Incentives in the water chain:
Wastewater treatment and reuse in developing countries

Michael F. Gengenbach

Thesis committee

Thesis supervisor

Prof. dr. E.C. van Ierland
Professor of Environmental Economics and Natural Resources
Wageningen University

Thesis co-supervisor

Dr. H.-P. Weikard
Associate Professor, Environmental Economics and Natural Resources Group
Wageningen University

Other members

Prof. dr. R. Brouwer, Free University Amsterdam
Prof. dr. W.J.M. Heijman, Wageningen University
Prof. dr. ir. J.G.A.J. van der Vorst, Wageningen University
Prof. dr. C. Withagen, Free University Amsterdam

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Thesis

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Abstract

The proper management of wastewater and its reuse is crucial in order to reduce hazards and maintain a variety of benefits. The merits of improvements in wastewater management are particularly high where effective wastewater treatment is not in place and completely untreated wastewater is reused. This setting applies to many developing countries. There is a need to study the trade-off between benefits and costs of the use of wastewater to establish efficient water management. Moreover, successful water management needs to take the individual incentives of stakeholders into account. The general objective of this thesis is to study how economic incentives of stakeholders determine welfare along the water chain of use, treatment and reuse and how these incentives can be regulated in order to maximize welfare. This thesis identifies four characteristic settings in which either asymmetric information or externalities cause welfare losses, at least in the absence of regulation. For each setting the thesis develops a game theoretic model that can be used to design incentive schemes that govern the generation, treatment, and reuse of wastewater in developing countries such that the highest possible welfare is obtained.

Chapter 1
Introduction

The proper management of wastewater and its reuse is crucial in order to reduce hazards and maintain a variety of benefits. The merits of improvements in wastewater management are particularly high where effective wastewater treatment is not in place and completely untreated wastewater is reused in irrigation because this introduces health hazards into the food chain. This setting applies to many developing countries. Concerning effective wastewater treatment, the 2000 WHO Global Water Supply and Sanitation Assessment Report states that the median percentage of effectively treated urban wastewater is zero for Africa, 35% for Asia, and 14% for Latin America and the Caribbean (WHO 2000 p.19). Concerning the reuse of wastewater in irrigation, Drechsel et al. (2006) report that in most West African cities, 60-100% of the consumed vegetables are produced in urban and peri-urban areas which are mainly irrigated with wastewater. Hence, it can be concluded that it is particularly important to improve wastewater management in developing countries.

The discharge of untreated or poorly treated wastewater into surface waters causes health hazards to the local population and environmental damages. Health hazards stem from excreta-related pathogens, vector borne diseases and chemicals (WHO 2006b) which threaten the wellbeing of consumers if they enter the food chain via wastewater irrigation (Seidu et al. 2008). Furthermore they threaten people who have direct contact to the polluted water, like workers on farms irrigating with wastewater and residents who live close to polluted surface waters (WHO 2006a p.9). Srinivasan and Reddy (2009) for example find higher morbidity rates in wastewater irrigated villages compared to control villages. Wastewater discharge brings about environmental hazards which result in costs through reduced productivity of the downstream environment. An example is how saline wastewater reduces soil productivity (Halliwell, Barlow and Nash 2001).

Besides damages, the availability of untreated or poorly treated wastewater also generates benefits for agricultural production. Four features of wastewater irrigation are particularly beneficial. First, wastewater irrigated agriculture can be conducted all year long because wastewater is steadily available (Raschid-Sally, Carr and Büchler 2005). This is an important advantage over rain fed agriculture and fresh water irrigation by means of surface water in areas with seasonal differences in water availability. Second, wastewater irrigated agriculture is conducted close to wastewater sources. It can therefore increase the supply of fresh vegetables in urban areas which otherwise would need to be transported from longer distances with negative effects on quality as refrigeration equipment is scarce (Keraita 2007). Third, wastewater contains nutrients which serve as substitutes for artificial fertilizer. In this context Ensink, Simmons and van der Hoek (2004) found that in Pakistan wastewater is sold at a higher price than fresh water when used for irrigation. Forth, when properly managed, wastewater irrigation becomes a low cost wastewater treatment step (Huibers and van Lier 2005). These benefits have the potential to reduce poverty as can be observed in urban and peri-urban agriculture (Graefe, Schlecht and Buerkert 2008).

In order to achieve the welfare optimum, the benefits and costs of the use of untreated wastewater have to be traded off efficiently. When costs dominate benefits, one option is to reduce or prohibit the use of wastewater. The latter is a drastic measure which is usually not efficient, sometimes not even feasible because it threatens livelihoods of poor people who depend on the use of wastewater (Drechsel 2008). Another option to achieve the welfare optimum is to apply wastewater treatment. Full treatment is generally not optimal because it removes the benefits from saved treatment costs and nutrient substitute. Partial wastewater treatment, however, can be applied to optimally reducing damages and maintaining benefits.

Wastewater treatment requirements for reuse have been addressed by different guidelines. The State of California for example established guidelines which are based on a 'zero risk' concept (State of California 1978). The World Health Organization on the other hand established guidelines which are based on less strict safety requirements. The "Health Guidelines for the Use of Wastewater in Agriculture and Aquaculture" (WHO 1989) define maximum acceptable concentrations for a variety of pollutants depending on the use of the wastewater in agriculture in order to reduce health risks to an acceptable level. Compliance with the WHO guidelines can be achieved with partial wastewater treatment which can usually be done by low cost treatment technologies.

The 1989 WHO guidelines failed to be effectively implemented, however, in many developing countries. This indicates that the guidelines require a treatment level which does not balance costs and benefits optimally. It was concluded that the guidelines were too strict for many developing countries rendering more flexible guidelines necessary. "There exists a complex relationship between urban return of wastewater and its irrigation use in peri-urban areas. A proper evaluation of various types of externalities is required to take policy measures which would maximise positive externalities. In other words evaluation of various externalities is very important to determine the economically and socially optimum level of wastewater discharge and treatment, and also the types of uses to which it can be put into safely" (Srinivasan and Reddy 2009).

The WHO reacted to this by revising their guidelines. The 2006 "WHO Guidelines for the Safe Use of Wastewater, Excreta and Greywater" (WHO 2006a) recommend that countries define individual health-based targets by applying the Stockholm Framework (WHO 2006b) which is an integrated approach that combines risk assessment and risk management to control water related diseases. The targets should be achieved by managing risks at different barriers along the entire chain - from wastewater generation to consumption of produce cultivated with wastewater. This allows national authorities to develop their own regulation which is in line with national socio-economic realities. Each country can implement individual solutions for the treatment and reuse of wastewater such that its benefits and costs are balanced optimally.

Identifying and implementing country- or region-specific solutions comprises two tasks. First, technical facilities which provide the appropriate wastewater treatment level need to be designed. Technical facilities cannot operate successfully, however, when the incentives of stakeholders do not support their viable operation. Hence, the second task is to design an institutional setting in which the technical facilities can be operated effectively. This requires a complementary incentive scheme that brings the incentives of stakeholders in line with effective wastewater management. To achieve this it is necessary to understand the complex behavioural pattern which emerges from strategic interaction between a large variety of stakeholders along the water chain of use, treatment and reuse. Asymmetric information and externalities make this interaction even more complex.

The general objective of this thesis is to study how economic incentives of stakeholders determine welfare along the water chain of use, treatment and reuse and how these incentives can be regulated in order to maximize welfare. This thesis identifies four characteristic settings in which either asymmetric information or externalities causes welfare losses in the absence of regulation. For each setting the thesis develops a game theoretic model that can be used to design incentive schemes that govern the generation, treatment, and reuse of wastewater in developing countries such that \ the highest possible welfare is obtained.

The remainder of the introduction is organized as follows. The next section presents a short overview over the relevant literature to the topic. Special focus is on non-cooperative game theory. Section 1.3 states the general objective of this thesis. Furthermore it presents the specific settings along the water chain with their corresponding research question which are answered in the following 4 chapters. Section 1.4 describes the methodology to answer these research questions and points out the novel contributions to the literature. Lastly, section 1.5 presents the overall organization of the remaining chapters.

1.1. Wastewater treatment and reuse in the literature

In this section I provide an overview over the development in managing wastewater over the last 30 years by means of a short literature review. Until the beginning of the 1990s management of water resources which includes wastewater treatment was mainly a technically dominated issue in the engineering domain. De Mello (1994) provides a literature review. With respect to the topic of this thesis, the economics of reuse of wastewater in irrigation, little work has been done before the mid-1990s. Moore, Olson and Marino (1985) provide a detailed assessment of the on-farm economics of reclaimed wastewater irrigation in California. Dinar and Yaron (1986) analyze the optimal treatment of municipal wastewater before its reuse in irrigation. Haruvy and Sadan (1994) provide a nation wide cost and benefit analysis for Israel. Haruvy et al. (1999) determine monthly optimal treatment levels and of the mix of crops calculated to maximize agricultural incomes, according to farmers' point of view. Game-theoretical approaches are discussed below.

As a result of the technically dominated approach to water management many facilities were designed solely according to engineering considerations. Many of these facilities proved to be unsuccessful in their operation. This was particularly observed in developing countries. As a response to this observation a new approach, the Integrated Water Resources Management (IWRM), was developed in the 1990s. It integrates economic, social, ecological, and legal considerations into the engineering design process. Solutions have to be not only technically efficient but also feasible from an economic, social, ecological, and legal point of view. Among the huge literature on IWRM the conceptual approaches to wastewater management with focus on the reuse of wastewater are particularly interesting with respect to this thesis. Examples are Harremoes (1997), Huibers and van Lier (2005), Nhapi, Siebel and Gijzen (2005), van Lier and Huibers (2007), Neubert (2009) and Guest et al. (2009).

A general drawback of IWRM is that finding optimal solutions becomes increasingly complex because the economic, social, ecological and legal domains have to be considered besides engineering. In large water basins the number of stakeholders is large, the ecological setting is diverse, and the legal framework demanding. This poses considerable challenges to researchers who want to describe the functioning of wastewater systems in formal models. Many models simply use an objective function which sums up the payoffs of stakeholders. Examples are Sousa et al. (2002), Wang and Jamieson (2002), Ward and Pulido-Velazquez (2008), Cunha et al. (2009), Zeferino, Antunes and Cunha (2009), and Murray and Ray (2010).

Assuming one aggregate objective function, however, misses an important point. Stakeholders try to achieve their own goals independently which makes outcomes depend on strategic interaction. While it is important to include effects from strategic interaction in the management of water resources, IWRM is not the appropriate approach to model and analyze it. Game theory, on the other hand, is a powerful tool to analyze the incentives of stakeholders resulting strategic interaction. It can therefore complement Integrated Water Resource Management by providing essential input to the design of incentive schemes in order to manage water resources efficiently.

Up to now game theory was applied to a variety of areas in water management. Here, I will focus on the application of game theory in wastewater management. Some papers apply axiomatic sharing rules to allocate treatment costs among stakeholders. Early examples are Giglio and Wrightington (1972), Loehman et al. (1979) and Kilgour, Okada and Nishikori (1988). More recent examples include Lejano and Davos (1995) who discuss a new solution concept, the normalized nucleus, and apply it to a water reuse project in California. Lejano and Davos (1999) apply cooperative game theory to allocate costs of a water resource project. Wu and Willet (2004) analyze an optimal location problem of a regional wastewater treatment plant assigning costs with cooperative game theory. Ni and Wang (2007) analyze how to split costs of cleaning the whole river among agents located along it. Dinar, Yaron, and Kannai (1986) analyze different allocation schemes to divide the benefits from regional cooperation in using wastewater for irrigation.

Some other papers analyze water pollution problems that are due to asymmetric information. Alban (1995) discusses regulation of industrial pollution when the regulator has limited information about the abatement costs of polluters. Dinar and Xepapadeas (1998) analyze agricultural non-point pollution of an aquifer. Asymmetric information between regulator and agricultural producer makes proper management and regulation a monitoring problem. Kerschbamer and Maderner (2001) model a game between upstream and downstream agents where downstream pays upstream to reduce pollution but has asymmetric information on the polluter’s concern for the environment. Dinar and

Xepapadeas (2002) analyze the optimal design of a tax scheme to prevent unobservable pollution from agriculture.

