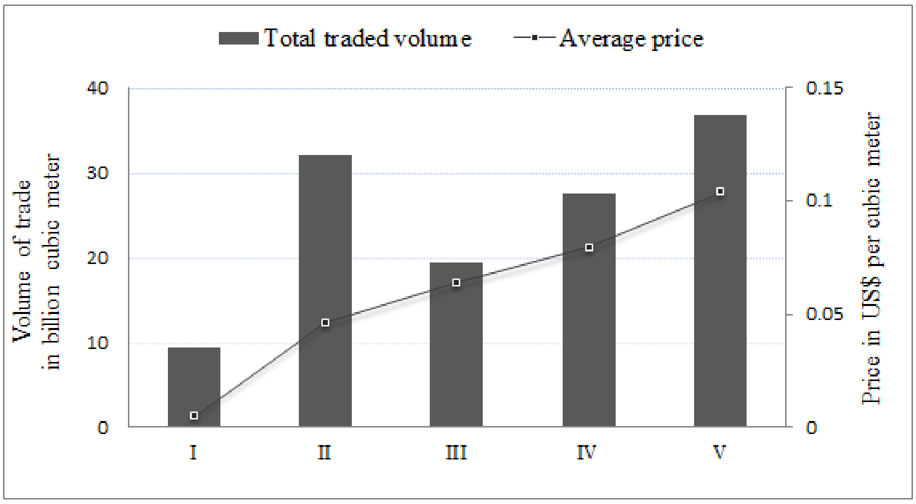

Figure 2.5: The Volume of Trade and Average Price of Nile Water for Different WRA

2.5.2 Welfare Values and Equity

The distribution of a common-pool resource and economic benefit from using the resource among riparian countries are hard to objectively assess (Hodgson, 2006). We claim to address equity using two sets of analysis. First, through comparing the baseline (status quo) resource use and economic benefit distribution among riparian countries with the efficient outcome. Second, through evaluating the performance (resource use and economic benefit distribution) of the proposed water rights arrangements with- and without-trade agreements.

Despite the fact that the extent of the participation of riparian countries is politically sensitive, the social planner's outcome results in the participation of all riparian countries, irrespective of the initial allocation. The social planner could assign 22.6% of Nile water to Ethiopia, the upstream riparian country, and 77.4% to Sudan and Egypt, the downstream riparian countries, as shown in Table 2.5. From the downstream portion of Nile water, 79% and 21% would be allocated to Egypt and Sudan, respectively. The 1959 bilateral agreement was designed to allocate 75% and 25% Nile water that reached the Aswan High Dam to Egypt and Sudan, respectively.

Compared with the the 1959 bilateral treaty in which 100% is allocated to Egypt and Sudan, the social planner could allocate Nile water similar to the suggestion of Nile Basin experts (Whittington et al., 1995). In other words, unlike the 1959 bilateral allocation, the efficient allocation requires the participation of all riparian countries in using the Nile water, as identified in proposition 1. Hence, the social planner's allocation not only addresses efficiency, but it helps solve equity issues, which is consistent with the implication from the theoretical formulation.

The social planner's allocation could generate the highest welfare value of $9.71 billion for the basin compared with $8.62 billion from baseline allocation. As approximated using the proportion of the basin's welfare among the three countries, the social welfare weights can be identified as 0.21, 0.25, and 0.54 for Ethiopia, Sudan and Egypt, respectively, as shown in Table 2.8. These welfare weights can also be used as an approximate indicator for assessing equity (Varian, 1992). The welfare weights resulting from the unilateral allocation are similar to Egalitarian use in which each country shares one-third of the economic gain, as stipulated in the United Nations Convention *Article 5* (United Nations, 1997).

Table 2.8: The Welfare Weight for Different Nile River Water Allocation Scenarios

Riparian Countries	Baseline Allocation	Unilateral Allocation	Social Planner	WRA I	WRA II	WRA III	WRA IV	WRA V
				Without trade				
Ethiopia	0.04	0.33	0.21	0.14	0.31	0.30	0.33	0.37
Sudan	0.31	0.34	0.25	0.28	0.34	0.26	0.26	0.26
Egypt	0.65	0.33	0.54	0.58	0.35	0.44	0.41	0.37
				With trade				
Ethiopia				0.15	0.31	0.32	0.29	0.33
Sudan				0.28	0.43	0.25	0.25	0.25
Egypt				0.57	0.35	0.43	0.46	0.43

The other approach in dealing with the issue of equity is evaluating the economic performance of the different water rights arrangements. Introducing water rights alone may not result in either a fair distribution of welfare among riparian countries, as shown in Table 2.8, or efficient outcome, Table 2.6. In order to attain full economic benefit, integrating water rights with water trade is found to be the best alternative option, as displayed in Table 2.8. This is because water trade could help secure the necessary volume of water for countries that use the water most efficiently based on their comparative advantage. This implicitly indicates that water trade will enable downstream riparian countries get equivalent volumes of water compared with the baseline scheme, and make better off those countries that hold firm to maintaining this allocation.

Along with the distribution of Nile water among all riparian countries and appropriate regulation, variation in shadow value is also an important indicator in attaining equity in resources management (Rogers et al., 2002). The shadow value could be used for selling water among riparian countries, and re-allocating profit based upon income could help to achieve equity goals (Olmstead and Stavins, 2008). This could lead to an important step in Nile dialogue that is stalled by the fear that any intervention could hamper the economic benefit of the downstream riparian countries.

2.5.3 Resource Degradation

The general objective function, specified in Eq. (2.13), is used for this section. Internalizing an externality without trade is an inferior option for all water rights arrangements, as shown in Table 2.9. Alternatively, almost all of the efficient outcomes can be recovered after internalizing externality and establishing trade. Moreover, as the extent of a water rights arrangement becomes more extreme favoring upstream country, trade, along with internalizing an externality, produces more economic welfare than without trade. Internalizing an externality and introducing trade produce welfare values with a smaller variation, from \$9.01 to 9.05 billion, among the different water rights arrangements compared with internalizing externality without-trade cases (\$6.83 to 8.87 billion). Therefore, one interesting implication is that no matter what the initial water rights assignment, water trade will recover similar level of basin benefits.

Table 2.9: The Net Economic Benefit of Internalizing Resource Degradation in the Eastern Nile River Basin

Scenarios	Social Planner	WRA I	II	III	IV	V
	Net Benefit, in Billion US$ per Annum					
Without Trade	9.05	8.87	7.83	8.49	7.75	6.83
With Trade	9.05	9.02	9.01	9.03	9.05	9.05
Gains from trade	-	0.15	1.18	0.54	1.30	2.22

As seen in Table 2.9, when water trade is introduced along with water rights arrangements, internalizing an externality becomes a cost-effective intervention, as claimed in proposition 2. Such intervention could save cost compared to the traditional regulation solution or command-and-control policy (Hansjurgens, 2005; Olmstead and Stavins, 2008). Compared with the social planner's outcome, implementing resource conservation and protection activities without assigning water rights arrangements is an efficient approach. This is because establishing water rights is a necessary condition for conserving and protecting resources. This result is consistent with the management practice of common-pool resources in which property rights play a vital role (Schlager and Ostrom, 1992).

Moreover, if there is an intrabasin consensus, in the form of a treaty or formal negotiation among riparian countries, that adopts the prevailing realities of the basin, a water market will provide more cost-effective tools for resource protection than water rights arrangements alone. Such trade will compensate the losing country and promote sustainable resource management practices. The merit of trade is that it provides sufficient abatement based on incentive and marginal returns of resource use (Hanley et al., 1997).

As shown in Table 2.9, the social planner's allocation provides the highest net social benefit for the basin after internalizing an externality cost. Ethiopia, Sudan and Egypt share \$157, 120 and 384 million of the resource protection and conservation costs, respectively, as shown in Table 2.10. In the case of trade, WRA IV and WRA V provide the highest net social benefit for the basin, around 9.05 billion. In addition, the gap in the level of abatement between with and without trade could reach \$212 million for WRA V.

In general, NEEOM provides an estimate for the level of abatement needed in the basin. In the short term, eastern Nile riparian countries need to allocate around \$600 to 660 million for protecting and conserving the natural resources base of the basin, as shown in Table 2.10. This abatement could solve unsustainable agricultural practices and deforestation which are the leading causes of soil erosion in Ethiopia and siltation in Egypt and Sudan (Longin et al., 2005).

2.5.4 Climate Change

Like the previous sections, the discussion here starts with estimating the welfare value of the efficient outcome, introducing water rights arrangements and trade for different GCM scenarios (see Table 2.3). The new objective function that takes into account a discounting factor for the future values is shown in Eq. (2.28). The result is presented using Box and Whisker graph where it facilitates

Table 2.10: Level of Abatement Needed in Million US$ per annum

Scenarios	Riparian Country	Social Planner	WRA I	II	III	IV	V
Without Trade							
	Ethiopia	157	76	252	282	274	271
	Sudan	120	169	225	107	85	63
	Egypt	384	416	134	234	175	116
	Basin	662	661	611	623	534	450
With Trade							
	Ethiopia	157	149	121	136	152	157
	Sudan	120	100	123	120	121	120
	Egypt	384	412	421	407	389	385
	Basin	662	661	665	663	662	662
Basin's Abatement Gap		-	0	54	40	128	212

Note: Some variations are due to rounding.

side-by-side comparison of different scenarios and explains the distribution of results without making a normal distribution assumption (Banacos, 2011).[12]

$$[\frac{1}{1+dis^{40}}][\frac{\sum_d \sum_t \beta_{dt}(D_{dt}^{IR})^{(\alpha_{dt}+1)}}{\alpha_{dt}+1} + \sum_d \sum_t P_{dt}^{HP}(kWh_{dt}) \quad (2.28)$$
$$+\sum_d \sum_t P_{dt}^{ED}(ED_{dt}) - c\sum_d \sum_t [(D_{dt}^{IR}) + (D_{dt}^{HP})]],$$

where dis is discounting factor 4% (Jeuland, 2010); 40 years from 2010.

The present value of the net benefit from the efficient allocation will range from $3.40 billion, in the case of CSIRO scenario, to $5.60 billion for CCSR scenario. The median efficient outcome will be around $4.10 billion, which will be lower than the Business-As-Usual (BAU) scenario's outcome of $4.47 billion, as shown

[12]In this section, economic values are discounted from 2050 to the present (2010).

in Figure 2.6. The distribution for the efficient outcome that can be expressed using the 25^{th} and 75^{th} quartile with the net present value of $3.88 billion and $5.59 billion, respectively, will be similar with most water trade results.

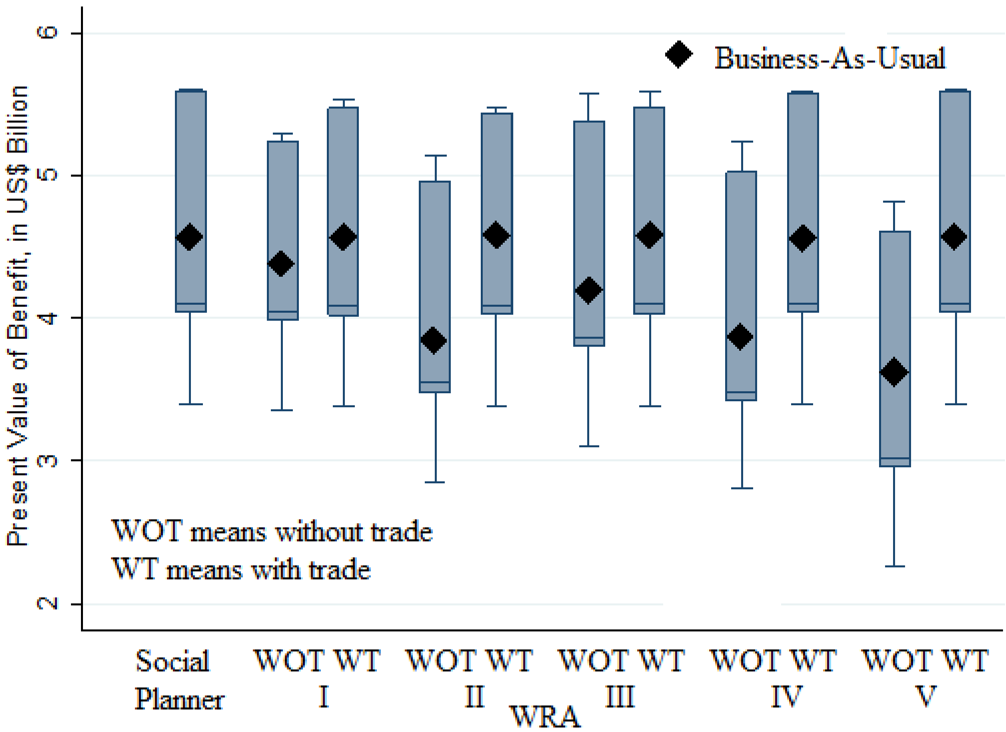

Figure 2.6: The Present Value of Benefit Under Different Climate Change Scenarios

Except for WRA I which assigns more Nile River water to the upstream riparian countries, the variation in the economic benefits resulted from assigning water rights arrangements and introducing trade is smaller than assigning water rights arrangements alone, as shown in Figure 2.6. For instance, in the extreme case of water rights arrangements, WRA V, the variation could reach as high as $2.56 billion for without-trade case, but the gap could be around $2.20 billion for with-trade case. In other words, when downstream Nile riparian countries face a water shortage, as in WRA V, the overall welfare value of the basin will be negatively impacted. Therefore, for each riparian country, the impact of climate change depends on water rights arrangements, available institutions and the diversity of the economic sectors (such as growing industrial sector water demand in the region).

For all of the water rights arrangements with- and without-trade agreement, the median economic benefit will be lower than the economic benefit from BAU scenario. Among the six GCMs, only two, namely CCSR and ECHMA scenarios will result in higher economic benefits than that of BAU scenario. This indicates that on average Nile Basin's economic benefit will be negatively impacted by climate change that will increase variability and reduce runoff of the Nile River, as seen from Table 2.3.

In general, water trade will recover nearly all of the efficient outcomes while without trade could only recover about 64% - 99% of the efficient outcomes, depending on the different GCM scenarios and water rights arrangements. More specifically, when the downstream countries face a water shortage as in the case of WRA V and CSIRO, water trade will recover all of the efficient outcomes, whereas no trade agreement would result in a recovery of about 66% of the efficient outcomes. This indicates that in an era of apparent climate change, implementing river basin management that is based on assigning water rights and introducing water trade will help recover almost all of the outcomes of the efficient allocation.