The game theory literature on the reuse of wastewater is still small. Feinerman, Plessner and DiSegni Eshel (2001) analyze the allocation of costs and benefits of wastewater treatment and reuse with a bargaining game between a wastewater producing city and irrigating farmers. Axelrad and Feinerman (2009) develop a planning model on how to maximize regional welfare when municipal wastewater is utilized for agricultural irrigation and river rehabilitation. In a second step they apply different approaches from transferable utility games to allocate benefits to stakeholders. Axelrad and Feinerman (2010) analyze the design of contracts that allocate profits from wastewater reuse among a wastewater generating city and two wastewater reusing farmers where the city has incomplete information about the farmers' demand for treated water. The above cited articles analyze characteristic settings where stakeholders interact strategically. This thesis contributes to this literature by identifying and analyzing strategic interaction in further characteristic settings. In the following section I present the general objective of this thesis and the specific settings that I will analyze.

1.2. Objective and research questions

The general objective of this thesis is to study how economic incentives of stakeholders determine welfare along the water chain of use, treatment and reuse and how these incentives can be regulated in order to maximize welfare. This thesis identifies four characteristic settings in which either asymmetric information or externalities causes welfare losses in the absence of regulation. Each setting is characterized by its stakeholders with their strategies and payoffs and by either asymmetric information or externalities which give each setting a specific problem that generates its research question. In this section I briefly sketch the four settings of this thesis and state the research questions which will subsequently be answered in the chapters 2 to 5.

(i) In chapter 2 I consider a setting where fresh water and wastewater irrigated products are supplied to the local food market where consumers prefer fresh water irrigated products, but cannot distinguish the two types of food. Hence, they face a situation of asymmetric information which might cause inefficiencies in the market. I assume that both fresh water and wastewater production is constrained because fresh water supply is limited. This supply is distributed between fresh water irrigation and a city for domestic use. The resulting domestic wastewater is reused for irrigation. Since the allocation of fresh water determines production constraints, it may help reducing the inefficiencies in the local food market which are caused by asymmetric information. This leads to the following research question.

Can the allocation of fresh water between a city and fresh water farmers be an instrument to reduce the asymmetric information inefficiency on the local food market?

(ii) In chapter 3 I turn to wastewater management in an urban water chain which involves water pollution, wastewater treatment to its reuse. I analyze a typical urban setting in a developing country where households and industrial firms are not separated into distinct zones and urban wastewater consists of domestic and industrial wastewater. A treatment scheme is suggested which requires firms to pre-treat their industrial wastewater before discharging it into urban wastewater. This scheme generates two advantages. First, it facilitates cost recovery of the scheme because it enables the application of a low cost treatment technology for urban wastewater. Second, it generates downstream benefits because it enables the safe reuse of treated urban wastewater for irrigation. The success of such a scheme depends on whether firms pre-treat. This is private information to them, however, and cannot be directly observed by a regulator without costly monitoring. Since monitoring is costly its benefits have to be traded off against its costs. This raises the following research question.

How much monitoring maximizes welfare in the urban water chain while the costs of the treatment scheme can still be recovered?

(iii) In Chapter 4 I analyze cooperation in wastewater treatment of cities along a river in a setting which is characteristic to many developing countries. Each city uses water from the river and discharges emissions into the river which causes damages to itself and all downstream cities. Each city can abate emissions by, for example, wastewater treatment which generates benefits to itself and all downstream cities by reducing damages. Emission abatement is costly, however, which makes cities trade off abatement benefits against abatement costs when choosing their optimal individual abatement levels. An authority which regulates emissions is missing. Cities rely therefore on cooperation in form of a self enforcing coalition in which members take abatement benefits of downstream coalition members into account. Coalition members distribute the coalition payoff in order to stabilize the coalition. Free riding is an obstacle, however, to such cooperation because downstream water users cannot be excluded from upstream cooperation treatment. This leads to the following research question.

Can voluntary cooperation in wastewater treatment among cities along a river improve the welfare in the river basin?

(iv) In chapter 5 I analyze cooperation in wastewater treatment in the Upper Citarum River Basin, Indonesia. Although guidelines for the discharge of wastewater are established, their enforcement is not effective which makes the Ciratum River one of the most polluted rivers in the world. Downstream population, therefore, suffer damages from upstream pollution. As demonstrated in the previous chapter, voluntary cooperation where downstream cities who suffer most from river pollution compensate upstream polluters for reducing pollution can improve welfare when cities are symmetric. The Upper Citarum River Basin consists, however, of asymmetric rural and densely populated urban regions. This leads to the following research questions.

Is there scope for stable coalition(s) in wastewater treatment in the Upper Citarum River Basin? What are general characteristics of the structure of the stable coalitions in transboundary river pollution games with asymmetric players?

1.3. Methodology

Non cooperative game theory offers an appropriate methodology to analyze economic incentives in interactive settings. It was applied to a variety of settings in water resources management as I have shown in section 1.2. After raising the research questions in the previous section, I spell out the methodology to answer them here. For each of the four research questions I develop a genuine non cooperative game which captures the core characteristics of the corresponding setting. Each game contributes to the existing literature of non cooperative game theory by incorporating some new features. These contributions are also sketched in this section.

As a methodology to answer the first research question - *Can the allocation of fresh water between a city and fresh water farmers be an instrument to reduce the asymmetric information inefficiency on the local food market?* - I develop a signalling game where farmers use price to signal whether they sell fresh water or wastewater irrigated food to consumers.

This chapter contributes to the literature of signalling games by integrating a public agency which sets production constraints by allocating a scarce resource. The allocation is common knowledge to consumers who infer market shares and probabilities to buy either type in case of uncertainty. The probabilities are therefore endogenously determined which complements Hertzendorf and Overgaard (2000) who model consumers who attach equal probabilities to each of two qualities. Furthermore, we can study how quality signalling by price depends on market shares, a key characteristic of the supply side. The model therefore complements Wilson (1979, 1980) who analyses quality signalling by price for different structures of the demand side. Besides contributing to the theoretical literature on quality signalling one feature distinguishes our model from the literature on water allocation. While most of these studies analyze direct effects of water allocation on the welfare of agents, our model describes an indirect welfare effect via the food market.

As a methodology to answer the second research question - *How much monitoring maximizes welfare in the urban water chain?* - I develop a compliance game where a water utility has incomplete information about the pre-treatment compliance of firms that produce industrial wastewater.

This game contributes to the literature by providing a formal model of the economic incentives in the entire water chain consisting of water pollution, wastewater treatment and its reuse. One distinguishing feature is related to the modelling of water. In economic studies on wastewater reuse wastewater is almost exclusively modelled with only one quality dimension. We model wastewater with multiple dimensions where each dimension represents the concentration level of one pollutant. This enables us to trace the concentration levels of each pollutant along the water chain which substantially increases transparency in two ways. First, welfare effects can be captured in more detail by specifying the benefit and cost functions for each pollutant along the chain. Second, the effect of pollutants on the treatment process can be specified explicitly.

As a methodology to answer the third research question - *Can voluntary cooperation in wastewater treatment among water users improve the welfare in the river basin?*- I develop a coalition formation game in a transboundary river pollution setting.

This game contributes to the literature in two domains. First, we add to the literature on transboundary river pollution games by analyzing coalition stability in a multi-player setting. This literature has largely focused on two player games which can be solved by bargaining approaches. Second, we contribute to the literature on international environmental agreements. This literature has largely focused on uniformly mixing pollutants where the abatement of one player is a public good for all others and the pollution stock is the same for all players. My setting, however, is characterized by unidirectional pollution flow where abatement is a public good for downstream players only and the emission stock varies between players unless all upstream players choose full abatement. Hence, a player's location matters in our game, which distinguishes our work from the literature on international environmental agreements.

In order to answer the research questions of the fifth chapter - *Is there scope for stable coalition(s) in wastewater treatment in the Upper Citarum River Basin? What are general characteristics of the structure of the stable coalitions in transboundary river* *pollution games with asymmetric players?* – I calibrate a coalition formation game with asymmetric players for the Upper Citarum River Basin and computing its equilibria.

The chapter continues the analysis of transboundary river pollution games in a multi-agent setting started in chapter 4 in which I assume symmetric agents. This assumption cannot be sustained when analyzing the Upper Citarum River Basin because the basin consists of asymmetric rural and densely populated urban regions. This chapter contributes to the literature in three ways. First, it is a case study which provides insights into the scope and structure of voluntary cooperation in wastewater treatment in the Upper Citarum River Basin. Second, it illustrates the applicability of the approach developed in Chapter 4. Third, its findings contribute to the theoretical literature on coalition formation games for transboundary river pollution. As analytical results of the asymmetric player game can only be obtained under very restrictive assumptions the findings of this chapter give an intuition on which assumptions should be made and how to proceed in the analytical analysis of these games.

1.4. Outline of the thesis

This thesis consists of six chapters including this introductory chapter. Chapter 2 to 5 contain the main contributions. In chapter 2 I analyze how the allocation of fresh water between a city and fresh water farmers be an instrument to reduce the asymmetric information inefficiency of the local food market. In chapter 3 I analyze how a regulator maximizes benefits of the urban water chain while being able to recover costs for wastewater treatment. In chapter 4 I analyze how and to what extent voluntary cooperation in wastewater treatment can improve welfare in a river basin. In chapter 5 I analyze whether voluntary cooperation in wastewater treatment can be an option to clean the Upper Citarum River Basin in Indonesia. Chapter 6 summarizes the main findings, presents a general discussion and conclusions and suggests some lines of future research.

Chapter 2

Wastewater irrigation, unobservable food quality and the efficiency of local food markets*

Food irrigated with untreated wastewater is considered low quality because of health hazards. When consumers cannot distinguish food qualities, asymmetric information threatens the efficiency of local food markets. We examine in a sequential game whether prices can credibly signal quality when farmers face production constraints due to the allocation of scarce water. Besides inefficient pooling equilibria and separating equilibria with distorted prices we surprisingly find efficient equilibria with undistorted prices if the water allocation to wastewater irrigated agriculture is large. We conclude that water allocation may have a crucial impact on the functioning of the market.

* This chapter is based on Gengenbach and Weikard (2010a) "Wastewater irrigation, unobservable food quality and the efficiency of local food markets" European Review of Agricultural Economics 37(1): 27-49.

2.1. Introduction

Wastewater irrigation substantially supplements fresh water irrigation in securing local food supply in water scarce regions in developing countries. Since wastewater hardly receives any treatment in most developing countries – Scott, Faruqui and Raschid (2004) report that the share of urban wastewater that is treated to secondary level is zero per cent for Africa, 35 per cent for Asia and 14 per cent for Latin America and the Caribbean – consumers face health hazards when crops are eaten raw (Shuval et al., 1986; WHO, 1989; WHO, 2006). To avoid these health hazards consumers would prefer to buy crops that are irrigated with fresh water for a higher price instead.[1] They cannot, however, distinguish between freshwater and wastewater irrigated crops by appearance alone. Farmers who irrigate with wastewater are aware of this lack of market transparency and disguise the origin of their produce. For instance, Obuobie et al. (2006: 116) observe in their study of wastewater irrigation in Ghana: '(Wastewater) farmers do not wish to be openly associated with the low (irrigation) water quality, owing to the media and some public criticism out of fear that such an association may possibly influence the sale of produce and livelihoods'. As a result asymmetric information about food quality where fresh water irrigated crops are high quality and wastewater irrigated crops are low quality threatens efficient trading in local food markets. Akerlof (1970) has shown that if price is the only signal for quality, asymmetric information can cause serious market failures by driving high quality out of the market. To enable that high quality supply and demand can trade efficiently credible quality signalling is necessary. But credible signalling of quality by means of advertising and certification is costly and not feasible for most small scale farmers in developing countries who supply to local food markets. They must rely on price to credibly signal quality which seems, in the light of Akerlof's result, impossible given low quality farmers' incentive to disguise their quality. This chapter shows that the initial water allocation which determines market shares for high and low quality food plays a crucial role for the possibility of quality signalling by price. This extends previous work on markets with asymmetric information about product quality.

Following Akerlof's (1970) seminal work, Wilson (1979; 1980) has shown that quality signalling by price alone can be credible if the low quality seller loses the incentive to mimic high quality by price. Price pooling, i.e. mimicking high quality by price, reduces demand because consumers face quality uncertainty. A low quality seller may, then, prefer

[1] To the best of our knowledge, all studies that estimate consumers' willingness to pay for a reduction of health hazards have been conducted in industrialised countries or rich urban centres, e.g. Rozan, Stenger and Willinger (2004).

to signal low quality by charging a low price if the reduction sales under price pooling is sufficiently large. This establishes a price separating equilibrium in which low quality sells at a low price and high quality at a high price. Later studies have analyzed whether prices are distorted in separating equilibria. Bagwell (1991), Bagwell and Riordan (1991), Overgaard (1993) and Ellingsen (1997) analyze monopoly seller settings and find that price separating equilibria exist, but prices are distorted compared to the full information case. Hence, market inefficiencies remain. For oligopolistic competition, little work has been done on quality signalling to consumers with price. Studies rather have focussed on costly signalling instruments. Milgrom and Roberts (1986) and Fluet and Garella (2002) consider advertising. Shapiro (1982) looks at seller reputation. Other studies focus on games where firms use price to signal private information, such as costs, to each other. Bagwell and Ramey (1991) and Martin (1995) analyze entry games. Bagwell and Ramey (1991) find that competition causes firms to behave as if there were full information. This contrasts the results of studies of monopolies (Overgaard, 1993; Bagwell and Riordan, 1991; Ellingsen, 1997) where prices are distorted upwards. The only studies where competing firms use price to signal quality to consumers are Hertzendorf and Overgaard (2000; 2001). They analyse how duopolistic competition affects firms' ability to signal quality through price. They find that prices are distorted in any separating equilibrium. Furthermore, they need non-standard equilibrium refinements to deal with multiple equilibria. Hertzendorf and Overgaard (2001) study advertising in a duopoly setting and find credible prices even for small quality differences. Hertzendorf and Overgaard's model approach has been extended by Yehezkel (2008) to examine equilibrium pricing behaviour if a fraction of consumers has quality information.

Our study extends the recent work on quality signalling by price in a different direction. We assume that consumers are informed about market shares of high and low quality and that these market shares result from the allocation of an essential input, water. Our study is motivated by the fact that water allocation for domestic and agricultural use implicitly determines the share of high and low quality food on a local market. We consider a developing country setting where a public agency allocates the scarce supply of fresh water between farmers and the city. The city discharges urban wastewater which is reused without prior treatment by wastewater farmers. We assume that water is the limiting input to agriculture. Hence, by allocating fresh water the agency sets production constraints for fresh water and for wastewater farmers. Both fresh water and wastewater farmers supply to the local food market where they compete with price. On the food market consumers consider fresh water irrigated crops as high quality and wastewater irrigated crops as low quality because of health hazards related to wastewater irrigation. Since consumers cannot observe the quality of a particular food item by appearance, asymmetric information about quality exists between consumers and producers. In this setting certification and advertising are usually not feasible or too costly which makes price the only possible signal for quality. This allows a low quality farm to – incorrectly - signal high quality to consumers by setting a high price. Both types of farmers take this into account when setting their prices on the market.

We construct a sequential signalling game. First, a public agency allocates fresh water and thereby determines production constraints for high and low quality production. Because we want to focus on the competition between the two quality segments we assume a duopoly on the production side where each quality is produced by one farm.[2] Subsequent to the water allocation, farms play a Stackelberg price setting game in which they signal quality by price to consumers. First, the high quality farm, who is the Stackelberg leader, sets its price. Then, the low quality farm follows either mimicking high quality by price pooling or setting a lower separation price. Finally, consumers observe prices and buy one unit of either high or low quality or abstain from buying.

Two features distinguish our model from the literature on signalling product quality to consumers. First, we integrate a public agency which sets production constraints by allocating a scarce resource. The agency's allocation is common knowledge and consumers infer market shares of high and low quality from it. In this setting we can study how quality signalling by price depends on market shares, a key characteristic of the supply side. Our study therefore complements Wilson (1979; 1980) who analyses quality signalling by price for different structures of the demand side. Furthermore, the probability to buy high quality in case of quality uncertainty is endogenously determined because consumers can infer it from known production constraints. This complements Hertzendorf and Overgaard (2000) who model ignorant consumers who attach equal probabilities to each of two qualities. A second distinguishing feature is that we conduct our analysis not only for the uniform distribution of consumer preferences which is the default in the literature. We conduct our analysis for two additional distributions: one where only few consumers have a high valuation for high quality and one where many consumers have high valuation for high quality. Thereby, we derive additional results for poor and prospering developing countries, respectively.

We find that the allocation of scarce fresh water between a city and irrigation determines the possibility of quality signalling by price and, thereby, affects the functioning of the local food market. More specifically, we find a pooling equilibrium, a separating

[2] This is a simplifying assumption. We discuss its implications below. A possible interpretation is that farmers' associations determine the price setting.

equilibrium with distorted prices and a separating equilibrium with efficient prices to exist for small, medium and large water allocation to the city, respectively. Therefore, water allocation may be used as an instrument to facilitate the functioning of the market. In any case the water allocation decision must not only balance domestic and agricultural demands for water but must also take the impact on the food market into account. We also find that, considering the food market only, it is optimal to allocate more fresh water to agriculture if the fraction of consumers with a high valuation for high quality food is larger, as in prospering developing countries. Thus higher incomes in urban centres lead to increasing urban water demand and, at the same time to increasing agricultural water demand. Given the increasing pressure on water resources it is important to implement policies that reduce health hazards – like establishing urban wastewater treatment facilities – while allowing for the re-use of waste water.

The remainder of the chapter is structured as follows. Section 2.2 introduces the model. Section 2.3 presents the full information case. Section 2.4 introduces asymmetric information. In section 2.3 and 2.4 we assume a uniform distribution of consumers' high quality reservation values. In section 2.5 we relax this assumption and compare the uniform distribution benchmark to cases with a concave and a convex cumulative distribution function. Section 2.6 discusses assumptions and relates our findings to the literature. Then we conclude.

2.2. The model

We study a sequential game with three stages. The public agency moves first and allocates the available water. Then, farms play a Stackelberg price setting game and signal quality to consumers. Finally, consumers observe prices and buy or abstain from buying. Each stage of the game is introduced in turn.

The public agency: At the first stage the public agency allocates a share α ($0 \le \alpha \le 1$) of available fresh water W to a city and the remaining share $1-\alpha$ to agriculture for fresh water irrigation. While fresh water irrigation does not discharge any water, the city discharges its share α as urban wastewater. All urban wastewater is recovered and used for wastewater irrigation. The agency sets α to maximise the sum of consumers' and producers' surplus in the food market. We neglect the direct welfare effect of urban water consumption in order to highlight the effect of water allocation on the food market.

Farms: At the second stage farms compete in the market by setting prices. We consider two qualities $Q = L, H$. In order to focus on competition between qualities, rather than competition within the quality segments, we assume that supply of each quality is bundled. This simplifies the analysis but does not affect our qualitative results as we will argue below. Hence, we consider a duopoly with two farms. One farm relies on fresh water irrigation and produces high quality. It is indexed by $Q = H$. The other farm relies on wastewater irrigation and produces low quality. It is indexed by $Q = L$. For ease of exposition we assume a linear production function $y_Q(\alpha)$ that only depends on water. We assume for both farms that marginal costs of production are zero, that water is the constraining factor in production and that therefore both farms produce at their production constraint. Hence, low quality production is $y_L(\alpha) = \alpha \cdot W$ and high quality production is $y_H(\alpha) = (1-\alpha) \cdot W$. Total production is $y = y_H + y_L = W$. Both farms supply their production to the local food market where they play a Stackelberg price setting game to maximise their profits. We choose a Stackelberg type game in which the high quality farm is the Stackelberg leader because this captures the stylised fact that high quality is dominant in the market. The high quality farm sets its price p_H . After observing p_H , the low quality farm follows setting price p_L which is set equal to the high quality price when mimicking high quality by price is beneficial or some lower price when signalling low quality is beneficial. Both prices determine the demand $X_Q(p_H, p_L)$ for either quality $Q = H, L$. A farm's profit is $\pi_Q = p_Q \cdot X_Q(p_H, p_L)$. Demand depends on both prices because consumers compare them before choosing which quality to buy. Each farm maximises its profit subject to the production constraint $X_Q(p_H, p_L) \leq y_Q(\alpha)$.

Consumers: Each of M consumers buys one unit of either high or low quality or refrains from buying. We assume $W = M$ such that all consumers can be served and normalise $M = 1$ for simplification. Like Bagwell and Riordan (1991) we assume that all consumers have a common reservation value R for low quality and heterogeneous reservation value θ for high quality. Hence, consumers payoff is $R - p_L$ or $\theta - p_H$ when buying low or high quality, respectively. The high quality reservation value is an add-on of at most 1 on the low quality reservation value, $\theta \in [R, R+1]$, and is distributed according to a density function $f(\theta)$ with cumulative distribution function $F(\theta)$ with

$F(R)=0$ and $F(R+1)=1$. After observing prices for each quality, all consumers with $\theta \geq R - p_L + p_H$ would prefer to buy high quality because they get a higher payoff than buying low quality. Aggregate demand is therefore $1-F\left(R-p_L+p_H\right)$ for high quality and $F\left(R-p_L+p_H\right)$ for low quality. Note that $0 \leq p_L \leq R$. Like Bagwell and Riordan (1991) we present the model assuming uniformly distributed reservation values, with $f(\theta)=1$ for $\theta \in [R, R+1]$ and $f(\theta)=0$ otherwise. In section 2.5, however, we relax this assumption.

The game is solved backwards and we start our analysis with the full information case.

2.3. Full information

If product quality is observable, prices do not have signalling function. This case serves as a welfare benchmark for the asymmetric information case.

The low quality farm has a dominant strategy. Its profit maximizing price under full information is $p_L^F = R$. Any price of $p_L > R$ generates zero profit because consumers refrain from buying as they would obtain a negative payoff. As H cannot serve more than $1-\alpha$ consumers, farm L faces a positive demand of at least α for any price $p_L \leq R$. Since α is also L 's production constraint, L does not gain in sales by reducing price below R. Hence, $p_L^F = R$ is independent of p_H^F and therefore a dominant strategy. Given $p_L^F = R$, H maximises profit subject to its production constraint by setting price

(2.1)
$$p_H^F(\alpha) = \begin{cases} \overline{p}_H & if \quad 0 \leq \alpha \leq \hat{\alpha} \\ \tilde{p}_H(\alpha) & if \quad \hat{\alpha} < \alpha \leq 1, \end{cases}$$

where $\overline{p}_H$ is implicitly defined by $\overline{p}_H \cdot \partial F \ \left(\overline{p}_H\right) / \partial \overline{p}_H = 1 - F\left(\overline{p}_H\right)$, $\tilde{p}_H(\alpha) = F^{-1}(\alpha)$ and $\hat{\alpha}$ is the threshold which is obtained by solving $\overline{p}_H = \tilde{p}_H(\hat{\alpha})$; see Appendix 2.1.

We call the full information prices, p_L^F and p_H^F, *undistorted* with respect to quality signalling. They are depicted in Figure 2.1.[3] The low quality price is constant over the entire interval. The high quality price depends on whether the high quality production constraint is binding. If it is not binding (in the interval $0 \le \alpha \le \hat{\alpha}$ with $\hat{\alpha} = (1-R)/2$) the high quality farm sets $\overline{p}_H = (R+1)/2$. If the production constraint is binding (in the interval $\hat{\alpha} < \alpha \le 1$), H sets the price which equates its production and demand, $\tilde{p}_H(\alpha) = R + \alpha$.