2.6 Conclusion

The social planner assigns Nile River water for an economic sector that generates the highest economic benefit to the basin regardless of the initial water rights arrangements. It allocates about 22.6, 16.1 and 61.3% of Nile River water to Ethiopia, Sudan and Egypt, respectively. The social planner's welfare gain is the "first-best" economic solution, which is practically challenging to implement in the real world, but this welfare gain helps evaluate the performance of "allocate-and-trade." The baseline and unilateral allocations are suboptimal compared with the social planner and other plausible, but politically sensitive, water rights arrangements. This provides the rationale for changing the baseline allocation when considering the long-term prospect of this highly fragile region of the world.

Water trade can help riparian countries secure equivalent volumes of water compared with the baseline allocation in order to derive superior economic benefits. In other words, intrabasin water trade could make better off those downstream riparian countries that hold firm to maintaining the baseline allocation. Intrabasin water trade could lead to an important step in Nile dialogue that is stalled by the fear that any intervention could affect the economic benefit of the downstream riparian countries.

We found that both water rights arrangements and trade are effective tools in dealing with existing externalities and expected climate change. As for the resource degradation, trade helps reach a higher level of abatement to internalize externalities than without trade. NEEOM estimates that riparian countries need to invest at least $660 million in the short term to avert the apparent resource degradation. Some of the conservation activities include using appropriate agricultural practices that reduce (eliminate) soil erosion and implementing alternative energy sources that reduce (eliminate) deforestation and resource degradation in Ethiopia. In addition, the basin's welfare could be significantly reduced due to the impact of climate change that decreases runoff and precipitation.

Finally, it is important to mention some of the limitations of NEEOM. First, it is an annual model that takes into account a one year Nile River water flow. Second, the model integrates an exogenous cost estimate for externality. Finally, NEEOM is a partial equilibrium model that includes only two economic sectors and three riparian countries among 11 countries. Due to time and resource limitation, it is difficult to solve these shortcomings. In the future, I will extend the model to resolve these issues and study the economic welfare of "allocate-and-trade" for the whole basin in a general equilibrium framework.

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Chapter 3

Carbon Price Volatility During the Global Recession: The Markov Regime Switching Model

3.1 Introduction

The value of a carbon market is currently about US$ 150 billion, as shown in Table 3.1, and will eventually exceed US$ three trillion (Daskalakis et al., 2009; Capoor and Ambrosi, 2010). The acceptance and growth of this market is, however, overshadowed by the financial crisis that started in 2008. Since the recession started during the first phase (2008-2012) of the Kyoto Protocol Action Plan, unlike any other commodity market hard hit by the impact of the recession, carbon market faces an enormous challenge at the preliminary stage of its establishment. It is argued that early regulatory efforts to mitigate climate change through emission or carbon markets undergo major scrutiny, whether or not this market brings the desired results. Moreover, carbon market faces a challenge in facilitating carbon credit supply and demand, abatement and damage costs. On top of that, the recession creates a considerable spotlight on the debate about relying on the market as a mechanism to bring the required economic, environmental and social changes (Glover, 2009; Schiermeier, 2009).

Table 3.1: Carbon Market at a Glance in Billions of US$, 2006-2009

	Years			
Type of Carbon Trade	2006	2007	2008	2009
Allowance Market				
European Union ETS	24.4	50.1	100.5	118.5
New South Wales	0.2	0.2	0.2	0.1
Chicago Climate Exchange	0.1	0.1	0.3	0.1
Regional Greenhouse Gas Initiative			0.2	2.2
Assigned Amount Units			0.3	2.0
Subtotal	24.7	50.4	101.5	122.8
Project-Based				
Primary CDM	5.8	7.4	6.5	2.7
Secondary CDM	0.4	5.5	26.3	17.5
Joint Implementation	0.1	0.5	0.4	0.4
Voluntary Transaction	0.1	0.3	0.4	0.3
Subtotal	6.5	13.6	33.6	20.9
Total	31.2	64.0	135.1	143.7

ETS - Emission Trading Scheme
CDM - Clean Development Mechanism
Source: Capoor and Ambrosi (2008, 2009, 2010)

In addition to the performance of a carbon market, emission allowances are the outcome of several variables including fundamentals (like weather) and unquantifiable regulatory, policy and sociological factors. The overall effects of these endogenous and exogenous factors can cause unexpected buyouts that lead to price jumps (Benz and Trück, 2009). Studies on the dynamic behavior of carbon spot price exhibit a time and price dependent volatility structure (Uhrig-Homburg and Wagner, 2007; Seifert et al., 2008). In another study, mean-reversion models with state-dependent price jumps perform far better in forecasting the pilot-period future prices, whereas mean-reversion models alone outperform the Kyoto-period for future carbon allowances (Lin and Lin, 2007).

There are several econometric and financial models that can be used to analyze the behavior of carbon price. For instance, Benz and Trück (2009) suggest the use of the Markov-switching (regime shift) and Autoregressive-Generalized Autoregressive Conditional Heteroskedasticity (AR - GARCH) models for stochastic modeling. For the dynamic behavior, Seifert et al. (2008) present the stochastic Optimal Control model and derive the characteristic Partial Deferential Equation that fully characterizes the solution. Daskalakis et al. (2009) use a jump diffusion model to approximate the random behavior of spot price. Paolella and Taschini (2008) present another GARCH-type econometric model on the basis of stylized facts of the data and investigate the behavior of emission allowances.

This paper provides one of the first econometric investigations for the behavior of carbon price and its volatility in both compliance (Kyoto signatory) and voluntary (non-signatory) markets. The approach focuses on the econometric characteristics of carbon price and its volatility before (pre), within and after (post) the 2008/09 global recession. In addition, the relationship between carbon market and some financial market indices will be studied using cointegration analysis.

The main research question is: What are the impacts of the recession (business cycle) on carbon price and its volatility? What is the influence of the recession on voluntary and compliance carbon prices and volatilities? What are the distinctive features of carbon price and its volatility before, within and after the recession? What is the relationship between (co-integration) carbon price volatility and the volatility of other financial assets?

The remainder of the paper is developed as follows. The next section describes the Model. The Data and Descriptive Statistics are given in section 3. The research findings will be discussed in the Empirical Results and Discussions section. Finally, a Conclusion summarizes the main results of the study and identifies the direction for future research.

3.2 The Markov Regime Switching Model

A common econometric model for studying volatility has been Generalized Autoregressive Conditional Heteroskedasticity (GARCH) models. They have however a limitation to deal with high persistence that results from financial and economic shocks (Klaassen, 2002). These shocks cause structural changes in the variance process. Even though the estimated GARCH volatility parameters may be statistically significant, these parameters may not be stable over time, and their forecasting performance is rather poor (Hamilton and Lin, 1996). Hence, applying regime-switching model (RSM) is an attractive approach in the case of studying business cycle, which periodically switches between boom and recession, and financial market, which frequently fluctuates between low- and high-volatile regimes (Kim and Nelson, 1999).

The original work on RSM dates back to Quandt (1958) and Goldfeld and Quandt (1973). For characterizing changes in the parameters for autoregressive process, Hamilton (1989) introduced Markov Regime Switching (MRS) models and suggested their use for financial time series analysis (Benz and Trück, 2009). MRS models capture the effect of political and economic events on the properties of financial and economic time series (Cai, 1994). As described by Franses and Dijk (2000), regimes or states of the world allow the possibility of the dynamic behavior of economic variables to depend on the regimes that occur at any given point in time.

Benz and Trück (2009) provide a brief survey of applying MRS for financial market, electricity spot prices and price and volatility behavior in modeling emissions allowance. The application of MRS is concentrated on analyzing the stock market and other financial derivatives (Marcucci, 2005). This paper is intended to use MRS in the framework of describing carbon price volatility in voluntary and compliance emission markets before (pre), within and after (post) the recent recession.

The switching mechanism between states is governed by an unobserved random variable, s_t. Assume two regimes that follow a Markov-Chain process, $s_t = \{i, j\}$.

In this particular case, emission or carbon prices may assume to reveal either low- or high-volatile regime at each point in time, t, depending on the prevalent of regime $s_t = i$ or $s_t = j$. The main assumption for the process is that the probability law that presides over the transition from one state to another is supposed to be independent. The state variable is assumed to evolve according to a first-order Markov-Chain, with transition probability

$$Pr\{s_t = j | s_{t-1} = i, s_{t-2} = 0, \ldots\} = Pr\{s_t = j | s_{t-1} = i\} = p_{ij}. \tag{3.1}$$

Eq. (3.1) indicates the probability of switching from regime i at $t-1$ to regime j at t. In practice, volatility is more likely affected by recent events, which carry more weight, than events in the past. Hence, in the above setting, the current regime can be determined through the probability of the previous one period event, where all the other past events are irrelevant. This is rather restrictive assumption, though, it is widely used in applied research. For instance, Klaassen (2002) describes that two regimes are sufficient in the case of forecasting volatility.[1]

For two regimes, the transition probability can be collected in a 2x2 transition matrix

$$\mathbf{P} = \begin{bmatrix} p_{ii} & p_{ji} \\ p_{ij} & p_{jj} \end{bmatrix} = \begin{bmatrix} \text{p} & 1-\text{q} \\ 1-\text{p} & \text{q} \end{bmatrix}, \tag{3.2}$$

where, row j column i elements of $\mathbf{P}$ is the transition probability, p_{ij} the probability that regime i will be followed by regime j.

[1]Hamilton (1994) provides more general treatment for N regimes Markov-Chain processes.

The important data in this analysis is the return data, r_t, that can be calculated using

$$r_t = 100 * [Ln(p_t) - Ln(p_{t-1})], \tag{3.3}$$

where, p_t is a closing price of carbon at time $t = -R + 1, \ldots, n$, and R is the first day when the price data was publicly available. The sample period can be divided into two parts: in-sample period, $t = -R + 1, \ldots, 0$, for estimation purposes and out-of-sample period, $t = 1, \ldots, n$, for evaluation and forecasting purposes.

The data generating process at regime $s_t = i$ is supposed to be drawn from the conditional distribution, f. The estimated parameters, $\hat{\theta}_{s_t}$, can be represented using

$$\hat{\theta}_{s_t}|I_{t-1} = f(\mu_{s_t},\ \sigma^2_{s_t}), \tag{3.4}$$

where, $\mu_{s_t} = E(r_t|I_{t-1}, s_t = i,\ j)$ is the conditional mean; $\sigma^2_{s_t} = var(r_t|I_{t-1}, s_t = i,\ j)$ is the conditional variance; and I_{t-1} conveys the information set at $t - 1$. The conditional mean and variance can be revealed through two state processes using the transition probability, p_{ij}.

Following Kim and Nelson (1999), the MRS model can be represented using

$$
\begin{aligned}
r_t &= \mu_{s_t} + \epsilon_t, \\
\epsilon_t &\sim N(0, \sigma^2_{s_t}), \\
\mu_{s_t} &= \mu_1 S_{1t} + \mu_2 S_{2t}, \\
\sigma^2_{s_t} &= \sigma^2_1 S_{1t} + \sigma^2_2 S_{2t}, \\
S_{jt} = 1, \text{if } S_t = j, \text{and } S_{jt} &= 0, \text{ otherwise}, \ j = 1, 2, \\
p_{ij} = Pr[S_t = j | S_{t-1} = i] \text{ and } \sum_{j=1}^{2} p_{ij} &= 1.
\end{aligned}
\tag{3.5}
$$

Hamilton (1994) and Kim and Nelson (1999) present the detailed mathematical formulation for characterizing and maximizing of the maximum likelihood function. Given the knowledge of the population parameters for two regimes, $\theta = (\mu_1, \mu_2, \sigma^2_1, \sigma^2_2, p_{11}, p_{22})$, and the available information at the time, Engel and Hamilton (1990) characterize the probability that the process was in some particular regime s_t at date t as

$$p(s_t | r_1, \ldots, r_T; \theta). \tag{3.6}$$

The joint probability distribution of the observed data for a sample of size $T(r_1, \ldots, r_T)$ along with the unobserved states $(s_1, \ldots, s_T)$ is given by

$$p(r_1, \ldots, r_T, s_1, \ldots, s_T; \theta) = p(r_T | s_T; \theta) \ . \ p(s_T | s_{T-1}; \theta). \tag{3.7}$$

The sample likelihood function could be identified through summation of Eq. (3.7) over all possible values of $s_1, \ldots, s_T$ as

$$p(r_1, \ldots, r_T; \theta) = \sum_{s_1=1}^{2} \cdots \sum_{s_T=1}^{2} p(r_1, \ldots, r_T, s_1, \ldots, s_T; \theta). \tag{3.8}$$

The first-order conditions for maximizing Eq. (3.8) with respect to θ help estimate the parameters, and the specification for estimating the coefficients are given in Hamilton (1994).

3.3 Data

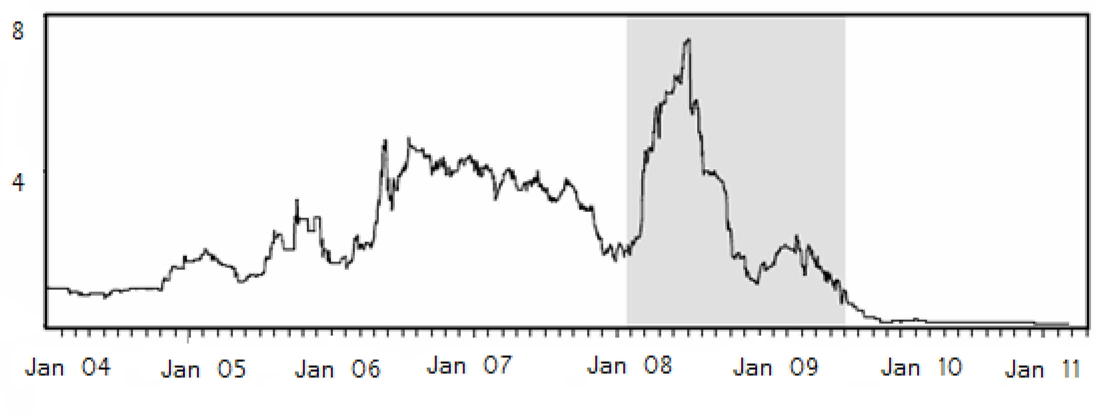
The daily closing carbon price data are obtained from two market sources: a voluntary carbon market from the Chicago Climate Exchange (CCX) (CCX, 2011) and compliance carbon market from the European Climate Exchange (ECX) (ECX, 2011). The period covers from December 2003 to January 2011. This period is divided into two segments: in-sample (December 2003 to December 2007) and out-of-sample (January 2008 to January 2011). The out-of-sample period is further analyzed in two time horizons: within-recession period that covers a period from January 2008 to June 2009 and after-recession period from July 2009 to January 2011. These classifications help capture price volatility and market performance in different economic regimes.