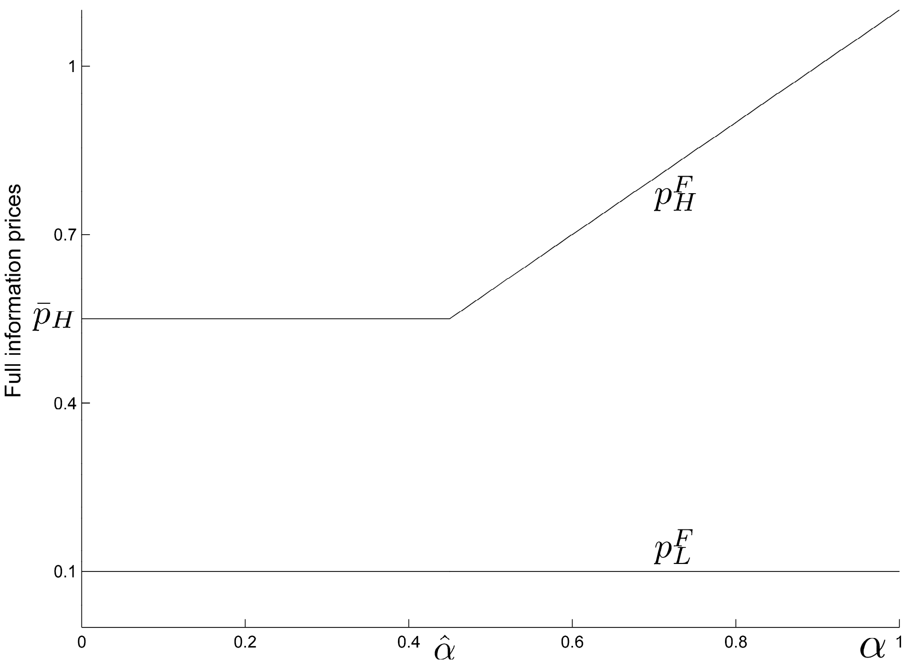

Figure 2.1: Full information prices p_L^F (Equation 2.1) and p_H^F depending on wastewater share α depicted for $R = 0.1$.

To evaluate welfare effects we determine producer and consumer surplus in both quality segments. Producer surplus in the low quality segment is the low quality farm's

[3] $f(\theta) = 1$ for $\theta \in [R, R+1]$ and $f(\theta) = 0$ otherwise.

profit $\pi_L^F = R \cdot \alpha$. Consumer surplus in the low quality market segment is zero since price equals reservation value for all consumers. Producer surplus in the high quality segment is the high quality farm's profit, $\pi_H^F = p_H^F(\alpha) \cdot \left[1 - F\left(p_H^F(\alpha)\right)\right]$. Each consumer with a reservation value $p_H^F(\alpha) \leq \theta \leq R+1$ buys high quality and obtains his reservation value minus price, $\theta - p_H^F$. Hence, aggregate consumer surplus in the high quality market segment is $\pi_C^F = \int_{p_H^F}^{R+1} \left(\theta - p_H^F\right) \cdot f(\theta) d\theta$. The agency's objective is to maximise welfare, i.e. the sum of the profits of the low and the high quality farm plus the consumer surplus for the high quality product, $\pi_A^F = \pi_L^F + \pi_H^F + \pi_C^F$. This yields $\pi_A^F(\alpha) = R \cdot \alpha + \int_{p_H^F}^{R+1} \theta \cdot f(\theta) d\theta$. The first term on the right hand side is low quality producer surplus. Low quality consumer surplus is zero. The second term is welfare generated in the high quality segment which is the sum of consumer and producer surplus.

Proposition 2.1: Under full information the agency maximises welfare by setting $\alpha^* = \hat{\alpha}$.
Proof: See Appendix 2.2.

The individual payoffs and aggregate welfare under full information is depicted in Figure 2.2. The low quality producer surplus strictly increases over the entire interval because its production constraint is relaxed. High quality producer and consumer surplus is constant for $0 \leq \alpha \leq \hat{\alpha}$ because in this interval the high quality farm charges its global profit maximizing price, $\overline{p}_H$ and serves $1 - F\left(\overline{p}_H\right)$ customers. For $\hat{\alpha} < \alpha \leq 1$ high quality producer and consumer surplus both decrease because the production constraint is binding and production decreases and hence high quality price $\tilde{p}_H(\alpha)$ rises in α and the fraction of served consumers drops. Total welfare reaches its maximum at $\alpha^* = \hat{\alpha}$.

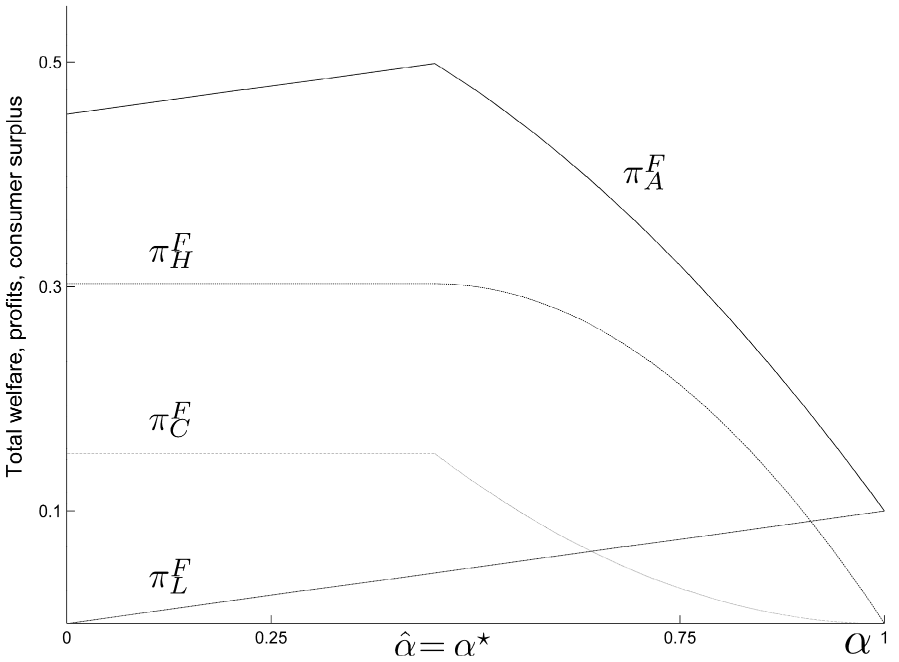

Figure 2.2: Total welfare $\pi_A^F(\alpha)$, high quality profits $\pi_H^F(\alpha)$, low quality profits $\pi_L^F(\alpha)$ and consumer surplus $\pi_C^F(\alpha)$ depending on wastewater share α under full information.

2.4. Asymmetric information

Under asymmetric information consumers observe only prices, not quality. In the pricing game the Stackelberg leader *H* sets price p_H. Given p_H the follower *L* has two pricing strategies: (i) a separation strategy that correctly signals low quality by a low price, $p_L < p_H$ and (ii) a pooling strategy that mimics high quality by price, $p_L = p_H$. Price pooling generates consumer uncertainty about quality. Of course, the Stackelberg leader H takes *L*'s incentive to pool into account when setting price p_H. If an incentive to pool exists, H may distort its price upward to force L to separate and *H* must decide whether a price distortion is preferable to tolerating pooling.

The structure of this section follows this line of argument. First, we calculate when L will pool *H*'s full information price and which price distortion is necessary to render L 's pooling unprofitable to assure price separation. Second, we check whether this distortion is preferable for H compared to price pooling. Third, we analyse the welfare effects of the price distortions depending on water allocation. We derive results for a uniform distribution of consumers' valuation of high quality. The next section relaxes this assumption.

To assure price separation, the Stackelberg leader H maximises profit subject to its production constraint and a separation constraint. The separation constraint holds if L 's separation profit, $\pi_L^S = R \cdot \alpha$, larger than or equal to its pooling profit, $\pi_L^P = p_H \cdot \alpha \cdot X^P$. L 's pooling profit is pooling price p_H times L 's market share, α , times total demand of uninformed consumers, X^P . We assume that demand X^P is a result of a lottery in which risk neutral consumers that maximise their expected utility. Consumers pay p_H and receive either high quality yielding utility θ with probability α or low quality yielding utility R with probability $1-\alpha$ assuming that consumers know the water allocation and can thereby infer high and low quality market shares. Hence, consumers' expected utility is $\theta \cdot (1-\alpha) + R \cdot \alpha$. The consumer with valuation $\hat{\theta} = (p_H - R \cdot \alpha)/(1-\alpha)$ is indifferent. Consumers with $\theta \geq \hat{\theta}$ will buy, while all others abstain from buying. Then demand under price pooling is $X^P = 1 - F\left(\hat{\theta}\left(p_H\right)\right)$.

Next, we obtain L 's pooling profit $\pi_L^P = p_H \cdot \alpha \cdot \left[1 - F\left(\hat{\theta}\left(p_H, \alpha\right)\right)\right]$ which enters the separation constraint that we use in H 's profit maximization problem in order to determine high quality price under separation p_H^S .

We obtain (see Appendix 2.3):

(2.2)
$$p_H^S\left(\alpha\right) = \begin{cases} p_H^D(\alpha) & if \quad 0 \leq \alpha \leq \hat{\hat{\alpha}} \\ p_H^F(\alpha) & if \quad \hat{\hat{\alpha}} \leq \alpha \leq 1, \end{cases}$$

where $p_H^D(\alpha)$ is the distorted price that assures price separation, implicitly defined by $\frac{R-p_H^D\cdot\left[1-F\left(\hat{\theta}\left(p_H^D,\alpha\right)\right)\right]}{p_H^D-R}=0$ and $\hat{\hat{\alpha}}$ is the threshold where distorted and undistorted high quality prices are equal, $p_H^D\left(\hat{\hat{\alpha}}\right)=p_H^F\left(\hat{\hat{\alpha}}\right)$. For the uniform distribution $p_H^D(\alpha)=1-\alpha$ and $\hat{\hat{\alpha}}=(1-R)/2$.

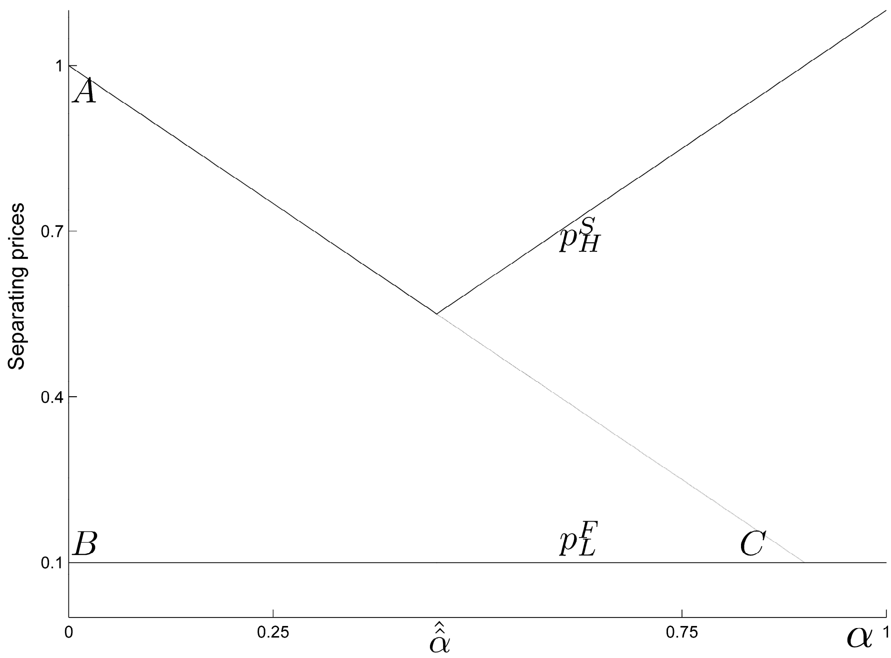

Figure 2.3: Separating prices p_H^S (Equation 2.2) and p_L^F depending on wastewater share α (solid lines) and (α, p_H) combinations for which L will pool p_H (triangle ABC).

Figure 2.3 depicts separation prices for high quality, $p_H^S(\alpha)$, and for low quality, p_L^F, for the uniform distribution. For $0\leq\alpha\leq\hat{\hat{\alpha}}$, L would mimic H's full information price. Hence, the separation constraint is binding and H needs to distort his price upwards to force L to separate. By setting $p_H^D(\alpha)$, L loses its incentive to pool and consequently separates by signalling low quality with p_L^F. For $\hat{\hat{\alpha}} \geq \alpha \geq 1$, L would never mimic high quality by price and H can set the full information price, $p_H^F(\alpha)$. Note, that in the uniform distribution case $\hat{\alpha} = \hat{\hat{\alpha}}$ which means that the interval where H has to distort prices coincides with the interval where the production constraint is not binding. The triangle ABC depicts all (α, p_H) combinations for which L will pool p_H since $\pi_L^S < \pi_L^P$.

Our next step is to analyse whether H prefers to distort prices or to tolerate price pooling. To do this we check whether H's separation profit is higher than the corresponding pooling profit. The pooling profit of H is given with $\pi_H^P = p_H^P \cdot (1-\alpha) \cdot X^P\left(p_H^P\right)$, where p_H^P is its profit maximizing pooling price and $(1-\alpha) \cdot X^P\left(p_H^P\right)$ is its sales. Here, the production constraint is never binding, since H's production of $1-\alpha$ is always larger than sales $(1-\alpha) \cdot \left[1-F\left(\hat{\theta}\left(p_H^P\right)\right)\right]$ since $F\left(\hat{\theta}\left(p_H^P\right)\right) \geq 0$ for all α. H maximises its profit by pooling in the interval $0 \leq \alpha < \hat{\hat{\hat{\alpha}}}$, setting price $p_H^P(\alpha)$; see Appendix 2.4. Asymmetric information prices are given by

(2.3)
$$\langle p_H, p_L \rangle = \begin{cases} p_H = p_L = p_H^P & \text{if} \quad 0 \leq \alpha < \hat{\hat{\hat{\alpha}}} \\ p_H = p_H^D, p_L = R & \text{if} \quad \hat{\hat{\hat{\alpha}}} \leq \alpha < \hat{\hat{\alpha}} \\ p_H = \tilde{p}_H, p_L = R & \text{if} \quad \hat{\hat{\alpha}} \leq \alpha \leq 1. \end{cases}$$

For $0 \leq \alpha < \hat{\hat{\hat{\alpha}}}$, tolerating pooling is profitable compared to separating. Hence, H sets $p_H = p_H^P$ which L mimics. For $\hat{\hat{\hat{\alpha}}} \leq \alpha < \hat{\hat{\alpha}}$, H sets $p_H^D(\alpha)$ to prevent pooling by distorting its price upwards. For $\hat{\hat{\alpha}} \leq \alpha < 1$, H sets the undistorted full information price

p_H^F. In either of the two last cases L charges $p_L = R$ separating from H by price. Figure 2.4 depicts the asymmetric information prices.

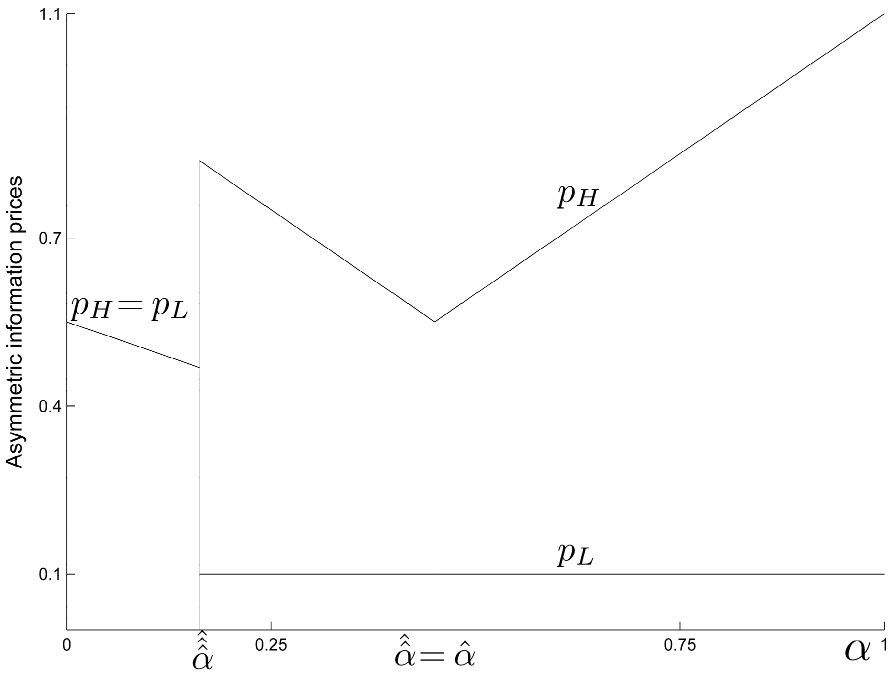

Figure 2.4: Asymmetric information prices $\langle p_H, p_L \rangle$ (Equation 2.3) depending on wastewater share α with threshold levels $\hat{\hat{\hat{\alpha}}} = 0.16$ and $\hat{\hat{\alpha}} = \hat{\alpha} = 0.45$.

Under asymmetric information, total welfare is (Appendix 2.5)

(2.4)
$$\pi_A(\alpha) = \begin{cases} \int_{\hat{\theta}}^{R+1} \left[\theta \cdot (1-\alpha) + R \cdot \alpha - p_H^P \right] d\theta + \pi_H + \pi_L & \text{if} \quad 0 \le \alpha < \hat{\hat{\hat{\alpha}}} \\ R \cdot \alpha + \int_{\hat{\hat{p}}_H^S}^{R+1} \theta \cdot f(\theta) \; d\theta & \text{if} \quad \hat{\hat{\hat{\alpha}}} \le \alpha < \hat{\hat{\alpha}} \\ R \cdot \alpha + \int_{\hat{p}_H^S}^{R+1} \theta \cdot f(\theta) \; d\theta & \text{if} \quad \hat{\hat{\alpha}} \le \alpha \le 1. \end{cases}$$

It contains total welfare for price pooling in $0 \leq \alpha < \hat{\hat{\alpha}}$, for distorted price separating in $\hat{\hat{\hat{\alpha}}} \leq \alpha < \hat{\hat{\alpha}}$ and for undistorted price separating in $\hat{\hat{\alpha}} \leq \alpha < 1$. Figure 2.5 depicts total welfare π_A and its elements, π_H, π_L and π_C. As α increases, total welfare drops in the price pooling interval ($0 \leq \alpha < \hat{\hat{\hat{\alpha}}}$). High quality profits and consumer surplus decrease while low quality profits increase because the loss in high quality profits (π_H) and consumer surplus (π_C) cannot be compensated by the increase in low quality profits (π_L). At $\hat{\hat{\hat{\alpha}}}$, π_L and π_C jump to a lower level because H switches in its pricing strategy from pooling to separating with distorted prices. Consequently, L loses the incentive to pool and is forced to reveal low quality by charging $p_L = R$. Consumers, gain certainty about quality, but have to pay an upwards distorted price for high quality. Since the effect of the latter dominates, consumer surplus jumps to a lower level. As α increases in $\hat{\hat{\hat{\alpha}}} \leq \alpha < \hat{\hat{\alpha}}$, the price distortion decreases, because increasing separation profits of L render pooling less attractive. Hence, overall welfare increases up to the global maximum at $\hat{\hat{\alpha}}$. For $\alpha \geq \hat{\hat{\alpha}}$, undistorted prices signal quality. Welfare decreases, however, since too much water is allocated to low quality and the high quality sector is constrained in production[4].

Summarising the results so far, we find that the allocation of scarce fresh water between domestic use and irrigation determines the equilibrium prices and thereby the transparency of the local food market. Allocating a small share of fresh water to domestic use yields a price pooling equilibrium with asymmetric information about food quality between consumers and producers. One price is set in the market and the low quality farm disguises its quality and mimics high quality by price. A medium share of fresh water for domestic use yields a separating equilibrium in which a distorted high quality price signals high quality to consumers. The high quality farm distorts its price upwards to prevent pooling. A large share of fresh water for domestic use also yields a separating equilibrium. The high quality farm is, however, not threatened by pooling and can therefore signal its quality by the undistorted full information price. The full information welfare optimum can

[4] See proof of proposition 2.1 for $\alpha \geq \hat{\hat{\alpha}}$.

be obtained because the farms signal quality with undistorted prices for water allocation that maximises welfare in the full information case.

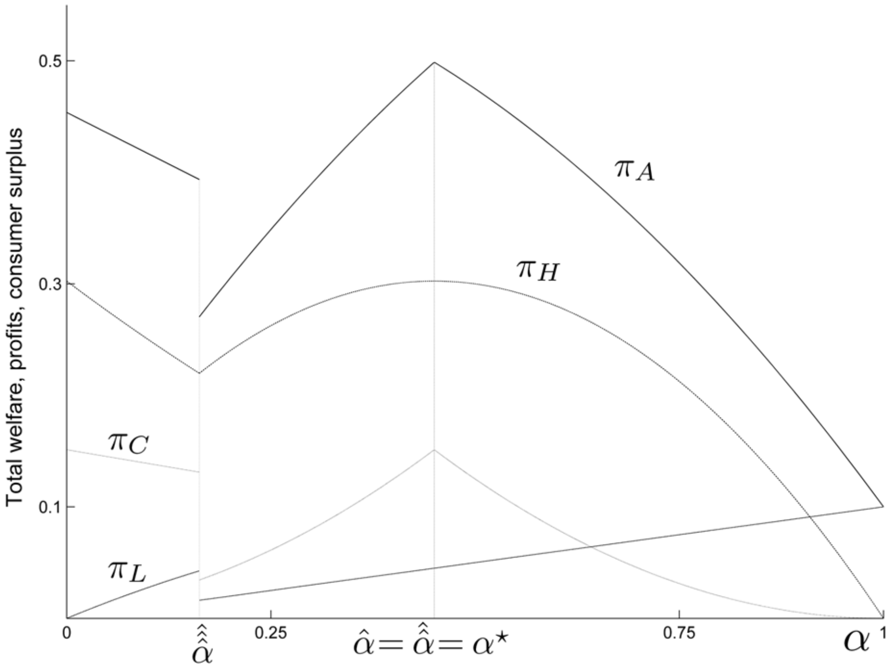

Figure 2.5: Total welfare $\pi_A(\alpha)$ (Equation 2.4), high quality profits $\pi_H(\alpha)$ (Equation A2.5), low quality profits $\pi_L(\alpha)$ (Equation A2.6) and consumer surplus $\pi_C(\alpha)$ (Equation A2.7) depending on wastewater share α under asymmetric information.

Another interesting insight into price signalling games with unobservable product quality appears in the last paragraph of Appendix 2.3. Our model shows that for $R > 1$ the low quality farm looses its incentive to mimic high quality by price independently of its share in the market. Hence, a separating equilibrium emerges and asymmetric information about quality does not have negative effects at all on market transparency. This result is driven by the relation between the maximal add-on, which we assumed to be one, and R. With a higher R pooling price and low quality separating price are getting closer and the low quality farm would only receive a slightly higher price when pooling, while it would still loose demand due to quality uncertainty. For $R > 1$ with a maximal add-on of one the net effect of pooling on the low quality farm's profit is negative for all possible market shares. Hence, it always separates. This is the relevant case when the unobservable quality of a product is only a minor characteristic compared to the observable ones. In our case, where the unobservable characteristic is health hazards, it is reasonable to assume that the consumers with the highest valuation for avoiding health risks are represented by a relatively large add-on. Hence, we assume $R < 1$.

2.5. Alternative distributions of consumer valuations

So far we have developed our model for a uniform distribution of consumer valuations. While this is sufficient to illustrate the mechanisms at work, interesting insights can be obtained when relaxing this assumption. In many developing countries the majority of consumers is poor and can be characterised by a low willingness to pay for avoiding the health risks attached to wastewater irrigated crops. Hence, the add-on for high quality is small for most consumers. This yields a concave cumulative distribution function of reservation value for high quality. In a prospering country, on the other hand, the majority of consumers may prefer high quality and may be willing to pay for it. This yields a convex cumulative distribution function. In the subsequent section we conduct our analysis with a concave and a convex cumulative distribution function.

We maintain the linearity of the density function and merely adapt its slope. The general linear density function is given by $f(\theta) = a + b \cdot \theta$ in the interval $R \leq \theta \leq 1 + R$ and $f(\theta) = 0$ otherwise. The cumulative distribution function is then $F(\theta) = \int_R^\theta f(\theta) d\theta = a \cdot \theta + b/2 \cdot \theta^2$. Using $\int_R^{R+1} f(\theta) d\theta = 1$ yields $a(b) = 1 - b \cdot (1/2 + R)$ which fully determines the density function by its slope b. Note that the uniform distribution is a special case with $b = 0$ which yields $a = 1$. In our analysis we use $b = -2$ and $b = 2$ to generate a concave and convex cumulative distribution function, respectively. The density functions are $f(\theta) = 2.2 - 2 \cdot \theta$ for the concave case and $f(\theta) = -0.2 + 2 \cdot \theta$ for the convex case. Using these densities in the equations for market prices (Eq. 2.3) and welfare (Eq. A2.5 –A2.8) yields the results that we present in Figures 2.6-2.8.