3.3.1 Descriptive Statistics

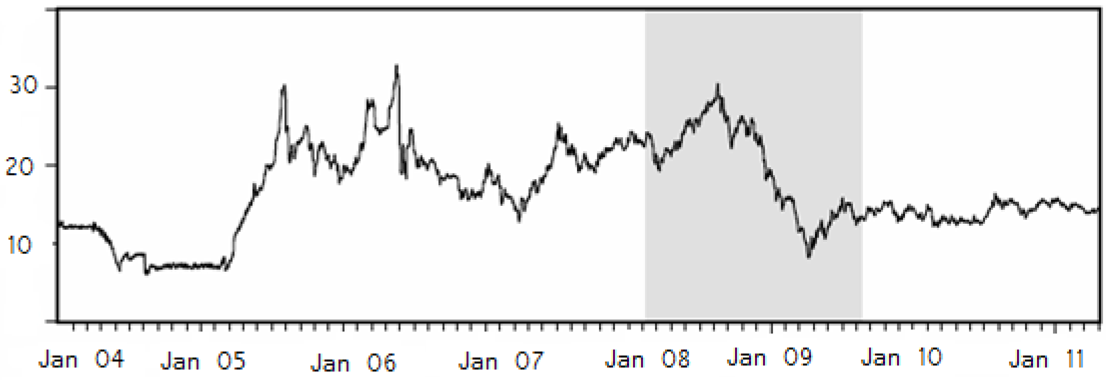
The trend in carbon price shows fluctuation in both markets, as shown in Figure 3.1. The fluctuation is especially more intense between January 2008 to June 2009 (shown using the shaded area in Figure 3.1) than other periods. During this period, prices ranged from \$0.05 to \$7.40 per ton of carbon dioxide (tCO_2) at CCX, and from €8.20 to €30.53 at ECX (or around \$11.50 - \$42.75, assuming an average exchange rate of 1€ = \$1.40). The Augmented Dickey-Fuller (ADF) test statistic values are -1.21 and -2.10 for CCX and ECX price data, respectively, which indicate the existence of a unit root (5 percent critical value is -2.86). As also shown in Figure 3.1, price data do not exhibit stationary properties. Hence, it is helpful to change the price data to return data.

3.3.2 Returns

Table 3.2 shows the basic descriptive statistics for the return data in various time segments, r_t, as specified in Eq. (3.3). The maximum returns for CCX and ECX were 40.55% and 21.17%, respectively, whereas, the minimum returns were -69.31% and -34.04%, respectively. Figure 3.2 shows that voluntary carbon market fluctuated more frequently than the counterpart compliance carbon market at different time horizons. Specifically, the variability of the return during within-recession period (shown using the shaded area in Figure 3.2) voluntary market was more profound than that of the compliance market.



(a) Carbon Price at CCX in US$ per metric ton



(b) Carbon Price at ECX in €per metric ton

Figure 3.1: Carbon Price at (a) CCX in US$ and (b) ECX in €per metric ton.

As shown in Table 3.2, the kurtosis values are significantly higher; they possess more fat-tail than the standard normal value, indicating that returns do not behave like normally distributed random variables. In other words, large observations arise much more frequently than one might expect from a normally distributed variable. The skewness values are negative; their left tails are longer than the normal distribution, and most observations are concentrated on the right-hand side of the distribution. These features suggest that large and negative returns tend to occur more often than large and positive returns (Franses and Dijk, 2000). As shown in Table 3.2, in absolute terms, the minimum returns were higher than

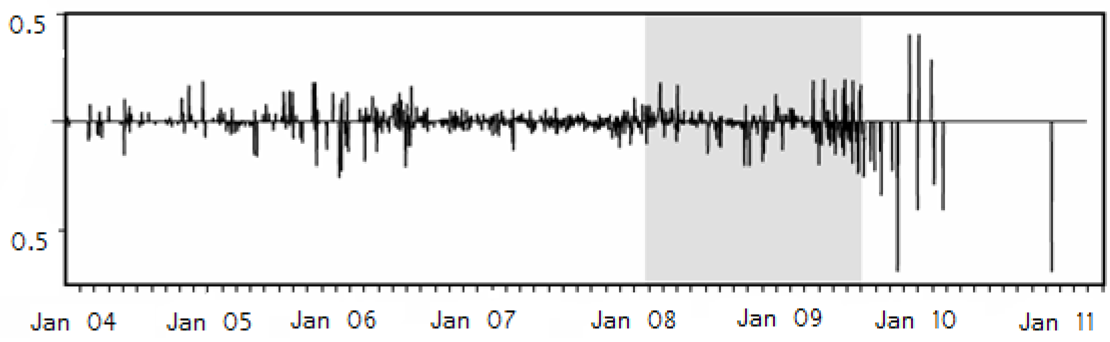
Table 3.2: Descriptive Statistics for CCX and ECX Log returns

	Mean	Max.	Min.	Std. Dev.	Skew.	Kurt.	No. of Obs.
Chicago Climate Exchange (CCX)							
In-sample	0.065	18.90	-25.49	3.58	-0.48	15.23	1020
Out-of-sample	-0.470	40.55	-69.31	6.50	-3.44	45.10	775
Within-recession	-0.197	19.78	-23.64	5.53	-0.28	8.050	380
After-recession	-0.732	40.55	-69.31	7.30	-4.60	52.34	395
All period	-0.166	40.55	-69.31	5.06	-3.33	55.91	1795
European Climate Exchange (ECX)							
In-sample	0.058	21.17	-34.04	3.39	-1.50	21.54	1030
Out-of-sample	-0.058	11.37	-9.43	2.41	-0.09	5.26	795
Within-recession	-0.150	11.37	-9.43	2.89	0.06	4.51	380
After-recession	0.026	4.980	-8.90	1.87	-0.39	4.44	415
All period	0.007	21.17	-34.04	3.01	-1.22	20.60	1825

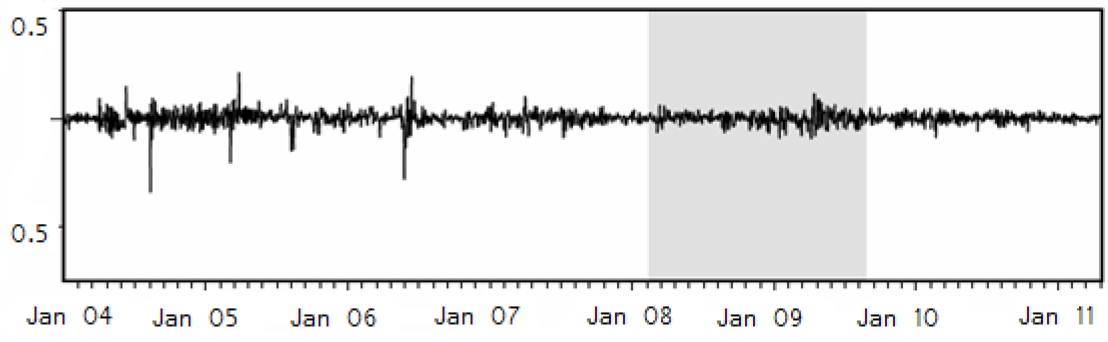
the maximum returns. The ADF test statistic values for the whole data are -40.9 and -43.1 for CCX and ECX return data, respectively, which indicate no unit root. Unlike price, the return data have stationary characteristics that help analyze the volatility of the market and other statistical characteristics.

3.4 Empirical Results and Discussions

The primary purpose of estimating MRS model is to understand carbon price volatility during pre- and post-recession period in voluntary and compliance market using two regimes. In this section, volatility estimate, test for regime switch-



(a) Logreturn at CCX



(b) Logreturn at ECX

Figure 3.2: Daily Log returns at (a) CCX and (b) ECX.

ing, the behavior of volatility and cointegration with other financial markets are discussed in detail.[2]

3.4.1 Estimating Volatility Using MRS

The maximum likelihood method identified by Engel and Hamilton (1990) is used to estimate the parameters, and the results are shown in Table 3.3 for voluntary (CCX) and Table 3.4 for compliance (ECX) market. For all period, the mean returns for voluntary carbon market during both low-volatile regime (Regime 1)

[2]The longer version of this paper includes estimation results from the different families of GARCH models. Model selection criteria, such as Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC), reveal the superior estimating power of Exponential GARCH (EGARCH) with general error distribution (GED). Some results from this model are presented for making comparison with the MRS results.

and high-volatile regime (Regime 2) are statistically insignificant. For compliance market, however, the mean returns for all period are statistically significant for both regimes. Consistent with volatility clustering assumption, negative and positive returns are associated with high- and low-volatile regimes, respectively. Even though some mean returns are statistically insignificant, voluntary market is also characterized by volatility clustering where a negative return is experienced during a high-volatile regime. Unlike compliance market, mean returns for within-recession period for voluntary market are not statistically different from zero.

For voluntary market, the variation in the variance estimate between the two regimes is extremely large for the different periods under consideration. In addition, the variances for the various periods are statistically significant. Considering the data from all periods, the expected lifespan of a given regime is less than a week, and a low-volatile regime remain in market twice more often than that of a high-volatile regime. Within-recession period, however, a high-volatile regime stay longer than any other period under consideration. It can be inferred that an unregulated carbon market has experienced strong but transient volatility.

For compliance market, the variances for the various periods are also statistically significant. The variance for a high-volatile regime is almost seven times that of a low-volatility regime for all period data. In other words, volatility during a high-volatile regime is three times stronger than that of a low-volatile regime. In addition, a low-volatile regime is expected to remain in the market for more than a month, but the lifespan of a high-volatile regime is almost two weeks. During

Table 3.3: MRS Model Results for CCX at Different Period

	In-sample	Within-recession	After-recession	Out-of-sample	All Period
	Voluntary Carbon Market (CCX)				
Mean, μ_i					
Regime 1	0.000	0.000	0.000	0.000	0.000
	(0.002)	(0.006)	(0.003)	(0.002)	(0.001)
Regime 2	0.162	-0.354	-17.93	-1.608	-0.470
	(0.269)	(0.539)	(7.834)	(0.796)	(0.589)
Variance, σ_i^2					
Regime 1	0.002	0.006	0.003	0.002	0.001
	(0.000)	(0.001)	(0.000)	(0.000)	(0.000)
Regime 2	31.94	54.82	989.3	142.6	72.26
	(2.24)	(5.35)	(350.1)	(13.41)	(4.07)
Probabilities					
P_{11}	0.699	0.501	0.963	0.821	0.756
	(0.019)	(0.039)	(0.010)	(0.016)	(0.013)
P_{22}	0.550	0.601	0.125	0.563	0.552
	(0.025)	(0.034)	(0.090)	(0.033)	(0.020)
Exp. Dur.					
Regime 1	3	2	27	6	4
Regime 2	2	3	1	2	2
No. of obs.	1020	380	395	775	1795
Log likelihood	104	-427	806	377	781

Exp. Dur. means Expected Duration.
Standard Error values are in parentheses.

within-recession period, a high-volatile regime remain longer than any other periods. The model also predicts that the volatility for compliance market lingers much longer than the counterpart market.

Moreover, the transition probabilities for compliance market are higher than that of voluntary market. This indicates that a system in either low- or high-volatile regime is likely to remain in that regime for longer period in compliance market. The transition probabilities for voluntary market are relatively small, but statistically significant, which points out that this market fluctuates between low-

Table 3.4: MRS Model Results for ECX at Different Period

	In-sample	Within-recession	After-recession	Out-of-sample	All Period
	Compliance Carbon Market (ECX)				
Mean, μ_i					
Regime 1	0.212	0.327	0.076	0.170	0.153
	(0.083)	(0.135)	(0.096)	(0.076)	(0.061)
Regime 2	-0.619	-0.500	-0.021	-0.360	-0.501
	(0.517)	(0.249)	(0.126)	(0.189)	(0.273)
Variance, σ_i^2					
Regime 1	4.466	2.410	1.422	2.146	3.672
	(0.397)	(0.339)	(0.183)	(0.233)	(0.289)
Regime 2	41.69	12.41	5.461	10.518	27.329
	(7.263)	(1.355)	(0.649)	(1.002)	(3.544)
Probabilities					
P_{11}	0.957	0.963	0.967	0.970	0.968
	(0.012)	(0.020)	(0.018)	(0.011)	(0.008)
P_{22}	0.812	0.970	0.966	0.958	0.888
	(0.062)	(0.018)	(0.019)	(0.016)	(0.030)
Exp. Dur.					
Regime 1	23	27	31	33	31
Regime 2	5	33	30	24	9
No. of obs.	1030	380	415	795	1825
Log likelihood	-1595	-561	-445	-1021	-2643

Exp. Dur. means Expected Duration.
Standard Error values are in parentheses.

and high-volatile regimes more frequent than what one would expect in regulated market. Hence, it can be inferred that voluntary carbon market is more susceptible to changes in economic fundamentals, and reveals more volatility features than the compliance market.

3.4.2 Test for Regime Switching

After finding the estimate for the respective parameters, the next logical step is to test whether there is a regime switching in the stochastic process or not. In this test, the null hypothesis, that returns follow a random walk against segmented trends, is tested using the Wald Test, based on the detailed specification presented in Engel and Hamilton (1990). First, a general null hypothesis, that claims the estimated parameters are identical, is formulated as

$$\begin{aligned} H_o^{'}: \quad & p_{11} = 1 - p_{22}, \\ & \mu_1 \neq \mu_2 \text{ and} \\ & \sigma_1 \neq \sigma_2. \end{aligned} \tag{3.9}$$

The alternative hypothesis is $H_a^{'} : p_{11} \neq 1 - p_{22}$. For $i = 1, 2$, let $v\hat{a}r(\hat{p}_{ii})$ denotes the asymptotic variance of $\hat{p}_{ii}$ and $c\hat{o}v(\hat{p}_{11}, \hat{p}_{22})$ is the asymptotic covariance. Then, under $H_o^{'}$, the test statistics is

$$\frac{[\hat{p}_{11} - (1 - \hat{p}_{22})]^2}{[v\hat{a}r(\hat{p}_{11}) + v\hat{a}r(\hat{p}_{22}) + 2 * c\hat{o}v(\hat{p}_{11}, \hat{p}_{22})]} = \chi^2(1). \tag{3.10}$$

The second hypothesis is identified based on the mean returns and specified as

$$H_o^{''}: \quad \mu_1 = \mu_2. \tag{3.11}$$

This can also be tested using the Wald Test. The test statistics for testing $H_o^{''}$ is given by

$$\frac{(\hat{\mu}_1 - \hat{\mu}_2)^2}{[v\hat{a}r(\hat{\mu}_1) + v\hat{a}r(\hat{\mu}_2) - 2 * c\hat{o}v(\hat{\mu}_1, \hat{\mu}_2)]} = \chi^2(1). \tag{3.12}$$

The 5 percent critical value for a $\chi^2(1)$ is 3.84. The results for these tests are presented in Table 3.5; all statistics are asymptotically $\chi^2(1)$.