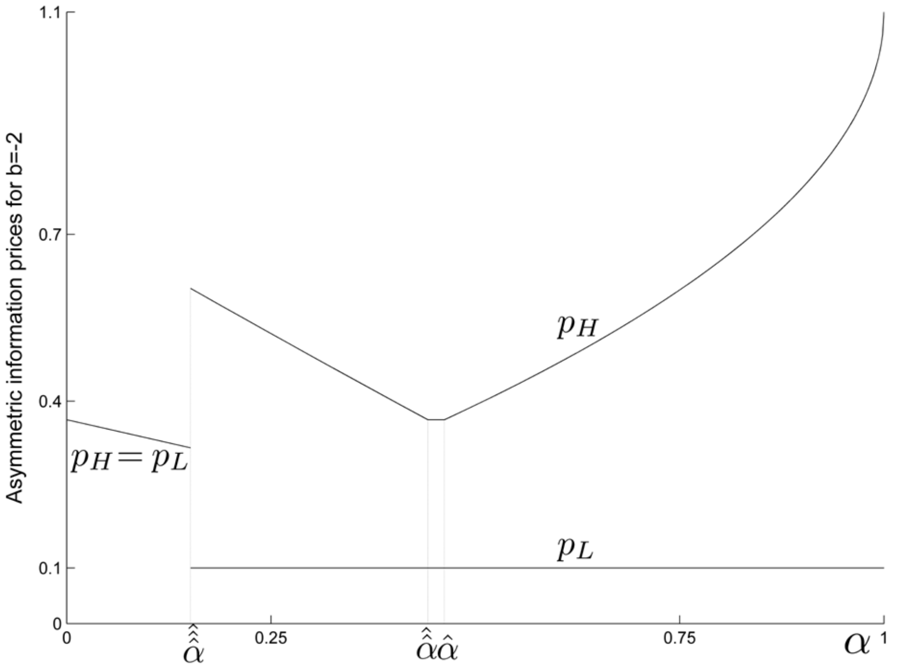

Figure 2.6: Asymmetric information prices $\langle p_H, p_L \rangle$ (Equation 2.3) for concave cumulative distribution function $(b = -2)$ depending on wastewater share α with threshold levels $\hat{\hat{\hat{\alpha}}} = 0.15$, $\hat{\hat{\alpha}} = 0.44$ and $\hat{\alpha} = 0.46$.

Figures 2.6 and 2.7 depict the asymmetric information prices (Eq. 2.3) for the concave and the convex cumulative density function, respectively. As in the uniform distribution case, a price pooling equilibrium exists for an interval of small α, a distorted price separating equilibrium exists for an interval of a medium sized α and an efficient price separating interval exists for an interval of large α. The values of the threshold levels $\hat{\hat{\hat{\alpha}}}$ hardly change because farms adjust prices to maintain demand as reaction to the change in consumers' valuation. The threshold $\hat{\hat{\alpha}}$ does, however, change considerably. It drops from $\hat{\hat{\alpha}} = 0.44$ in the concave case to $\hat{\hat{\alpha}} = 0.36$ in the convex case. The interval of undistorted prices is therefore much larger in the convex case. For both cases the full information welfare maximizing $\hat{\alpha}$ is no longer equal to $\hat{\hat{\alpha}}$, the threshold of the efficient price separating equilibrium interval. $\hat{\alpha}$ still lies in the interval of undistorted prices for the concave case. This changes, however, in the convex case. There, the full information welfare optimal water allocation $\hat{\alpha} = 0.3$ lies in the separation interval with distorted prices, $\hat{\hat{\hat{\alpha}}} \leq \hat{\alpha} < \hat{\hat{\alpha}}$. The difference between the dotted line and p_H at $\hat{\alpha}$ in Figure 2.7 depicts price distortion which is necessary to assure profit maximal price separation.

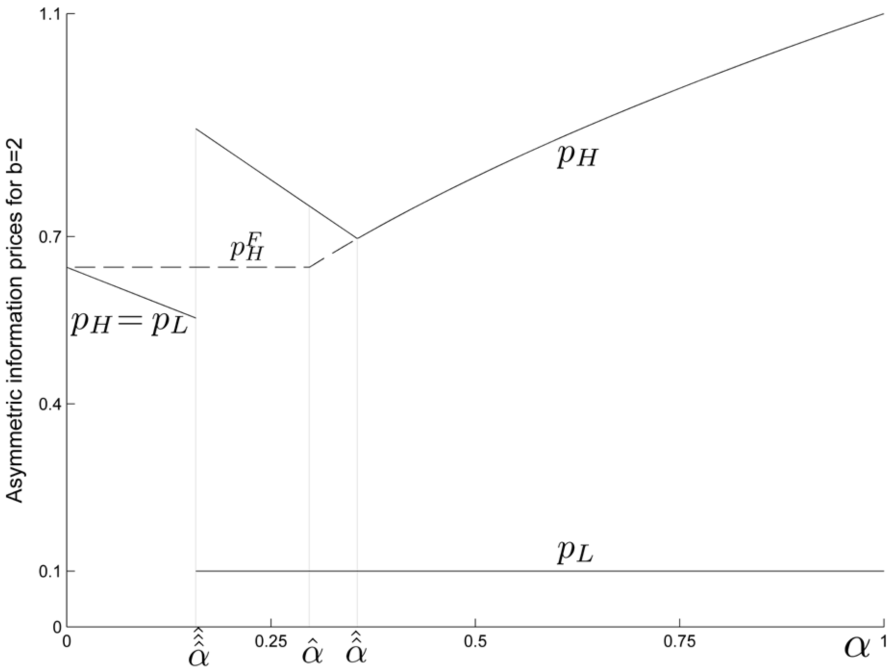

Figure 2.7: Asymmetric information prices $\langle p_H, p_L \rangle$ (Equation 2.3) for concave cumulative distribution function $(b = 2)$ depending on wastewater share α with threshold levels $\hat{\hat{\hat{\alpha}}} = 0.16$, $\hat{\hat{\alpha}} = 0.36$ and $\hat{\alpha} = 0.3$. Full information price p_H^F (Equation 2.1) for the interval $0 \leq \alpha \leq \hat{\hat{\alpha}}$ (dashed line).

Figure 2.8 depicts the implications on welfare in the convex case. As in the uniform case (Figure 2.5), there are two local maxima. The difference to the uniform case is that the full information welfare level is not one of the two local maxima. It cannot be obtained because at $\hat{\alpha}$ distorted prices cause welfare losses. The local maximum at $\alpha = 0$ is slightly higher[5] than the one at $\hat{\hat{\alpha}}$. The agency maximises total welfare under asymmetric information by setting $\alpha^* = 0$. This establishes de facto consumer certainty by allocating all water to high quality production. H charges $p_H^F(\alpha = 0) = \overline{p_H}$ (Eq. 2.1) and sells $y_H = 1 - \hat{\alpha}$ (Figure 2.1). Since water allocation to high quality is $1 - \alpha = 1$, $\hat{\alpha}$ is wasted unproductively for the sake of market efficiency.

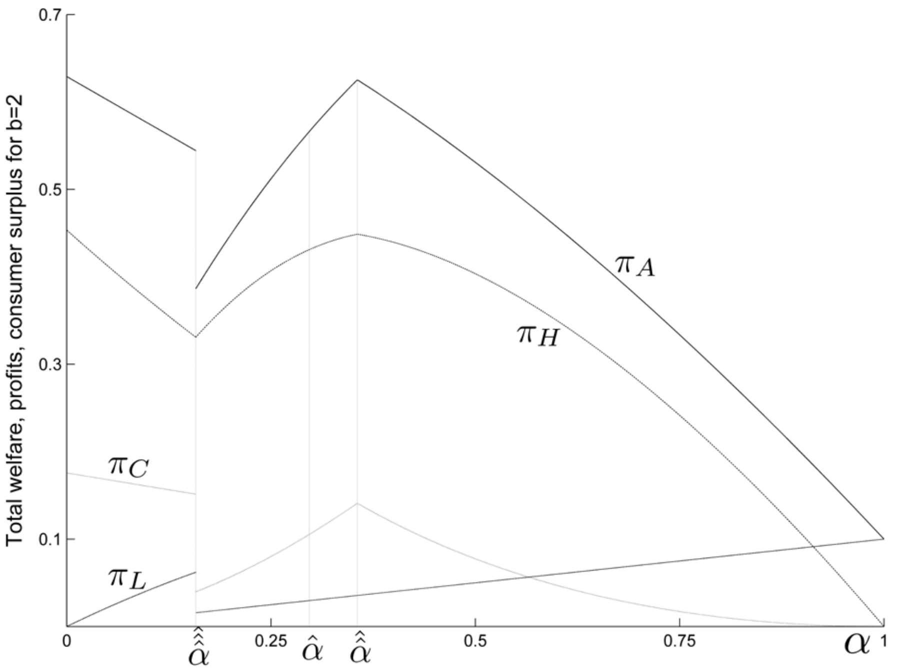

Figure 2.8: Total welfare $\pi_A(\alpha)$ (Equation 2.4), high quality profits $\pi_H(\alpha)$ (Equation A2.5), low quality profits $\pi_L(\alpha)$ (Equation A2.6) and consumer surplus $\pi_C(\alpha)$ (Equation A2.7) depending on wastewater share α under asymmetric information for $b = 2$.

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[5] $\pi_A(0) = 0.6291 > 0.6253 = \pi_A\left(\hat{\hat{\alpha}}\right)$

We have shown in this section that the distribution of consumers' valuation for high quality is crucial for the welfare maximum in the market. If only few consumers have a high valuation for high quality food, the above mentioned reallocation of fresh water to domestic use does not pose a serious threat to maximizing welfare in the food market. This changes, however, if more consumers have a high valuation for high quality food, as in prospering countries. Then our model suggests allocating all water to fresh water irrigation to maximise welfare on the food market. This result does not consider welfare from domestic use. We return to this assumption in the discussion below.

2.6. Discussion

In this section we first relate the results of our model to the theoretical literature on quality signalling by price. Then we discuss the main assumptions.

Our model displays a typical feature of models of unobservable product quality. The three types of equilibria that we find in our study can be found in the related literature. Examples are Cho and Kreps (1987) who find the full information prices when qualities are sufficiently different. For a duopoly Hertzendorf and Overgaard (2000: 7) find price pooling or distorted price separation but they argue that 'full information prices can never be a separating equilibrium pair'. Contrary to their finding we show in our duopoly case that efficient prices can signal quality. This result is driven by the fact that the water allocation determines production constraints for both qualities and, hence, the size of the market shares.

Another typical feature is that in a price pooling equilibrium the high quality producer and high quality demanding consumers suffer losses, while the low quality producer gains extra profits. This can be seen for the uniform distribution case when comparing the corresponding welfare functions for the pooling interval in Figures 2.2 and 2.5. Welfare levels for the high quality farm and consumers are strictly lower in the asymmetric information case while they are strictly higher for the low quality farm.[6] This may cause adverse selection in models where marginal high quality demand and high quality producers can withdraw from the market as in Akerlof's (1970) market for lemons. In our setting, however, the high quality producer stays in the market since this yields positive profits. This result might change if one introduces positive marginal costs of high

[6] We assumed that producers pool for $\alpha = 0$. This, however, is a degenerate case in which quality certainty exists because only high quality is produced. Therefore there is no difference in the welfare levels between the full and the asymmetric information case.

quality production or alternative productive options. Sufficiently high marginal costs might render high quality production unprofitable under asymmetric information. Alternative production options in form of crops with known quality might also cause high quality to leave the market. Extending our model with these features might contribute to understanding cropping patterns in developing countries.

Now we turn to the discussion of assumptions. We derive our main result that water allocation may affect the functioning of the food market with the simplest possible model. In particular we assume that there is a single seller for each of two qualities. In some cases where farmers' associations bundle supply this assumption is warranted. In most cases, however, there will be many sellers of either quality. First, consider competition in the high quality segment. Here price competition is not effective because the production constraint is binding for each farmer. There is no point in lowering prices to sell more. The equilibrium price for high quality will be the highest market clearing price. Second, if there are many low quality farms, some fraction of low quality farms might mimic high quality. Then a consumer can no longer be certain to receive high quality for a high price. The pricing equilibrium is determined by consumers' reactions to the risk of receiving low quality for a high price. If a sufficient fraction of consumers prefers low quality for a low price rather than taking the risk, demand for high-priced food drops which reduces the incentive to mimic and a separating equilibrium exists. Hence, relaxing our assumption of a single farm of each type would not change our qualitative results.

A restriction of our analysis is that we do not model consumers' fresh water demand for domestic use. Of course, fresh water allocation is not determined with the primary purpose to influence food prices but mainly driven by demands for domestic and agricultural use. Since the objective of this study is to provide insight how water allocation effects the functioning of the local food market, we restrict our attention to welfare effects from the food market. To integrate domestic water demand into our model would provide further interesting insights into welfare effects on the water basin scale, but is left to future research.

We assume that water allocation and therefore production constraints are common knowledge. Consumers know the probability of getting high quality under price pooling. This feature provides an endogenous determination of the probabilities consumers take into account in a price pooling case while Hertzendorf and Overgaard (2000) assume exogenous equal probabilities for both quality types. Endogenous probabilities impact the market shares and may render the low quality producer's incentive to mimic high quality by price unprofitable. The endogenous determination of the probabilities is a major difference to

Hertzendorf and Overgaard's (2000) model. While one can question the accuracy with which consumers translate water allocation into probabilities, we show that some prior information on market shares affects the pricing behaviour in equilibrium.

2.7. Conclusion

Data on water allocation between cities and agriculture show that agriculture gets the 'lion's share'. Molle and Berkoff (2006) report that in developing countries 80-95 per cent of the water resources get diverted to agriculture. This provides an indication that the order of magnitude of parameter α is between 5 per cent and 20 per cent. It is for these parameter values that our model predicts welfare losses in the food market due to either a pooling equilibrium or a separating equilibrium with distorted prices. Our model provides a tool to assess the size of these losses. This underlines the potential relevance of our model although an empirical estimate of the welfare losses may be difficult.

We have shown that equilibrium prices in the food market crucially depend on consumers' probabilities of getting high quality under price pooling. Obviously, then, results from models where these probabilities are exogenous can be questioned and particular attention must be paid to setting the exogenous probabilities. How consumers process indirect information in case of quality uncertainty and how this determines producers' pricing behaviour and consumers' purchasing decisions is an interesting area for future research in signalling games. Our findings suggest that consumers' knowledge of market shares mitigates the negative effects of asymmetric information.

With increasing competition for fresh water due to, for instance, climate change and population growth, fresh water is likely to be reallocated to domestic use. For this case our model predicts that initial price distortions will be reduced or even removed because the wastewater irrigated crops get a larger market share and their producers lose some of (or entirely) the incentive to mimic high quality. Besides the price distortions, our model captures welfare in the food market and determines the welfare maximising water allocation. Furthermore, our results describe the potential effects of a shift of consumers' valuation of high quality. If many consumers have a high valuation for high quality food, as in prospering developing countries, all water should be allocated to fresh water irrigation in order to maximise welfare on the food market. Hence, clearly, there is a trade off. Reallocating fresh water to domestic use increases domestic users' welfare but hampers the functioning of the food market with a corresponding decrease in welfare. We conclude that policy makers should consider options to reconcile domestic users' demand for fresh water and food consumers' increasing preference for safely irrigated food. The provision of at least partial wastewater treatment before its use in irrigation or the introduction of a monitoring system that establishes transparency in the local food supply chain are possible options.

Appendix

Appendix 2.1: High quality price under full information

Maximisation problem of the high quality farm under full information:

Since L has a dominant strategy ($p_L^F = R$), H optimises given $p_L^F = R$. Hence, demand is $X_H\left(p_H\right) = 1 - F\left(p_H\right)$, the production constraint is $1 - F\left(p_H\right) \leq 1 - \alpha$ and profits are $\pi_H = p_H \cdot \left[1 - F\left(p_H\right)\right]$.

If the production constraint is not binding, let $\overline{p}_H$ be the interior solution which solves $\partial\pi_H / \partial p_H = 0 \Leftrightarrow 1 - F\left(p_H\right) - p_H \cdot \partial F\left(p_H\right) / \partial p_H = 0$.

If the production constraint is binding, the profit maximising price $\tilde{p}_H$ solves $1 - F\left(p_H\right) = 1 - \alpha$. Hence,

(A2.1)
$$\tilde{p}_H = F^{-1}\left(\alpha\right).$$

We obtain a threshold value $\hat{\alpha}$ where *H*'s production constraint becomes binding. At the threshold $\hat{\alpha}$ equates $\overline{p}_H = \tilde{p}_H$. Using (A2.1) we obtain

(A2.2)
$$\hat{\alpha} = F\left(\overline{p}_H\right).$$

Hence, the high quality full information price is given with

(2.1)
$$p_H^F = \begin{cases} \overline{p}_H & if \quad 0 \leq \alpha \leq \hat{\alpha} \\ \tilde{p}_H & if \quad \hat{\alpha} < \alpha \leq 1. \end{cases}$$

Appendix 2.2: Proof of Proposition 2.1

Proof: First, note that $\pi_A^F(\alpha)$ is continuous at $\hat{\alpha}$ because $\bar{p}_H = \tilde{p}_H$ yields $\hat{\alpha}$ (A2.2). We can show that the welfare function is increasing for $0 \le \alpha \le \hat{\alpha}$ and decreasing for $\hat{\alpha} < \alpha \le 1$. First, we show that the welfare function is increasing for $0 \le \alpha \le \hat{\alpha}$. The welfare function is $\pi_A^F(\alpha) = R \cdot \alpha + \int_{\bar{p}_H}^{R+1} \theta \cdot f(\theta) \; d\theta$. The integral is a constant because $\bar{p}_H$ is independent of α. The derivative of total welfare with respect to α is strictly positive $\partial W(\alpha)/\partial\alpha = R > 0$. Hence, increasing α increases total welfare because water is transferred from unproductive use in high quality to productive use in low quality. Second, we show that the welfare function is decreasing for $\hat{\alpha} < \alpha \le 1$. The welfare function is $\pi_A^F(\alpha) = R \cdot \alpha + \int_{\tilde{p}_H(\alpha)}^{R+1} \theta \cdot f(\theta) \; d\theta$. Both terms on the right side of the equation depend on α. The derivative $\partial\pi_A^F(\alpha)/\partial\alpha = R - \tilde{p}_H$ describes the welfare effect of the switch of the marginal consumer from the high quality sector to the low quality sector. R is the welfare gain in terms of L 's profits in the low quality segment. $\tilde{p}_H$, on the other hand, is the welfare in the high quality segment. With increasing α, H is more constrained in its production and increases price until demand meets corresponding production. We have $\tilde{p}_H(\alpha) > R$ and $\partial\pi_A^F(\alpha)/\partial\alpha$ is strictly negative. The maximum of the welfare function is therefore $\alpha^* = \hat{\alpha}$. ■

Appendix 2.3: High quality separation price

To assure price separation the high quality farm sets a price that renders the low quality farm indifferent between separation and pooling. Hence, the separation constraint is $\pi_L^S = \pi_L^P$, which is $R \cdot \alpha = p_H \cdot \alpha \cdot \left[1 - F\left(\hat{\theta}\right)\right]$.

1) A degenerate equilibrium results for $\alpha = 0$. Since the low quality farm does not produce, its profit is zero no matter its price. Furthermore, consumers face certainty about quality since only the high quality farm produces. The high quality farm sets its full information price, $p_H^F(\alpha = 0)$.

2) For $\alpha \neq 0$ we have to solve $R - p_H \cdot \left[1 - F\left(\hat{\theta}\right)\right] = 0$. We obtain two solutions. The first is $p_H = R$. Then $\hat{\theta} = R$ and consequently $F\left(\hat{\theta}\right) = F(R) = 0$. The second solution is $p_H = p_H^D$, where p_H^D equates $\left[R - p_H^D \cdot \left(1 - F\left[\hat{\theta}\left(p_H^D, \alpha\right)\right]\right)\right] \;/\; \left(p_H^D - R\right) = 0$

The threshold $\hat{\hat{\alpha}}$ between the (distorted) separating price $p_H^D(\alpha)$ and the (undistorted) full information price $p_H^F(\alpha)$ equates $p_H^D\left(\hat{\hat{\alpha}}\right) = p_H^F\left(\hat{\hat{\alpha}}\right)$.

For $0 \leq \alpha < \hat{\hat{\alpha}}$ it is profit maximizing to set the separating price while for $\hat{\hat{\alpha}} \leq \alpha \leq 1$ it is profit maximizing to set the undistorted price. The high quality separation price is therefore

(2.2)
$$p_H^S = \begin{cases} p_H^D & if \quad 0 \leq \alpha < \hat{\hat{\alpha}} \\ p_H^F & if \quad \hat{\hat{\alpha}} \leq \alpha \leq 1. \end{cases}$$

For the uniform distribution $p_H^D = 1 - \alpha$. This means that for any high quality price $R < p_H < 1 - \alpha$, the low quality farm will pool, since $\pi_L^S < \pi_L^P$. Note, that $R < p_H$ is a dominant strategy for H because $\pi_H^S\left(p_H^D\right) = (1-\alpha)\cdot(\alpha + R) > (1-\alpha)\cdot R = \pi_H^S(R)$ which allows prices which the low quality farm will pool only if $R < 1 - \alpha$. Otherwise, if $R \geq 1 - \alpha$, the polling profit of the low quality farm is lower or equal to its separating profit for all high quality prices. Since the minimum value of α is zero, any high quality price higher than R induces a separating equilibrium when $R \geq 1$. The high quality farm does not need to distort its price.

Appendix 2.4: Pooling price

The high quality farm sets p_H to maximise its pooling profit $\pi_H^P = p_H \cdot (1-\alpha) \cdot \left(1 - F\left\lfloor\hat{\theta}\left(p_H\right)\right\rfloor\right)$.

1) A degenerate equilibrium results for $\alpha = 1$: Any price $p_H \geq 0$ yields zero profit because there is no high quality production.

2) For $\alpha < 1$, let p_H^P equate $1 - F\left(\hat{\theta}\left(p_H\right)\right) - p_H \frac{\partial F}{\partial \hat{\theta}} \cdot \frac{\partial \hat{\theta}}{\partial p_H} = 0$.

The threshold $\hat{\hat{\alpha}}$ equates pooling and separating profit

$$p_H^P\left(\hat{\hat{\alpha}}\right)\cdot\left(1-\hat{\hat{\alpha}}\right)\cdot\left[1-F\left(\hat{\theta}\left[p_H^P\left(\hat{\hat{\alpha}}\right),\hat{\hat{\alpha}}\right]\right)\right]=p_H^S\left(\hat{\hat{\alpha}}\right)\cdot\left(1-F\left[p_H^S\left(\hat{\hat{\alpha}}\right)\right]\right).$$

Appendix 2.5: Total welfare under asymmetric information

Total welfare under asymmetric information is the sum of high quality profit, low quality profit and consumer surplus. High quality profit is

(A2.3)

$$\pi_H=\begin{cases}\tilde{p}_H^P\cdot(1-\alpha)\cdot\int_{\hat{\theta}}^{R+1} f(\theta)\ d\theta & \text{if}\quad 0\le\alpha<\hat{\hat{\alpha}}\\ p_H^D\cdot\int_{p_H^D}^{R+1} f(\theta)\ d\theta & \text{if}\quad \hat{\hat{\alpha}}\le\alpha<\hat{\alpha}\\ \tilde{p}_H\cdot\int_{\tilde{p}_H}^{R+1} f(\theta)\ d\theta & \text{if}\quad \hat{\alpha}\le\alpha\le 1.\end{cases}$$

Low quality profit is

(A2.4)

$$\pi_L=\begin{cases}\tilde{p}_H^P\cdot\alpha\cdot\int_{\hat{\theta}}^{R+1} f(\theta)\ d\theta & \text{if}\ 0\le\alpha<\hat{\hat{\alpha}}\\ R\cdot\alpha & \text{if}\ \hat{\hat{\alpha}}\le\alpha\le 1\end{cases}$$

Consumer surplus in the low quality segment is zero and in the high quality segment