Except for one data series, voluntary market during after-recession period, all of the other tests reject $H_o^{'}$ implying that the estimated parameters are different in both low-and high-volatile regimes, as shown in Table 3.5 column (a) and (c). During within-recession period, both markets experienced a certain degree of regime switching. When considering all period for both markets, the result confirms that both markets have undergone through both regimes at different point in time.

Table 3.5: Wald Test for the Null Hypothesis that Returns Follow a Martingale and Equal Mean Return

	CCX		ECX	
	$H_o^{'}$ (a)	$H_o^{''}$ (b)	$H_o^{'}$ (c)	$H_o^{''}$ (d)
In-sample	62.63	0.36	124.3	2.43
	(0.00)	(0.55)	(0.00)	(0.12)
Out-of-sample	105.4	4.08	1631.7	6.31
	(0.00)	(0.04)	(0.00)	(0.01)
With-recession	3.75	0.43	779.8	8.15
	(0.05)	(0.51)	(0.00)	(0.00)
After-recession	0.95	5.24	841.1	0.36
	(0.33)	(0.02)	(0.00)	(0.55)
All Period	169.6	0.64	664.4	5.20
	(0.00)	(0.42)	(0.00)	(0.02)

Asymptotic p values are in parentheses.

For the mean of the two regimes' test, $H_o^{''}$, the results are mixed. Before the recession, we accept the null hypothesis which states that the mean returns for both regimes are not statistically different in both markets. For voluntary market during within-recession and all period, the mean returns for low- and high-volatile regimes are equal, but significant for out-of-sample and after-recession as shown in Table 3.5 column (b) and (d). On the other hand, for compliance market, the mean returns are statistically different in both regimes for out-of-sample, within-recession and all period data.

To test the variation in variance between or among k segments (k segments are in-sample, within-recession, after-recession and out-of-sample) in each regime, the Bartlett test is performed. This test is used to examine the null hypothesis, shown in Eq. (3.13), that k segments from the whole period have equal variances against the alternative, $H_a^{'''}$, that variances are unequal for at least two segments. It can be formulated as

$$H_o^{'''}: \quad \sigma_1^{2(i)} = \sigma_2^{2(i)} = \cdots = \sigma_k^{2(i)}, i \text{ is a regime,} \tag{3.13}$$

where the alternative hypothesis is $H_a^{'''}: \sigma_l^{2(i)} \neq \sigma_m^{2(i)}$ for at least one pair segment (l, m). The test statistics for $H_o^{'''}$ is given by

$$\frac{(N-k)ln(\sigma_p^2) - \sum_{m=1}^{k}(n_m - 1)ln(\sigma_m^2)}{1 + \frac{1}{3(k-1)}(\sum_{m=1}^{k}(\frac{1}{n_m-1}) - \frac{1}{N-k})} = \chi_{k-1}^2, \tag{3.14}$$

where n_m is sample size in k segment; $N = \sum_k^{m=1} n_m$ is the total sample size; σ_m^2 is the variance of k segment and $\sigma_p^2 = \frac{1}{N-k}\sum_m(n_m - 1)\sigma_m^2$ is the pooled estimate for the variance (Snecdecor and Cochran, 1989).

Table 3.6: Bartlett Test for the Null Hypothesis of Equal Variance among Different Periods

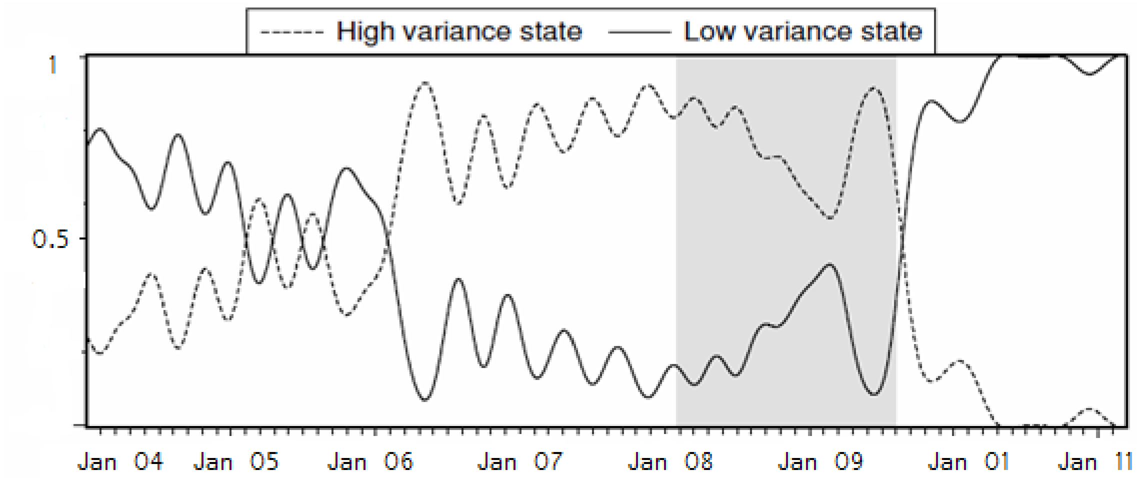
	CCX		ECX	
	$H_o''' : \sigma^{2(i)}_{in-sample} = \sigma^{2(i)}_{within-Recession} = \sigma^{2(i)}_{after-recession}$			
	Regime 1	Regime 2	Regime 1	Regime 2
Bartlett's test	263	2108	182	533
$k = 3$	(0.00)	(0.00)	(0.00)	(0.00)
	$H_o''' : \sigma^{2(i)}_{in-sample} = \sigma^{2(i)}_{out-of-sample}$			
	Regime 1	Regime 2	Regime 1	Regime 2
Bartlett's test	2.53	481	114	375
$k = 2$	(0.11)	(0.00)	(0.00)	(0.00)

Asymptotic p values are in parentheses.

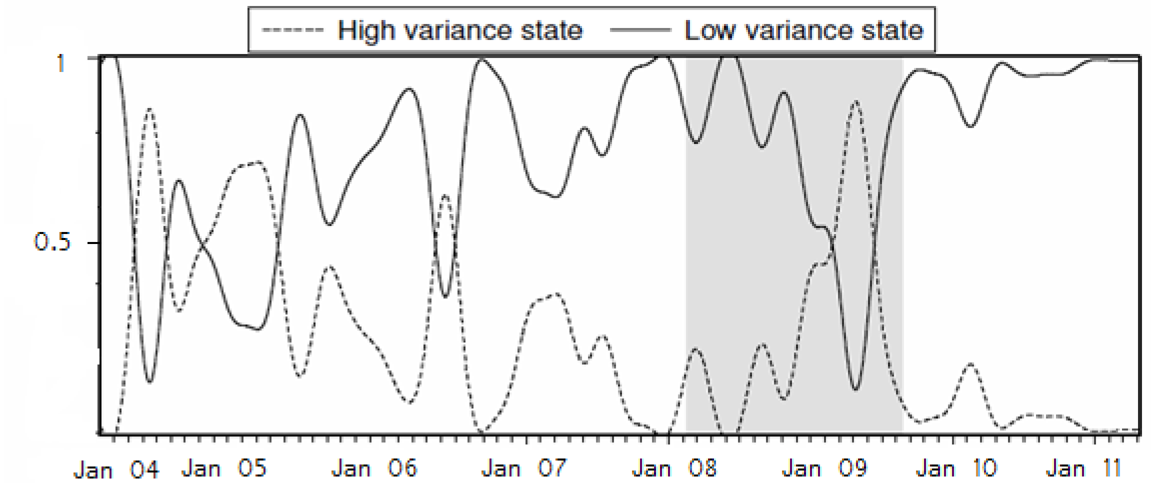
The first result presented in Table 3.6 shows that there are significant variations among in-sample, within-recession and after-recession variances. This confirms that there are significant volatility differences among in-sample, within-recession and after-recession segments. For the second result, except in regime 1 for voluntary market, there are also significant variations in the variances between in-sample and out-of-sample periods. Because of a lower volatility in voluntary market in regime 1, the Bartlett test could not identify whether there is a variation in the volatility between in-sample and out-of-sample periods.

3.4.3 The Behavior of the Volatility

It is already identified that the unregulated voluntary market is more volatile than regulated compliance market. In order to understand the behavior of the prevailing volatility at different points in time, the probability of being at a low- and high-volatile regime is calculated for different periods under consideration, and the result is presented in Figure 3.3.



(a) CCX Market



(b) ECX Market

Figure 3.3: Smoothed Probability of a Low- and High-Variance State for (a) CCX and (b) ECX Markets.

Overall, the probability result indicates that a high-volatile regime in voluntary carbon market is more pronounced than the counterpart market. Specifically, during the entire recession period, there was a high probability for voluntary carbon market to be in a high-volatile regime. In other words, the probability for the occurrence of this regime is greater than 0.5, as shown in Figure 3.3 (a) using the shaded region. It can be inferred that the probability of being at a high-volatile regime is, however, not caused by the recession *per se*. This is because, almost two years before the recession (around January 2006), voluntary market was already in a period of high-volatile regime. Hence, the extreme volatility experienced during within-recession period is a continuation of another high-volatile regime before the recession.

On the contrary, except during a brief period at the end of the recession (from February to April 2009), the probability for compliance market experiencing a low-volatile regime is higher than that of a high-volatile regime, as shown in Figure 3.3 (b) using the shaded region. Like voluntary market, compliance market entered the recession after undergoing relatively high probability of being in a low-volatile regime for almost two years.

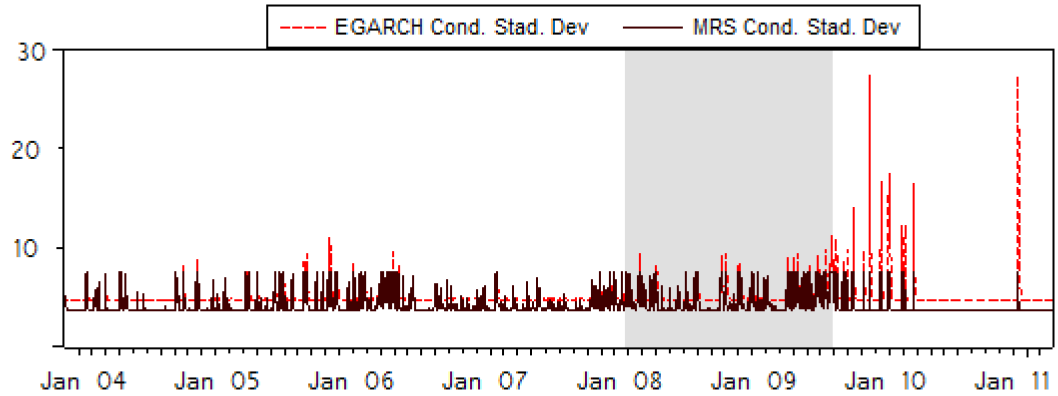
Both markets have undergone stable and low-volatile regimes since the end of the recession. It can also be inferred from Figure 3.1 that these markets experienced stable price trends since the aftermath of the recession (Mid 2009). During the first two years (from January 2004 to January 2006), both markets experienced little persistence of either in a low- or high-volatile regime.

3.4.4 Comparing GARCH and MRS Volatility Estimates

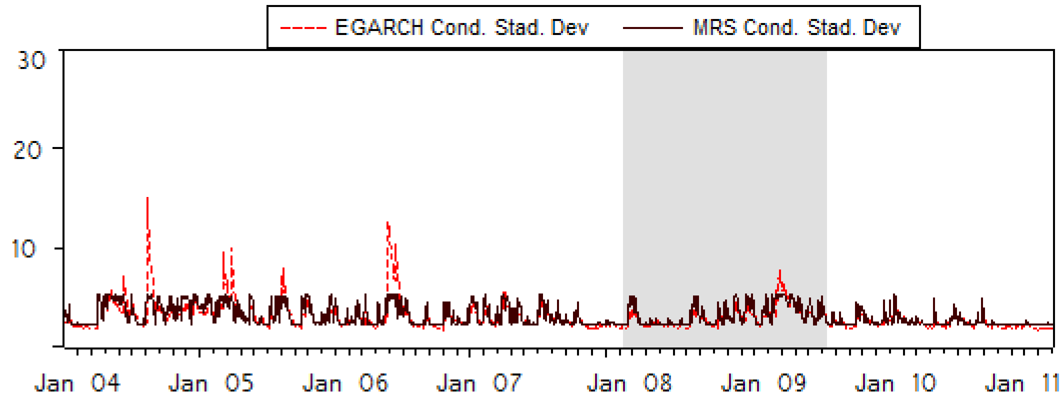
The conditional standard deviation estimate from GARCH model has been widely used to study volatility. For comparison purpose, the results from both GARCH and MRS model is presented in this part. Before the recession, high and sporadic volatility from GARCH model for compliance market is revealed using a relatively smooth volatility from MRS model, as shown in Figure 3.4. For the voluntary market, both models capture almost similar volatility estimate, but at different magnitudes.

During within-recession period, the estimated volatilities from both models for compliance market are similar, except for one occasion. The occasion was a time when the price of carbon in European market reached its bottom low, as seen in Figure 3.1. This is because the recession decreased the overall economic output and then created a lack of demand for carbon credit from large polluting companies.[3] Unlike MRS, the volatility result from GARCH model reveals this significant historical fact in the European carbon market. On the contrary, during this period, the estimated volatilities using both models for voluntary carbon market express a different scope of volatility. Especially at the end of the recession period, GARCH model picks a higher volatility in the voluntary market than the counterpart MRS model. This is consistent with the decreasing price trend observed in Figure 3.1.

[3]Around the same time, *The Guardian* newspaper posted an article about the status of the carbon market in Europe entitled, "A Collapsing Carbon Market Makes Mega-Pollution Cheap"



(a) CCX Market



(b) ECX Market

Figure 3.4: MRS and GARCH Conditional Standard Deviation for (a) CCX and (b) ECX.

After the recession, MRS model reveals a low-volatility regime for voluntary market than GARCH model, yet for compliance market, the volatility from MRS is comparable with that of GARCH model. Overall, the level of volatility estimated using MRS model is lower and more stable than that of GARCH model for both markets. GARCH model reveals some of the most prominent historical occasions in carbon market. For instance, the price of carbon plummeted to US$ 0.05 per

(Glover, 2009). *The Nature* magazine also published an article entitled, "Prices Plummet on Carbon Market" (Schiermeier, 2009).

tCO_2 in voluntary market, as evident from the price data as well as the prevailing volatility expressed using GARCH model.

3.4.5 Cointegration with Financial Markets

In this section, the interaction between carbon and financial markets are analyzed using cointegrating equation. For this purpose, two financial market indices are identified: the Standard and Poor's 500 index (SP500) from the U.S. stock market and FTSE100 Index from London Stock Exchange. The ADF test statistics values are -1.57 for SP500 and -1.80 for FTSE100 and indicate that both indices have a unit root.[4]

Engle and Granger (1987) indicated that a linear combination of two or more non-stationary series may be stationary, and the series are said to be cointegrated. The first step in this process is testing for the presence of cointegration using a method developed by Johansen (1995). Since the main economic agents that are involved in trading carbon credits are multinational companies trading in either stock market platforms, the cointegration test is performed based on the relationship between carbon markets and the two indices.

The test statistics are based on a model with two lags and a constant trend. Table 3.7 presents the test statistics and their critical values for the null hypotheses of no cointegration (a zero maximum rank) and one or fewer cointegrating equations (other ranks). The Eigenvalues are used to compute the trace statistic.

[4]Engle and Granger (1987) and Hamilton (1994) provide detailed specification about formulating the cointegration processes and estimating Vector Autoregressive (VAR) and Vector Error Correction Model (VECM). In this paper, only the results from these formulations are presented.

Table 3.7: Johansen Tests for Cointegration

Maximum Rank	Log Livelihood	Eigen Value	Trace Statistics	5% Critical Value
		CCX, SP500 and FTSE100		
0	-15672	0.02	41.54	29.68
1	-15654	0.002	5.17*	15.41
		ECX, SP500 and FTSE100		
0	-18633	0.019	52.7	29.68
1	-18615	0.008	18.1	15.41
2	-18608	0.002	3.19*	3.76
		CCX, ECX, SP500 and FTSE100		
0	-16974	0.021	59.85	47.21
1	-16955	0.008	21.69*	29.68

*Indicates cointegration at the corresponding rank.

Johansen test strongly rejects the null hypothesis of no cointegration and fails to reject the null hypothesis of at most one cointegrating equation for CCX and two cointegrating equations for ECX. Thus, we accept the null hypothesis that there is one cointegrating equation for CCX and two cointegrating equations for ECX in the trivariate model. With all four markets, there is at most one cointegrating equation. Hence, this test result confirms the existence of a long-run relationship between carbon prices and the performance of financial markets. The performance of both voluntary and compliance carbon markets are interrelated with the performance of the global economic sectors.

Table 3.8: Cointegration Equation Parametric Estimate

	CCX and Indices		ECX and Indices		All Markets	
	(a)	(b)	(a)	(b)	(a)	(b)
CCX	-0.0005	1			-0.0005	1
	(0.0005)				(0.0006)	
ECX			-0.0004	1	0.0003	-3.375
			(0.0007)		(0.0004)	(0.90)
SP500	0.0001	-41.52	-0.0005	14.53	0.0002	-32.80
	(0.001)	(5.74)	(0.003)	(2.35)	(0.0002)	(3.85)
FTSE100	-0.0007	42.29	0.002	-17.51	-0.001	37.92
	(0.0001)	(6.24)	(0.0002)	(2.55)	(0.0001)	(4.68)

(a) is the long-run equilibrium relationship and
(b) is the parameters of the cointegration.
Standard Error values are in parentheses.

The next step is to estimate the long-run equilibrium relationship among these markets and the cointegrating parameters using vector error-correction models (VECMs), as shown in Table 3.8 columns (a) and (b), respectively. The long-run equilibrium relationship between both carbon markets and FTSE100 is significant but extremely weak, as shown in Table 3.8, columns (a). SP500 does not have a significant long-run relationship with both carbon markets. Hence, the performance of regulated and unregulated carbon markets is linked with the European economy where carbon regulation is fully enforced.

The integration among the markets is highly significant and strong, as seen from the parameter of cointegration in Table 3.8, columns (b). Voluntary carbon market is negatively cointegrated with SP500, but positively cointegrated with FTSE100 Index when analyzed separately. Compliance market is positively cointegrated with SP500, but negatively cointegrated with FTSE100. The overall market interaction results in mixed outcomes; negatively cointegrated with SP500 but positively cointegrated with FTSE100. Finally, the interaction between the two carbon markets is not significant.

3.5 Conclusion

The results show that unregulated voluntary carbon market is more vulnerable to the performance of market, and it possesses more volatile features than compliance market. The extreme volatility experienced in voluntary carbon market during within-recession period is, however, a continuation of another high-volatile regime before the recession. The regulated carbon market is in a low-volatile regime during much of the recession period. The statistical tests also confirm that both carbon markets experienced a regime shift at a certain point in time.

The level of volatility estimated using MRS model is lower but more stable than that of GARCH model for both markets. On the other hand, GARCH model depicts some of the most prominent historical occasions in carbon market better than MRS model. In addition, it is confirmed that there is a long-run relationship between carbon prices and the performance of financial markets. Hence, it can be extrapolated that the performance of emission markets are highly cointegrated with the global economic sectors.

This research is based on two regimes, identified as low- and high-volatile regimes. One caveat in interpreting the results is that, the number of regimes is constrained by assumption. For a typical stochastic variable, like carbon price, there could possibly be more than two regimes.

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Chapter 4

Economic Growth and PM10 Pollution: A Nonparametric Environmental Kuznets Curve

4.1 Introduction

Damage to the environment, both in terms of quality and quantity, has recently been experienced to a greater extent than ever before. Acres of forest destroyed; amount of soil and organic matter eroded; number of wildlife lost and extent of biodiversity threatened are part of everyday news around the world (Weber and Kunzelman, 2012). The reduction in air quality, emission of dangerous pollutants, apparent global warming and other environmental confrontations are often mentioned as a result of uncontrolled human interactions with the environment. These interactions are diverse, but most importantly, they are based on the economic activities experienced at different stages of economic development.

More specifically, the accumulation of hazardous agricultural and industrial wastes and by-products, such as Particulate Matter 10 (PM10), is growing at an unprecedented rate in the developing world. This is due to extensive use of agricultural chemicals, machines and equipments that are outdated which release more emissions than the standards; tax and resource incentives to transfer these technologies to developing countries; and less preference and hence lower investment to the environment, to mention a few factors. In this respect, a developing country could hurt the environment on its way to economic development.

As described by Selden and Song (1994), agricultural modernization and industrialization, typical characteristics of the "take-off" stage of development, may initially lead to increased air and water pollution. On the other hand, a host of other favorable factors such as positive income elasticity for environmental quality, changes in the composition of production and consumption, higher levels of education and environmental awareness, and more open political systems would cause an eventual reduction in certain pollutants. As the same time, it is recognized that it is possible to "grow out of" some environmental problems (Shafik and Bandyopadhyay, 1992).

The relationship between economic development, expressed in Gross Domestic Product (GDP) per capita, and environmental quality and quantity has been broadly explored in recent years. This relationship also has an important implication in crafting appropriate joint economic and environmental policy, depending on whether there is a negative or a positive impact of economic development on environmental quality and quantity (Azomahou et al., 2006). One widely applied tool used to understand this relationship is the environmental Kuznets curve (EKC henceforth) hypothesis.[1]

EKC is a *bell*-shaped, or an inverted U-shaped relation between environmental damage or pollution and the status of economic development measured by GDP per capita. It is a systematic relationship between the fortune (GDP per capita) and level of environmental quality or ambient pollution level. The main notion of EKC is that at the initial stage of economic development, pressure on the environment increases until a country reaches a certain level of GDP per capita (usually called a threshold level of income). When the intrinsic values of environmental goods and amenities exceed the value of goods and services they are used to produce, stress on the environment diminishes at a certain pace. In other words, after attaining a certain threshold level of income, effort is given to restore damaged resources and conserve existing amenities.

Despite some exceptions, empirical studies on EKC hypothesis are generally based on ad-hoc parametric specifications with little attention paid to model robustness. The popular parametric functional forms are quadratic and cubic polynomials. In such specifications, the perceived income-environment interactions have been aggregated and averaged to satisfy strict assumptions with minor or no effort to understand each and every interaction as it presides. In addition, different parametric specifications could lead to different conclusions and ultimately

[1]This is a direct analog of Simon Kuznets's work on the relationship between income distribution and the economic fortune of the U.S. (Kuznets, 1955).

inconsistent policy recommendations. In using parametric models, it is apparent that functional misspecification problems are likely to occur.

In recent years, however, nonparametric and semiparametric methods have been introduced for detecting the relationship between environment and economic development (Taskin and Zaim, 2000; Millimet et al., 2003; Bertinelli and Strobl, 2005; Azomahou et al., 2006; Zapata et al., 2008). One essential advantage of these methods is that interaction can be found at the local level, with minimal assumptions and no advance specified functional forms. In addition, the interaction of the occurrence of events (for instance, the likelihood of low GDP per capita and low PM10 level) can be studied by finding a smoothing function with minimal pre-established assumptions. More specifically, a nonparametric model is better for capturing neglected nonlinearities in the data that can facilitate flexibility in analyzing the relationship. Another advantage of this model is that the results can be used to identify appropriate counterpart parametric models.

The paper is organized as follows. Some parametric and nonparametric research studies are reviewed in the Literature Review section. Section 3 has two parts: Econometric Methodology and Data. Nonparametric and semiparametric specifications and model testing procedures are given in the Methodology subsection. The Data subsection illustrates the main data, their descriptive statistics and densities. In section 4, regression estimations are shown, along with the analysis and interpretation of the results. Finally in section 5, a Conclusion summarizes the main findings of the study and the direction of future works.

4.2 Literature Review

The literature on EKC is rather vast; it is possible to mention hundreds of papers, especially in parametric settings.[2] For the purpose of this paper, only some previous studies are discussed briefly. This is by no means an all-inclusive review, and emphasis is given to functional specifications and their results. As mentioned by Dinda (2004), the analogous name for EKC was given by Panayotou (1993). Dinda also provided a survey of EKC in respect to its theoretical development and presented empirical studies dealing with the phenomenon. In addition, he reviewed the underlying principles and intuitions towards EKC hypothesis in terms of, for instance, technological change, international trade and regulation, tax and subsidy incentive.

In response to Club of Rome's "The Limits to Growth" hypothesis (Meadows et al., 1972), Malenbaum (1978) derived an inverted U-shaped relationship between intensity of metal use and income for the first time in a parametric specification. This book is often cited as the first empirical analysis in attempting to find the relationship between resource use and economic development. Since the early 1990s, the advent of data from different sources for a variety of pollutants has helped to test EKC hypothesis.[3]

In their seminal paper, Grossman and Krueger (1991) used comparable measures of three air pollutants in a cross-section of urban areas in 42 countries to

[2] The *Journal of Environment and Development Economics* November 1997 and *Journal of Ecological Economics* May 1998 issues were devoted to EKC.

[3] These data sources include Global Environmental Monitoring System (GEMS), U.S. Environmental Protection Agency (EPA), International Energy Agency (IEA), and Oak Ridge Laboratory.

study the relationship between air quality and economic growth in a random effect model. The main result of this research was that for two pollutants, sulfur dioxide (SO_2) and smoke, the concentration of the pollutant increases at a lower level of GDP per capita, but later decreases at higher levels of income (4,000-5,000, in 1985 US$). A year later, a study by Shafik and Bandyopadhyay (1992) presented earlier research in finding the evidence for EKC using quadratic and cubic models and found that most environmental indicators deteriorate initially. When countries approach "middle-income" levels, however, except for access to safe water and urban sanitation, environmental quality will be initially improved and essentially solved by higher income.[4]

Once more, Grossman and Krueger (1993) studied the effect of GDP per capita on various local environmental indicators. In this time, using random city-specific effect quadratic and cubic models, they found that SO_2 concentrations, suspended particulate matter (SPM), biological oxygen demand, chemical oxygen demand and arsenic in rivers showed an inverted U-shaped relationship. In particular, the estimated GDP per capita turning point for these pollutants was under 8,000 US$ (in 1985 US$). A year later, Shafik (1994) examined the relationship between various environmental quality indicators and income per capita for the period 1960-1990 using a quadratic and cubic parametric model and obtained several results, among them evidence for the existence of EKC for deforestation, SPM, and SO_2.

[4] According to a recent World Bank classification, a country with less than 1,000 US$, 1,000-12,000 US$, and greater than 12,000 US$ per capita national income is categorized as a low-, middle- and high-income country, respectively. http://data.worldbank.org/about/country-classifications.

Again using the data from Grossman and Krueger (1993), Selden and Song (1994) explored the relationship using four air pollutants, SPM, SO_2, nitrogen oxide (NO_x), and carbon monoxide (CO), with a quadratic fixed effect parametric model. They also found evidence for EKC for all four pollutants. Using more data, Holtz-Eakin and Selden (1995) examined the relationship between national carbon dioxide (CO_2) emissions per capita and real GDP per capita for a sample of 130 countries over the period 1951-1986. They used a quadratic polynomial model with a fixed country- and year-specific effects model, and found EKC in terms of the marginal propensity to emit, though the turning income level is higher than expected.

There are also many literatures for country-specific EKC studies. For instance, for the U.S., among other studies, Carson et al. (1997) used a 1990 cross-section of state-level point source emissions for air toxins, CO, NO_x, SO_2, volatile organic compounds (VOC), and PM10, and found that per capita emissions of all pollutants monotonically declined as income increased. Although the research supports EKC hypothesis, they found no relationship between changes in income and per capita emission for air toxins. In addition, List and Gallet (1999) studied the trend for SO_2 and NO_x for the U.S. states using reduced form quadratic and cubic models. They confirmed the initial evidence for an inverted U-shaped that characterized the relationship between per capita emissions and per capita income at the state level, although “They appear to be driven by substantially different processes across states” (Carson, 2010).

Turning to China, Shin and Hashimoto (2004) found that five pollutants (arsenic, chemical oxygen demand [COD], cadmium, SO_2, and dust fall) showed an inverted U-shaped relationship, while the other two pollutants (Mercury and industrial waste stock) showed an N-shaped relationship between pollutant emission and per capita income using cross-province panel data in a cubic parametric fixed-effect model. Recently, Auffhammer and Carson (2008) explored China's per capita CO_2 emission based on unique province-panel data for 1985-2004. Their forecasting result shows that per capita CO_2 emission growth rates was slowing down. This suggested a moderate growth emissions trajectory as income in China increased.

To some extent, critics against EKC are profound in both econometric method and conceptual formulation. For instance, Barbier (1997) disparaged the threshold income level which appeared to be unstable, suggesting that EKC may not show accurate representations of environment-income relationships. In addition, Moomaw and Unruh (1997) compared EKC models to structural transition countries using carbon emissions per capita and GDP per capita and found no correlation. In checking the existence (or nonexistence) of an inverted U-shaped type relationship, a common methodology adopted has been a trial-and-error approach where different polynomial functional forms are estimated to depict a statistically significant fit between some crude measures of environmental performance and per capita income (Taskin and Zaim, 2000). Hayward (2005) also argued that EKC is not statistically robust, that it does not apply to the full range of environmental impacts. When it comes to the basic construction of EKC, it does not include concepts such as carrying capacity and ecological resilience (Rothman and de Bruyn, 1998). These limiting factors deter the wider applicability of EKC in understanding the interactions between economic development and the environment and formulating appropriate policies.

On the other hand, some authors have recently adopted semi- and nonparametric techniques, which do not require a particular functional form to investigate EKC hypothesis. For instance, Taskin and Zaim (2000) employed nonparametric production frontier techniques to study environmental efficiency. One of their findings is that the relationship between environmental efficiency index and GDP per capita displayed an U-shaped followed by an inverted U-shaped. In other words, EKC hypothesis holds only for countries with sufficiently high GDP per capita (more than 5,000 US$).

Millimet et al. (2003) used semiparametric partially linear models for the U.S. states data (1929-1994), and obtained EKCs for SO_2 and NO_x. In addition, they rejected the null hypothesis of the parametric models (a cubic or a piecewise linear spline specification) in favor of more flexible semiparametric alternative. Bertinelli and Strobl (2005) also applied a partially linear model for a panel of countries for 1950-1990, using a fixed effects estimator for SO_2 and CO_2. They discovered a positive relationship between economic development and the environment for low-income countries where the relationship flattens out before increasing again for high-income countries. In a semiparametric setting and using a panel data, Nguyen-Van (2010) investigated the relationship between energy consumption and economic development and found little evidence for EKC. A brief survey on nonparametric EKC can be found at Azomahou et al. (2006). In addition, functional form analysis and specification test using semiparametric and nonparametric models can be found at Zapata et al. (2008).

So far, the parametric and nonparametric results are mixed regarding for and against the support of EKC hypothesis. The critics against the model's limited application to few pollutants (SO_2 and CO_x) is also harsh. Research for PM10 and economic development is rather scant, to the best of our knowledge. On the other hand, the U.S. Environmental Protection Agency (EPA) categorized PM10 as one of the more hazardous local pollutants with a complex mixture of small and large particles of varying origin and chemical composition. Even though PM10 does not have a direct link with global warming and climate change, it is dangerous in terms of the health and well-being of humans and other living organisms. Hence, investigating the relationship between this pollutant and economic growth of countries is worthwhile for policy formulation and development intervention.

To fill the gap, this study is designed to investigate the relationship between PM10 and GDP per capita in a nonparametric method. In the meantime, parametric results are also presented for comparison purposes. Using additional control variables, a semiparametric analysis is presented to show whether or not a nonparametric relationship is affected by including more control variables.

4.3 Methodology

4.3.1 Econometrics Methodology

Pagan and Ullah (1999) stated the potential advantages of nonparametric econometric method in applied research, owing to the method's ability to adapt many unknown features of the data. The method also helps to get smooth representation of the prevailing dynamics within the data. In addition, structural changes in analyzing the relationship can easily be captured by employing appropriate nonparametric methods. An acceptable starting point for analyzing the relationship between GDP per capita (Y_{it}) and the level of PM10 pollution (P_{it}) is to estimate the underlying individual and joint density using the Kernel method. This is because density is important in capturing the stylized facts needed for estimating regression.

Here, the panel data are formed by drawing observations on N countries for T consecutive periods, yielding a dataset of the form $\{P_{it}, Y_{it}\}_{i=1,t=1}^{N,T}$. A Kernel density estimate, $\hat{f}(x)$, for a random variable $X(P_{it}, Y_{it})$ is given by

$$\hat{f}(x) = \frac{1}{NTh} \sum_{i=1}^{N} \sum_{t=1}^{T} K(\frac{X_{it} - x}{h}), \tag{4.1}$$

where $i = 1, \ldots, N$ are countries; $t = 1, \ldots, T$ are years; h is a bandwidth; and X could be pollution, PM10 (P_{it}), or GDP per capita (Y_{it}) for individual density case or both for the case of joint product density, and $K(.)$ is a smoothing Kernel function.

Many methods to estimate nonparametric regression fall into formulation of local constant smoothing (Nadaraya and Watson, 1964); locally weighted scatterplot smoothing (Cleveland, 1979); and local polynomial smoothing (Fan, 1992), to mention a few. In general, nonparametric regression is specified without imposing a specific functional form *a priori* and estimating the unknown parameter of the assumed density function. The specification can be represented by a nonparametric panel data regression model

$$P_{it} = m_t(Y_{it}) + \mu_i + u_{it}, \tag{4.2}$$

where $i = 1, 2, \ldots, N$; $t = 1, 2, \ldots, T$; and $m_t(.)$ is an unspecified smoothing functional form that makes the regression estimate nonparametric. The random effect, u_{it}, is assumed to be *i.i.d* with zero mean, finite variance and independent of Y_{it} for all i and t. In addition, a country-specific effect, μ_i, is allowed to be correlated with Y_{it} with unknown correlation structure which completes the fixed effect specification for Eq. (4.2). Under the assumption of poolability, the functional form can be written as $m(.)$, which does not change over time.

A common empirical approach to eliminate a country-specific effect, μ_i, is to take the first difference of Eq. (4.2).[5] The new specification becomes

$$P_{it} - P_{i,t-1} = m_t(Y_{it}) - m_{t-1}(Y_{i,t-1}) + u_{it} - u_{i,t-1}. \tag{4.3}$$

[5] Jeffrey S. Racine, the leading scholar in nonparametric econometric techniques presents another argument. He states, "When contemplating the nonparametric estimation of panel data models, one issue that immediately arises is that the standard (parametric) approaches that are often used for panel data models (such as first-differencing to remove the presence of so-called fixed effects) are no longer valid unless one is willing to presume additively separable effects, which for many defeats the purpose of using nonparametric methods in the first place (Racine (2009)."

Taking the expectation of Eq. (4.3) and adopting the first difference assumption stated in Azomahou et al. (2006), the error term first difference can be further specified as

$$E[u_{it} - u_{i,t-1} | Y_{it}, Y_{i,t-1}] = 0, \tag{4.4}$$

for $i = 1, 2, \ldots, N$; $t = 2, 3, \ldots, T$; and the remaining equation can be represented as an identity of

$$\Psi_t(\mathbf{Y}_{it}) := E[P_{it} - P_{i,t-1} | Y_{it}, Y_{i,t-1}] = m_t(Y_{it}) - m_{t-1}(Y_{i,t-1}), \tag{4.5}$$

where $(\mathbf{Y}_{it}) = (Y_{it}, Y_{i,t-1})'$.

For estimating the nonparametric model, we follow the procedure described in Azomahou et al. (2006). Let the vector $\mathbf{P}$, with dimension $N(T-1)$, represents the first difference of the dependent variable, PM10, as $P_{it} - P_{i,t-1}$. Let us also assume that $\mathbf{Y}^*$, with a matrix of dimension $N(T-1)X2$, is the first difference of the explanatory variable. Including vector of ones, ι, with dimension $N(T-1)$, let us set $Y = (\iota, \mathbf{Y}^*)$. Let $K_h(.)$ be a bivariate Kernel, smoothing function with bandwidth $h = (h_1, h_2)'$, a smoothing parameter corresponding to y_{it} and $y_{i,t-1}$, respectively. The bandwidth parameter could be determined by ad-hoc, plug-in (two stage) or cross validation methods, depending on the smoothness of the fitted relationship.

The next step is designing the estimation procedure for the item described in the LHS of Eq. (4.5), $\Psi_t(\mathbf{Y}_{it})$.[6] This can be done by formulating a local linear Kernel estimator given by

$$\hat{\Psi}(y_o) = e'(\mathbf{Y}'Z_{y_o}\mathbf{Y})^{-1}\mathbf{Y}^{'}Z_{y_o}\mathbf{P}, \tag{4.6}$$

where $e = (1, 0, 0)'$; and $Z_{y_o} = diag[K_h(\mathbf{Y}^*_{1,1} - y_0), \ldots, (\mathbf{Y}^*_{N,T} - y_0)]$. The Kernel function needs to satisfy some conditions before it is used for smoothing purpose. One of the important features is that Kernel is a density estimator that integrates to one.

The choice of a Kernel is determined by computational cost, simplicity, and the speed of convergence of the density estimator (Pagan and Ullah, 1999). The Kernel in this case is given by standard normal (Gaussian) Kernel. Let $(\frac{Y^*_{it}-y_o}{h}) = \psi$. Standard normal Kernel, $K(\psi)$, can be defined as

$$K(\psi) = (2\pi)^{(\frac{-1}{2})}exp[\frac{-1}{2}(\psi^2)]. \tag{4.7}$$

The rationale for using Kernel regression is that the function gives more weight to observations that are closer to the point of interest, y_o, but the weight is decreasing for further tails within a particular window of bandwidth. The objective of this functional specification is to get a smooth depicting relationship between the two variables in all evaluation points without a particular local or global re-

[6]Once $\hat{\psi}(y_o)$ is obtained, the RHS of Eq. (4.5) or the individual function, $m_t(,)$ and $m_{t-1}(,)$, can be retrieved using marginal integration method described in Linton and Nielsen (1995) and applied by Azomahou et al. (2006). I extend my thanks to Prof. Francois Laisney and his colleagues for providing the Gauss software code.

striction. This is in contrast to, for instance, parametric specification on which quadratic function allows one turning point as a global restriction.

The next logical step is related to the functional form $m_t(.)$ and $m_{t-1}(.)$. A poolability test will be undertaken using a method proposed by Racine (2009). The basic framework of this method is to introduce an unordered categorical variable $\delta_i = i$ for $i = 1, 2, \ldots, N$, and nonparametrically estimate $E(P_{it}|Y_{it}, \delta_i) = \hat{m}(Y_{it}, \delta_i)$ using the mixed categorical method described in Hayfield and Racine (2008). From the result of the nonparametric estimation, it is possible to determine whether the data is poolable or not. Let $\hat{\tau}$ denotes the cross-validated smoothing parameter associated with δ_i. If $\hat{\tau} = 1$, the data is then poolable for estimation. That is $m_t(.) = m_{t-1}(.) = m(.)$, ignoring the time series dimension. If, in another extreme case, $\hat{\tau} = 0$ or close to 0, then the data is nonpoolable and effectively estimated using Eq. (4.5). Finally, if $0 < \hat{\tau} < 1$, one may interpret this as a case in which the data is partially poolable.

In addition, nonparametric consistent model specification test, Li and Wang (1998) test, will be used to check whether or not parametric models (quadratic, cubic, quartic) can be rejected against nonparametric model. The test is based on the residuals of parametric model. The null hypothesis is the first-difference version of parametric models and the alternative nonparametric specification shown in Eq. (4.5). The statistic for this one-sided test has an asymptotic standard normal distribution under the null of correct specification of the parametric model (Azomahou et al., 2006). Finally, the Kernel regression significance test will be performed for a consistence test for the significance of the explanatory variable in a nonparametric regression setting that is similar to a simple t-test in a parametric regression setting. This test is based on Hayfield and Racine (2008) and is given as *np program* in *R* software.

In regards to the explanatory property of GDP per capita, there are, however, other factors related to the level of pollution, along with economic development of a specific country. These factors could have direct and indirect impacts on the interaction between pollution level and economic development. Therefore, following some previous research works and underlying economic theories, we have included few additional controls to investigate how their presence affect EKC hypothesis. The specification presented in Eq. (4.2) is modified to a semiparametric specification with additional controls, Z_{it}. The semiparametric specification becomes

$$P_{it} = m_t(Y_{it}) + \beta Z_{it} + \varepsilon_{it} \tag{4.8}$$

where ε_{it}s are random disturbances, $\varepsilon_{it} = \mu_i + u_{it}$ and $E[\varepsilon_{it}|Y_{it}] = 0$.

Taking the conditional expectation on the level of GDP per capita, Y_{it}, of Eq. (4.8) yields

$$E[P_{it}|Y_{it}, Z_{it}] = m_t(Y_{it}) + \beta Z_{it}. \tag{4.9}$$

The semiparametric estimation can be performed by using a difference-based estimation method, as specified by Lokshin (2006).

4.3.2 Data

Panel data for 160 countries from the period 1991-2005 is collected from different sources. The PM10 country level (the urban-population weighted PM10 levels in residential areas of cities with more than 100,000 residents), the proportion of urban population and the real GDP per capita (in constant 2000 US$) are obtained from the World Bank (The World Bank, 2011). Trade openness (percentage in 2005 constant price) and population data are collected from the Penn World Table 6.3 (Heston et al., 2009). In addition, coal consumption (in million short tons) data are collected from the Energy Information Administration (EIA) and converted to coal consumption per capita for the ease of analysis (EIA, 2012).[7]

Table 4.1: Descriptive Statistics

Variable	Units	Mean	Std. Dev	Min	Max
PM10	$\mu g/m^3$	62	47	7	428
GDP per capita	constant 2000 US$	5,717	8,905	56	51,590
Trade openness	% in 2005 constant price	82	46	10	446
Coal consumption per capita	short ton	1	2	0	15
Proportion of urban population	% of total population	51	23	6	98

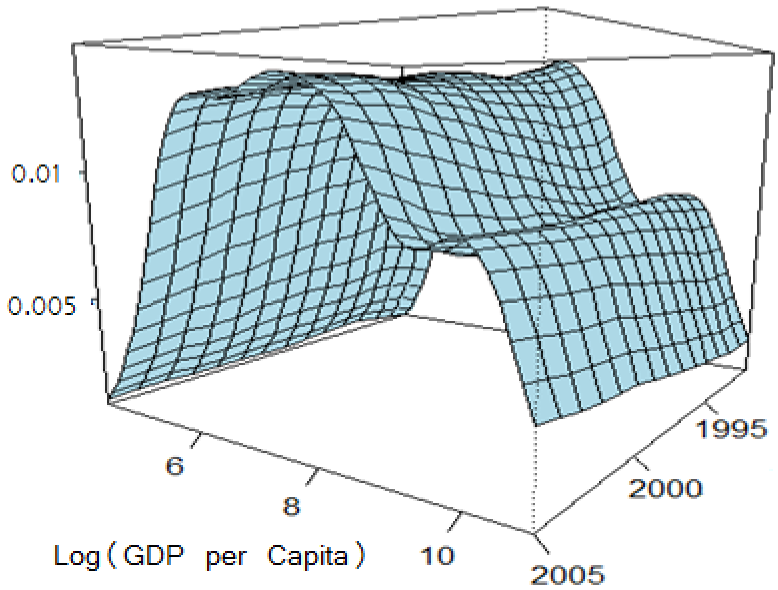
The level of PM10 pollution varies from 7 micrograms per cubic meter ($\mu g/m^3$), the level of pollution in Gabon during 2005, to 428 $\mu g/m^3$, the level of pollution

[7]The principal source of PM10 is transportation service. The data I have for motor vehicle ownership starts from 2003 (The World Bank, 2012). Hence, due to data problem, I couldn't include transpiration in this research.

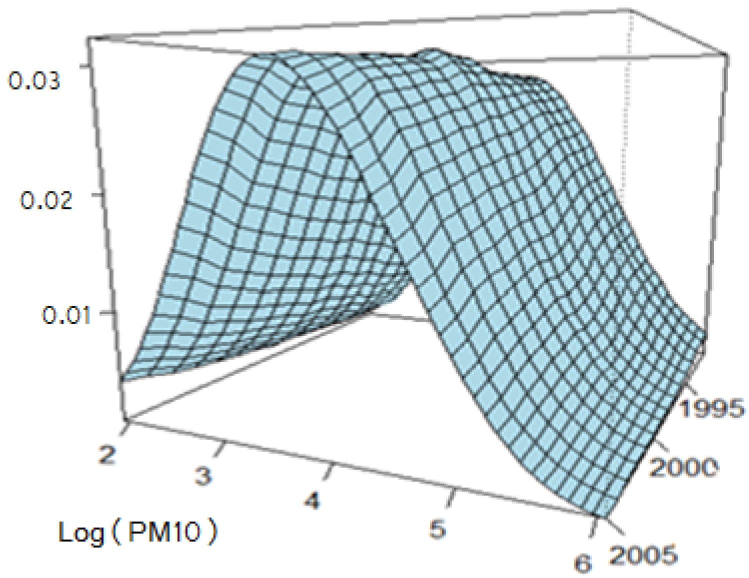
in Armenia during 1991, with a global average of 62 $\mu g/m^3$, as shown in Table 4.1. The maximum pollution level during the recent year (2005), 173 $\mu g/m^3$, was recorded in Sudan. EPA's existing 24-hour PM10 standard is 150 $\mu g/m^3$ (EPA, 2012). Regarding income, GDP per capita varies from $56 (measured in constant 2000 US$ in Liberia during 1995) to $51,590 (in Luxembourg during 2005) with the global average of $5,717 for the period under consideration.

In addition to income-pollution variables, this study includes three controls to improve the explanatory power of the model in a semiparametric setting. Singapore with a trade openness value of 446% is the most open economy, while Estonia (10%) is a very closed economy. The world's average international trade openness measurement is about 82%. The highest coal consumption per capita (15 short tons per capita) was recorded in Estonia in 1992, while the global average for the stated period was around 1 short ton per capita. Finally, 6% of Nepalese, but 98% of Kuwaitis, live in urban areas with the global average of 51% of the world's population living in urban areas.

Kernel density is estimated using second ordered Gaussian, maximum likelihood and fixed bandwidth selection method. In Figure 4.1, the density for GDP per capita and PM10 is characterized by bimodal and uni-modal distribution, respectively. This implies a normal distribution assumption used in parametric estimation is not observed from the income data. Hence, the result from the density indicates that a nonparametric estimation is a feasible alternative for the analysis. It can also be inferred that, since the early 1990s, GDP per capita shows an increasing trend, while the level of PM10 pollution decreases. Furthermore,



(a)



(b)

Figure 4.1: Kernel Density Estimate for (a) GDP per Capita and (b) PM10 for the Period 1991-2005

low-income countries have a higher level of PM10 than the rest income groups.

The proportion of low-income countries is higher than the rest income groups.

4.4 Results and Discussion

First, the nonparametric poolability test specified by Racine (2009) is performed, and the cross-validated smoothing parameter associated with an individual country dummy is calculated. The value of the bandwidth is close to zero (0.00034); hence, the data is non-poolable. That means the given individual countries' variable of interest is not stable over time. Consequently, the unspecified functional form for the nonparametric regression is not generalized using a single setting or constant functional form. As suggested by Baltagi et al. (1996), the Chow test is performed to the parametric fixed-effect model poolability check using data before and after 1998. The calculated F-statistics result equals 215.5. This statistical result is greater than the critical value of 1.645 at 5%. Hence, the Chow test also rejects poolability and confirms the nonparametric results. This leads to a separate functional specification for the nonparametric model over time, and hence $m_t(.) \neq m_{t-1}(.)$.

To avoid a possible specification error, the Kernel regression method specified in Eq. (4.2) and the approach adopted from Hayfield and Racine (2008) are used for estimating the non-pooled data. These procedures also help to capture the underlying systematic relationship between the two variables, which is the point of interest of this paper. The result for the nonparametric regression using local linear regression, continuous second order Kernel and a plug-in bandwidth selection method is shown in Figure 4.2.[8]

[8]Cross validation and ad-hoc methods of bandwidth selection provide a very rough curve. Hence, plug-in bandwidth selection is chosen to represent a smooth relationship between the variables of interest.

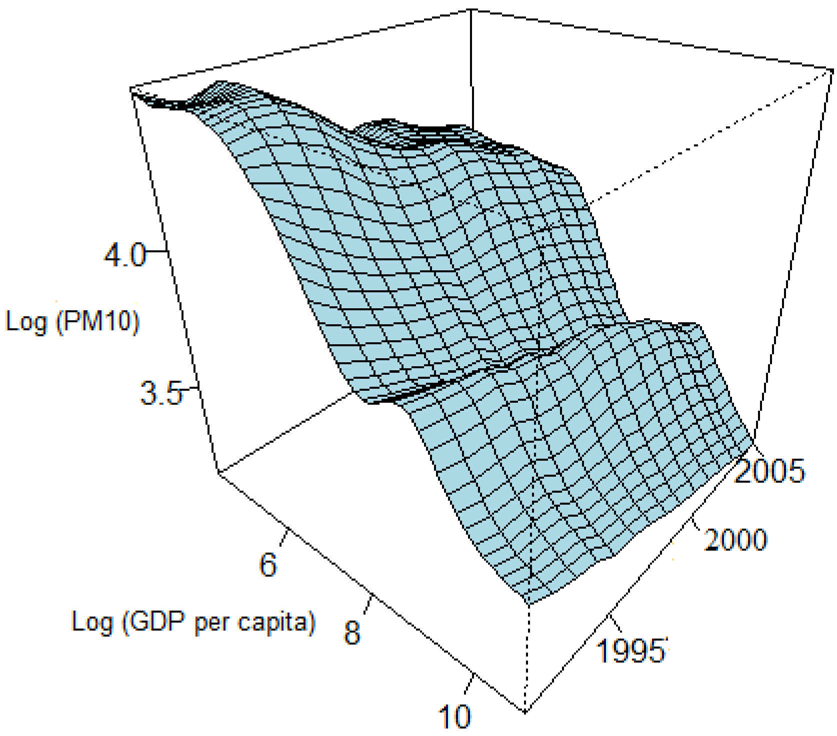


Figure 4.2: Nonparametric (np) Estimation Result, Non-pooled Data

In Figure 4.2, for low-income countries, pollution level increases (or remains constant) until income reaches a local threshold level of around 500 US$. This result is in line with EKC hypothesis. For middle-income countries, however, the pollution level first decreases and later increases until GDP per capita reaches a local threshold income level of 3,500 US$. Hence, EKC hypothesis is partially satisfied for middle-income countries. For high-income countries, the general trend shows that the level of pollution reduces as the level of income increases. Unlike middle-income countries, the result for high-income countries is consistent with EKC hypothesis.

The differences to the usual inverted U-shaped curve are worth noting. It can be inferred from Figure 4.2 that when least developed countries start the process of economic development, the level of PM10 pollution begins to increase, but at a decreasing rate overtime. It is also shown that, on average, the pollution level for low-income countries receded overtime. After reaching around 500 US$ GDP per capita, the pollution level began to ebb at a higher rate than the suggestion of EKC hypothesis. Overall, it reveals the existence of EKC at low GDP per capita, but at an earlier stage of economic development than most previous studies suggested.

The challenge for the complete existence of EKC comes from the result that a continuous decline in the level of PM10 pollution for middle-income countries, GDP per capita around 3,500 to 10,000 US$, is followed by unprecedented pollution increase. As shown in Figure 4.3, for some middle-income and oil-producing high-income countries, the trend for the level of PM10 pollution is exceptionally higher than what is normally expected from EKC hypothesis. More specifically, Middle East oil-producing countries (Saudi Arabia, Bahrain, Kuwait, and United Arab Emirates) and South American countries (Argentina and Uruguay) have higher levels of pollution than countries with comparable income groups.[9]

Finally, the local maximum PM10 level is reached when GDP per capita is around 10,000 US$. Afterward, the level of pollution decreases for high-income countries, which verifies the existence of EKC hypothesis. These results are also confirmed after finding the 95% confidence interval for nonparametric regression using non-pooled data (the result is not shown here). Therefore, the existence of EKC is partially accepted for low- and high-income countries in nonparametric

[9]Countries identified in numbers (with their 2005 GDP per capita in 2000 US$) are 1) Uruguay ($6,548), 2) Oman ($9,930), 3) Saudi Arabia ($9,864), 4) Trinidad & Tobago ($9,309), 5) Argentina ($8,094), 6) Bahrain ($14,776), 7) Kuwait ($20,577), 8) United Arab Emirates ($25,376), 9) China ($1,451), and 10) the United States ($37,084).

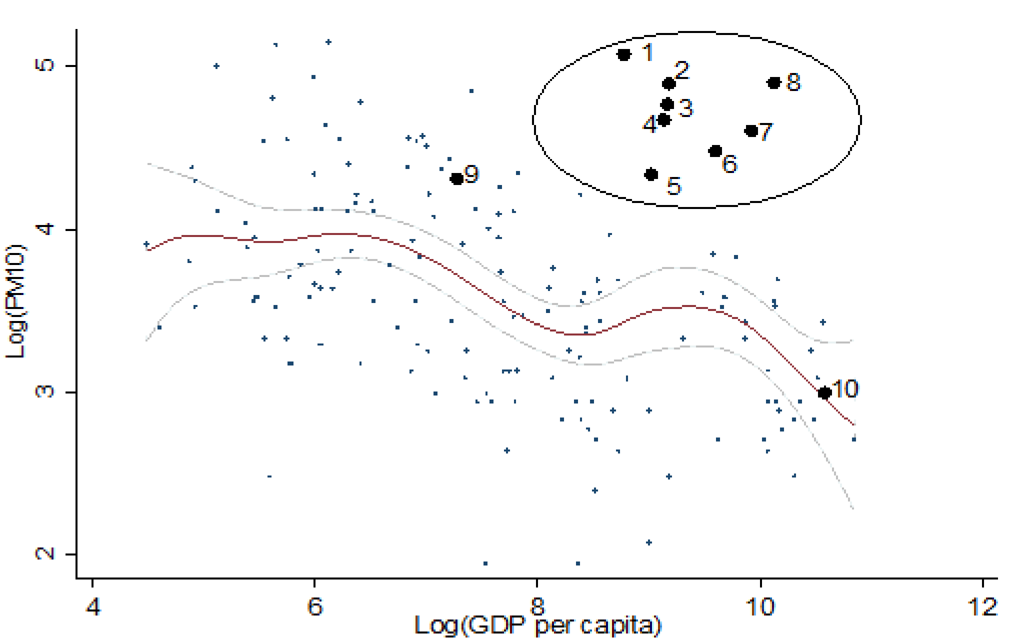


Figure 4.3: Nonparametric (np) Estimation Result, 2005 Data

specification with non-pooled data. The pattern of the graph can be expressed as a loose M-shape instead of an inverted U-shape. Therefore, it can be inferred from the results that economic development and the level of pollution have an inverse relationship, with few exceptions.

Even though the poolability test rejects the possibility of pooling the data, the results in Figure 4.2 and the density in Figure 4.1 show a consistence in maintaining the structure of the relationship over time. More specifically, the stability of density over time can help to capture the pooled relationship, if there is any. Hence, as specified in Eq. (4.7), nonparametric and parametric fixed-effect models will be analyzed to further verify the existence of EKC hypothesis using pooled data. This also helps to facilitate the Li and Wang (1998) significance test. In addition, Figure 4.2 implies the possibility of specifying the relationship between

GDP per capita and the level of PM10 pollution using cubic or quartic (polynomial of root 4) parametric specification. The result for pooled nonparametric regression is shown in Figure 4.4.

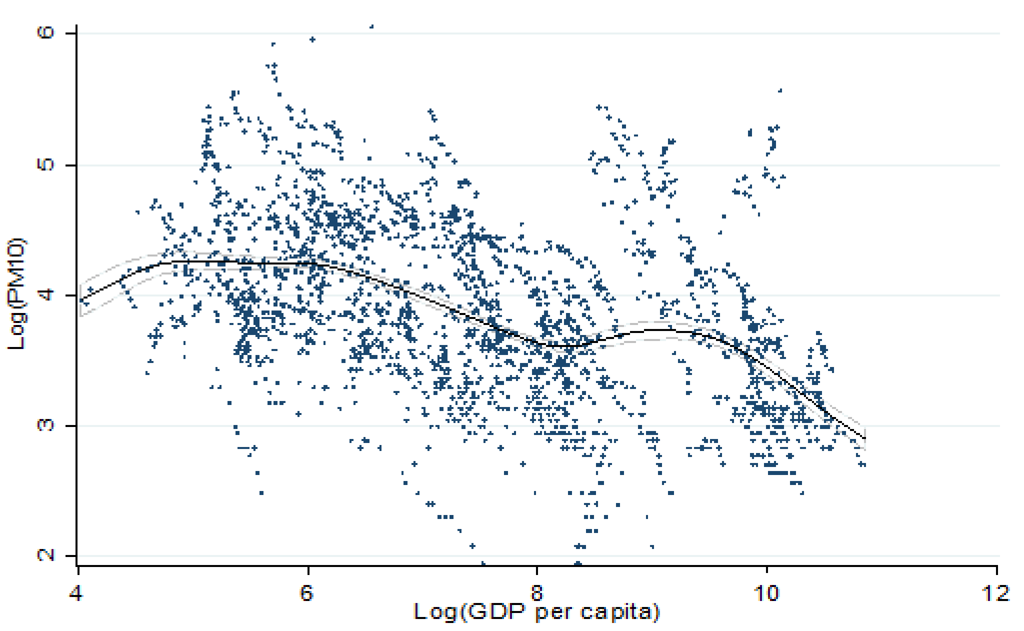


Figure 4.4: Nonparametric (np) Estimation Result, Pooled Data

As shown in Figure 4.2 and Figure 4.4, the results for non-pooled and pooled data, respectively, present more or less identical results for low-income countries, with GDP per capita less than 500 US$. Figure 4.4 is considered as a smooth replica of Figure 4.2 with small increase in the level of pollution for middle-income countries. In Figure 4.4, however, the level of pollution in middle-income countries reveals a complex trend. The pooled data represents a relatively smoother EKC than the panel data, but both results imply an identical relationship.

As implied in Figure 4.2 and Figure 4.4, a counterpart parametric regression can be inferred from the two results. The result of the parametric specification is shown in Table 4.2 and Figure 4.5. The within fixed-effect model result confirms that the systematic relationship relation can be expressed using a cubic parametric model. In addition, using BIC, AIC and $\bar{R} - square$ values (commonly used as parameter for model selection) shown in Table 2, the first-difference parametric specification can better express the systematic relationship. Graphically, as shown in Figure 4.5 both the within (the solid line) and the first difference (dashed line) have similar patterns that support the hypothesis of EKC, except for the extremely high income countries.

Table 4.2: Parametric and Nonparametric Estimation Results with Pooled Data

Variable	Nonparametric	Within		First-difference	
		Coeff.	t-stat.	Coeff.	t-stat.
		(1)		(2)	
Linear term		1.265	2.17	2.170	6.08
Quadratic term		-0.200	-2.55	-0.332	-5.96
Cubic term		0.009	2.61	0.015	5.74
F-value		$F(3, 2396) = 180$		$F(3, 2236) = 218$	
Probability		0.0		0.0	
$\bar{R}$-square	0.268	0.184		0.226	
AIC		-2394.5		-713.7	
BIC		-2424.9		-2266.9	
No. of Obs.	2240	2400		2240	

The statistical results for both nonparametric and parametric regression are shown in Table 4.2. All the regression coefficients for both models are statistically significant.[10] In addition, the goodness-of-fit for nonparametric panel regression is 26.8%, whereas that of the cubic fixed-effect and first-difference parametric models is 18.4% and 22.6%, respectively. To compare the results with previous studies, the quadratic parametric result is also shown in Table 4.2. By all standards, the quadratic parametric specification is not desirable as compared to both the nonparametric and the parametric cubic specification.

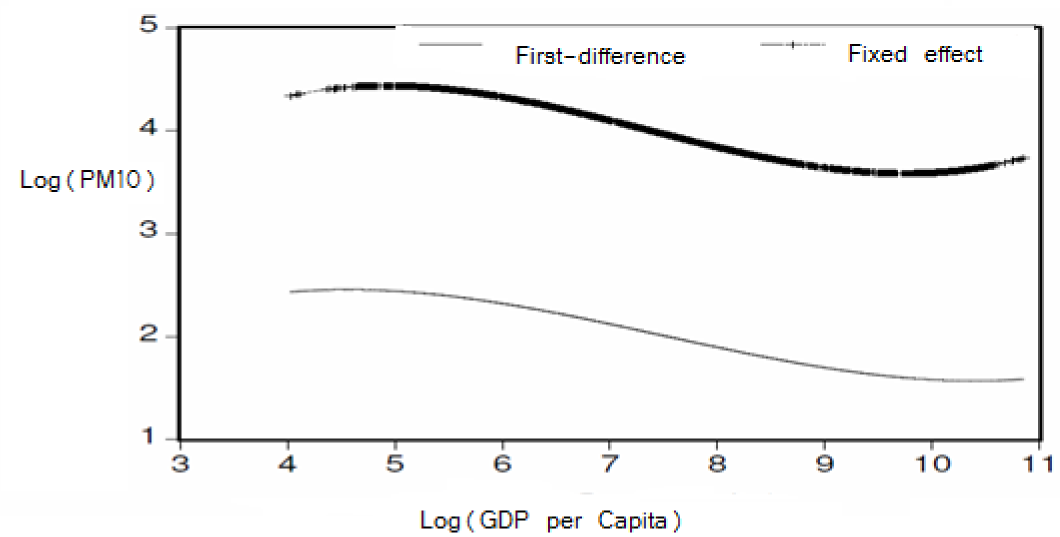


Figure 4.5: Parametric Estimation Results with Pooled Data

Moreover, the nonparametric regression significance test described in Hayfield and Racine (2008) was performed using GDP per capita as an explanatory variable. It is found that the independent variable is significance at all conventional levels (where $p < 0.0001$) for the local linear nonparametric model. The nonparametric model consistence specification test, the Li and Wang test, results for quadratic and cubic models are 41.0 and 41.2, respectively. These results reveal that the

[10]The Hausman test result, ($prob > \chi^2 = 0.000$) , is significant, and the fixed-effect model is chosen for parametric specification.

null hypothesis of correct parametric specification is rejected for both quadratic and cubic models. In general, these results show that the nonparametric model is better than the parametric specifications for studying the systematic relationship between the level of PM10 pollution and GDP per capita.

As mentioned earlier, EKC itself reflects an unconditional account of how pollution level changes with the level of economic development of a country. To the same extent, different economic and non-economic factors could affect the level of pollution as a country progresses toward development. Since a seminal work by Kraft and Kraft (1978) on the relationship between energy and GDP, one nexus of EKC work is devoted to the interaction between economic growth and the environment. One of the controls designed to investigate the interaction in this research is coal consumption per capita where PM10 is its main by-product.

In this study, coal consumption per capita, that is, a country's total coal consumption divided by the total population at a given time, is used as a control in a semiparametric setting. The result is shown in Figure 4.6 and Table 4.3 (Model 1). The inclusion of coal consumption per capita improves the smoothness in portraying the relationship between PM10 and GDP per capita and supports the existence of EKC hypothesis. Another important finding in this case is an inverse but significant relationship between coal consumption per capita and the level of PM10 pollution, as shown in Table 4.3 (Model 1). Hence, it can be inferred that coal consumption per capita is not associated with a higher level of PM10, which goes against the results of most research and the claims of most environmentalists (Guo et al., 2008).

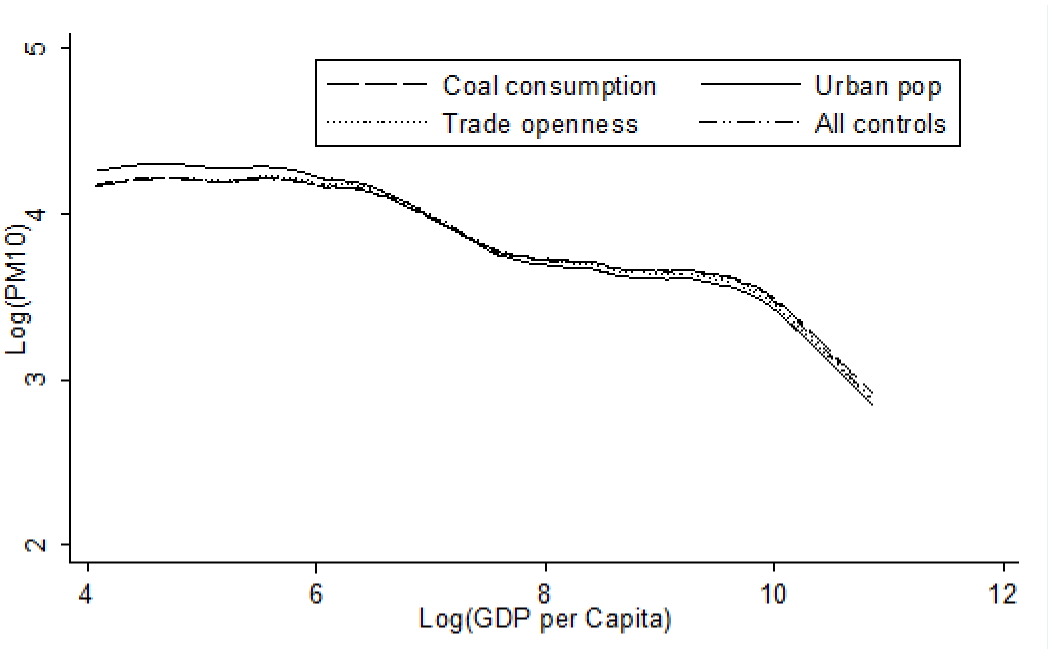


Figure 4.6: Semiparametric Estimation Result

The other control is country's openness to international trade (Frazer, 2006). The effect of trade openness on environmental quality has attracted the attention of policy makers. Since the original work of Grossman and Krueger (1991), such effect has been dealt with different settings and institutional frameworks. For instance, Dinda (2004) stated that international trade is an important factor that explains EKC. Managi et al. (2009) investigated whether or not trade improves environmental quality and found that the beneficial effect varies depending on pollution and the country under study. For instance, trade is beneficial in improving the environment for OECD countries. In this research, as shown in Figure 4.6 and Table 4.3 (Model 2), the level of pollution decreases as trade openness increases. This is relatively similar to the finding that trade openness exhibits a negative, but statistically significant relationship with pollution (Cole, 2004).

It is also widely recognized that the level of PM10 pollution is mostly ubiquitous in urban areas. Various economic activities of urban population (such as vehicle exhaust) are among the major sources of PM10. As seen in Table 4.3 (Model 3), there is a direct but insignificant relationship between the proportion of urban population and PM10.

Table 4.3: Semiparametric Estimation Results for Linear Coefficients

Controls	Model 1		Model 2		Model 3		Model 4	
	Coeff.	st.err	Coeff.	st.err	Coeff.	st.err	Coeff.	st.err
Coal consumption per capita	-0.067	0.01					-0.072	0.01
Trade openness			-0.130	0.03			-0.138	0.03
Proportion of urban population					0.052	0.04	0.051	0.04

Finally, the result of the semiparametric regression with all the control variables is shown in Figure 4.6 and Table 4.3 (Model 4). It has all the features of individual semiparametric results, the inverse relationship between the level of PM10 pollution and coal consumption per capita and trade openness while a positive but statistically insignificant with proportion of urban population. Overall, including individual or all controls in the estimation improves the smoothness of the curve and support the existence of EKC hypothesis.

4.5 Conclusion

One of the main findings of this paper is the existence of partial relationship between GDP per capita and the level of PM10 pollution for low- and high-income countries. This, in turn, means that EKC hypothesis is partially accepted, in the sense that some middle-income countries have higher levels of PM10 that hinder the systematic relationship to become more complete. The significance tests reveal that quadratic and cubic parametric specifications, widely used in previous studies, are not suitable for the relationship between PM10 and GDP per capita. Nonparametric methods provide statistically better estimates for the relationship between GDP per capita and PM10, and support the existence of EKC more formally than cubic counterpart. Adding more control variables in the semiparametric setting improves the shape of the relationship toward supporting EKC hypothesis.

When it comes to the extent of economic growth and pollution, the first assumption that least developed countries start to pollute environment when they begin economic growth is found to be a valid assumption using nonparametric analysis. After reaching about $500 GDP per capita, however, the trend toward releasing more PM10 pollution decreases. This phase is followed by increased pollution level for some middle-income countries, which is the main reason for partially accepting the hypothesis. That means that in the nonparametric analysis, there are two maximum turning points, one for the global at a lower GDP per capita and one for the local at a higher GDP per capita income level.

Poolability test rejects the possibility of pooling the data. Hence, one of the caveats for interpreting the results is on the impact of poolability on the nonparametric relationship between pollution level and GDP per capita. Future research will be design to check poolability assumption and test using other pollution data. In addition, more investigation will be undertaken to reconcile poolability and density estimate, where density results indicate a smooth poolability of data across different time. One of the limitation of this research is that the principal source of PM10, transportation, is not included in the study due to lack of data.

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Chapter 5

Concluding Remarks

The major contributions of this dissertation to economics, in general, and to environmental and resource economics literature, in particular, are summarized in this section. In addition, the direction for future research is proposed for each study.

For water allocation and management study, for the first time, we propose an alternative approach of "allocate-and-trade." Water trade signifies the "second-best" alternative option with the objective of improving the welfare value of a basin. Almost all of the outcomes of the efficient allocation can be recovered through introducing water trade and facilitating a cost-effective transfer payment among riparian countries. This is supported by the Second Fundamental Theorem of Welfare Economics; efficient outcome could be sustained through competitive equilibrium along with transfer payment.

In today's Nile River water hydropolitics which is characterized by the 1959 bi-lateral allocation, the existence of an inefficient allocation system complicates the management of the resource base. To take advantage of the water trade that addresses regional water allocation and management, establishing a basin institution is a prerequisite. A possible role for the NBI could be to centralize planning, to administer water rights arrangements, and to redistribute side payments that arise from water trade. The other valuable insight is that the basin's welfare could be increased through Nile River water demand management practices such as decreasing evaporation loss, improving irrigation technology and increasing hydropower production efficiency. Evaluating the potential Pareto improvement from water demand management practices, engaging in hydropower and agricultural output trade and introducing damage function to study externalities will be part of future research.

For price volatility study, we found that at different reference points in time, carbon markets react differently to known and unknown shocks. This paper characterizes the behavior of carbon price and its volatility in reference to the 2008/09 recession. MRS model has more attractive features in identifying the different processes in the market, for instance, identifying a low- and high-volatile regime than the commonly used GARCH models. Moreover, MRS model helps to understand carbon price volatility during pre- and post-recession period in the voluntary and compliance market using two regimes.

As a policy implication, establishing a regulatory framework leads to a stable market that assists in predicting the performance of the market at different periods in the business cycle. Future research will include identifying factors that affect carbon demand and supply, estimating the equilibrium carbon price and forecasting carbon market performance based on the overall economy.

Finally, for application of nonparametric econometrics, one of the main findings is the partial relationship between GDP per capita and the level of PM10 pollution for low- and high-income countries. Hence, a policy designed to reduce the level of PM10 pollution must emphasize middle-income countries, more specifically oil-producing countries. In addition, in absolute measurement, the level of pollution in low-income countries is higher than both middle- and high-income countries. Hence, development intervention and economic growth policies can be designed to address the problem of pollution in low-income countries. This is because the cost of taking action now is less than doing it later.

Future research will be undertaken by adding more control variables, such as population density, proportion of agricultural and industrial sector in the economy, proportion of car ownership and public transport coverage. In addition, policy formulation and the impact of regulation on the behavior of EKC will be investigated. Technically, the issue of poolability needs more analytical and empirical analysis in formulating the systematic relationship between GDP per capita and pollution level.