(A2.5)

$$\pi_C=\begin{cases}\int_{\hat{\theta}}^{R+1}\left[\theta\cdot(1-\alpha)+R\cdot\alpha-\hat{p}_H^P\right]\ d\theta & \text{if}\quad 0\le\alpha<\hat{\hat{\alpha}}\\ \int_{\hat{\hat{p}}_H^S}^{R+1}\left(\theta-\hat{\hat{p}}_H\right)\cdot f(\theta)\ d\theta & \text{if}\quad \hat{\hat{\alpha}}\le\alpha<\hat{\alpha}\\ \int_{\hat{p}_H^S}^{R+1}\left(\theta-\hat{p}_H\right)\cdot f(\theta)\ d\theta & \text{if}\quad \hat{\alpha}\le\alpha\le 1.\end{cases}$$

Total welfare is the sum of A2.3 – A2.5:

(A2.6)

$$\pi_A(\alpha)=\begin{cases}\int_{\hat{\theta}}^{R+1}\left[\theta\cdot(1-\alpha)+R\cdot\alpha-p_H^P\right]d\theta+\pi_H+\pi_L & \text{if}\quad 0\le\alpha<\hat{\hat{\alpha}}\\ R\cdot\alpha+\int_{\hat{\hat{p}}_H^S}^{R+1}\theta\cdot f(\theta)d\theta & \text{if}\quad \hat{\hat{\alpha}}\le\alpha<\hat{\alpha}\\ R\cdot\alpha+\int_{\hat{p}_H^S}^{R+1}\theta\cdot f(\theta)d\theta & \text{if}\quad \hat{\alpha}\le\alpha\le 1.\end{cases}$$

Chapter 3

Incentives and Cost Recovery in Wastewater Treatment in Developing Countries: Modelling the Urban Water Chain*

To improve wastewater treatment in developing countries new approaches to design wastewater treatment schemes have been developed. These can be operated successfully only if the right incentives are in place and costs can be recovered. In this chapter we analyze how a regulator should set incentives to maximize benefits of wastewater treatment while cost recovery is feasible. We study incentives by integrating a compliance game between a regulator and small scale industrial polluters into a model of the urban water chain. Our model indicates that costs can be recovered without charges to polluters or beneficiaries of wastewater treatment in some settings where fines are collected from firms for violating water quality regulations. Furthermore, we find that net benefits of wastewater treatment can be negative and conclude that cheaper treatment technologies need to be developed.

*This chapter is based on Gengenbach and Weikard (2010b). Paper presented at the Tenth Biennial Conference of the International Society of Ecological Economists (ISEE) 2008 in Nairobi, Kenya. Manuscript submitted.

3.1. Introduction

In many developing countries urban wastewater is insufficiently treated resulting in health risks and environmental hazards. Scott, Faruqui and Raschid (2004) report that the proportion of urban wastewater that is treated to secondary level is zero for Africa, 35% for Asia, and 14% for Latin America and the Caribbean. Wastewater treatment in developing countries has largely failed because it has been designed as 'high-tech' centralized treatment similar to treatment plants operated in industrialized countries. The drawbacks of this design are high initial investments and high costs for operation and maintenance. Consequently, cost for operation and maintenance could not be recovered in many cases where facilities have been installed. Hence, centralized systems "are now being questioned with respect to sustainability as well as their applicability to developing countries" (Asano 2005).

New conceptual approaches to designing wastewater treatment schemes in developing countries are suggested. The water chain approach (Huibers and van Lier 2005) designs schemes taking into account the entire chain of water pollution, wastewater treatment and its reuse integrating pollution reduction with wastewater treatment and wastewater treatment with the reuse of treated wastewater. The reuse of treated wastewater in irrigation serves for example as a wastewater treatment step. Nhapi, Siebel and Gijzen (2005) propose a three step strategic approach consisting of pollution prevention and minimization (step 1), reuse after treatment (step 2), and discharge into the environment (step 3). Both approaches integrate regulation of water pollution, wastewater treatment and its reuse in the design process and claim that effective treatment can be established at lower costs. Regulation of water pollution is the crucial factor in both approaches because it is the most upstream action in the chain. A common example is when domestic and industrial polluters discharge wastewater in a common sewer where it blends together as urban wastewater. Regulation of water pollution demands pre-treating industrial wastewater to prevent industrial pollutants from entering urban wastewater which avoids the need to employ costly 'high-tech' treatment. For regulation to be effective it has to be enforced. As in many developing countries proper institutions are not established, enforcement of environmental regulation can be difficult. Lonholdt, Elberg Jorgensen and O'Hearn (2006, p.126) report that "industries in Thailand, as in many other Asian countries, are traditionally rather 'closed' towards the outside world" which results in "a sometimes rather sporadic enforcement effort". In this chapter we integrate a compliance game between a regulator and industrial polluters into a model of the urban water chain in order to analyze how the regulator should set incentives to maximize benefits of wastewater treatment while cost recovery is feasible.

Studies on economic incentives for the entire wastewater treatment chain from water pollution to wastewater treatment and to its reuse for irrigation are scarce in a developing country context. The literature has rather focused on parts of the chain in industrialised countries where strong institutions assure treatment cost recovery and enforce safety guidelines for wastewater reuse. Kilgour, Okada and Nishikori (1988) and Sauer et al. (2003) have focused on incentives in regulating water pollution, whereas incentives in wastewater treatment were studied by Schwarz and McConnell (1993) and Earnhart (2004). Incentives in wastewater treatment and reuse were studied by Haruvy et al. (1999), Feinerman, Plessner, and DiSegni Eshel (2001) and Axelrad and Feinerman (2009, 2010). The reuse of wastewater in irrigation was studied by Dinar and Yaron (1986), Haruvy (1997, 1998) and Fine, Halperin and Hadas (2005). They conduct cost benefit studies on wastewater reuse in irrigation focusing on optimization of regional or national net benefits concerning wastewater reuse in different settings in Israel and the USA. Other studies analyze individual incentives of stakeholders. Loehman et al. (1979), Dinar, Yaron and Kannai (1986), Loehman and Dinar (1994) and Lejano and Davos (1995) use cooperative game theory to allocate costs and benefits of wastewater reuse projects for different settings in Israel and the USA.

In this chapter we consider a typical urban setting in a developing country where households and firms are not separated into distinct zones. Households and firms produce domestic and industrial wastewater, respectively. The following wastewater treatment scheme is designed in accordance with the water chain approach. Firms are required to pre-treat their industrial wastewater to domestic wastewater quality before discharge. A public water utility monitors whether firms pre-treat their wastewater. Pre-treated industrial and domestic wastewater is captured jointly and conveyed to a treatment plant which is designed to treat domestic wastewater to enable its safe reuse in irrigation. This setting raises two research questions. First, how does the water utility maximize net benefits of a treatment scheme by choosing the optimal monitoring rate? Second, can the costs of the treatment scheme be recovered for the optimal monitoring rate?

To answer these questions we model a two stage compliance game where the water utility cannot readily observe the compliance of firms. At the first stage the water utility chooses the monitoring rate in order to set incentives for firms to comply. At the second stage each firm decides to comply and discharge pre-treated wastewater or to defect and discharge raw industrial wastewater. These decisions determine the fraction of raw industrial wastewater in urban wastewater which determines the effectiveness of wastewater treatment and ultimately benefits of wastewater reuse. We model the treatment of urban wastewater as a production process with urban wastewater as input, treated wastewater as output and the treatment technology as production function: the higher the fraction of raw industrial wastewater in urban wastewater, the less effective is the treatment process; the less effective the treatment process, the higher the damages to downstream population, farmers, and the environment.

Our study contributes to the literature in several ways. First, it provides a formal model to analyze economic incentives in the entire urban water chain consisting of water pollution, wastewater treatment and its reuse in a developing country context. The model can, however, easily be adapted to developed country settings. One topical application in Europe is wastewater treatment upgrading under the EU Water Framework Directive which aims at managing water at the basin level to achieve good ecological status under the full cost recovery principle (European Commission 2000). The second distinguishing feature is related to the modelling of water. In economic studies on wastewater reuse wastewater is almost exclusively modelled with only one quality dimension. We model wastewater with multiple dimensions where each dimension represents the concentration level of one pollutant. This enables us to trace the concentration levels of each pollutant along the water chain which substantially increases transparency in two ways. First, welfare effects can be captured in more detail by specifying the benefit and cost functions for each pollutant along the chain. Second, the effect of pollutants on the treatment process can be specified explicitly. Salinity, for example, can strongly inhibit the aerobic biological treatment of wastewater (Lefebvre and Moletta 2006). We develop this example further in a later section.

This chapter is structured as follows. The next section introduces the model. Section 3.3 provides the general solution. Then we turn to a common scenario where industrial wastewater is highly saline to illustrate how our approach works. Section 3.5 offers discussion and conclusions.

3.2 The Model

We introduce the model in two parts. First, we present the relevant bio-chemical, physical, and technical characteristics of the urban water chain. This comprises identifying the pollutants in the wastewater, the wastewater treatment technology and the pollutants' concentration levels before and after treatment. Subsequently, we introduce the economics of the urban water chain: the agents of the compliance game, firms and the water utility, with their strategies and payoffs. A list of symbols summarising the use of notation can be found in the Appendix of this chapter. Our model is static where the parameters (water flow, monitoring, costs, etc.) are specified for one period which can be e.g. a week or a season, depending the setting.

The urban water chain

We model the entire urban water chain consisting of water pollution, wastewater treatment and its reuse. We assume that a fixed quantity of wastewater discharge per period, of which households and firms generate shares α and $1-\alpha$, respectively. Domestic and raw industrial wastewaters are characterized by their concentration levels for a set $K=\{1,\ldots,k\}$ of pollutants. For the purpose of this study it is sufficient to consider a pollutant either if it generates costs or benefits downstream (reuse) or if it influences the effectiveness of the treatment process.[7] The k concentration levels characterize the quality of domestic and raw industrial wastewater. Formally domestic and raw industrial wastewater quality is represented by vectors $q^D=\left(q_1^D,\ldots,q_k^D\right)$ and $q^R=\left(q_1^R,\ldots,q_k^R\right)$, respectively. Households and firms discharge their wastewater into the sewer where it becomes urban wastewater which is characterized by $q^U=\left(q_1^U,\ldots,q_k^U\right)$. While households discharge directly, firms are required to pre-treat their raw industrial wastewater to domestic wastewater quality. Firms, however, might not comply with the requirement to pre-treat and discharge raw industrial wastewater which renders urban wastewater a blend of domestic wastewater and raw industrial wastewater. Let the compliance rate χ be the fraction of complying firms. Then the concentration for each pollutant $i\in K$ in urban wastewater is

(3.1)
$$q_i^U(\chi)=(\alpha+(1-\alpha)\cdot\chi)\cdot q_i^D+(1-\alpha)\cdot(1-\chi)\cdot q_i^R.$$

Urban wastewater is conveyed to a treatment plant. Treated wastewater is characterized by $q^T=\left(q_1^T,\ldots,q_k^T\right)$. The concentration levels of pollutant $i\in K$ in treated wastewater is

(3.2)
$$q_i^T=\phi_i\left(q_1^U,\ldots,q_k^U\right)\cdot q_i^U$$

where $\phi_i\left(q_1^U,\ldots,q_k^U\right)$ is the treatment function for pollutant i which may depend on the concentration levels of all pollutants in urban wastewater. The treatment function has a straightforward interpretation. Its value is the fraction of pollutant i's concentration that remains in treated wastewater. Hence, the lower the value of the treatment function, the

[7] See Toze (2006) for a general overview on risks and benefits of the reuse of effluent.

lower is the concentration of pollutants in treated wastewater. The treatment function can take values between $\hat{\phi}_i$ ($0 \le \hat{\phi}_i \le 1$) and 1.[8] The value $\hat{\phi}_i$ reflects the maximum treatment effectivity. Maximum treatment effectivity is achieved when the concentrations of all pollutants in urban wastewater are at the level for which the treatment process was designed.[9] Here we assume that the treatment plant is designed for domestic wastewater, $q_j^U = q_j^D$ for all $j \in K$. If, however, the concentrations of some pollutants $j \in K$ deviate from this level, $q_j^U \neq q_j^D$, and the treatment process is sensitive to this deviation, $\partial\phi_i\left(q_1^U,..,q_k^U\right)/\partial q_j^U > 0$ for $q_j^U > q_j^D$ or $\partial\phi_i\left(q_1^U,..,q_k^U\right)/\partial q_j^U < 0$ for $q_j^U < q_j^D$ the treatment process becomes partially ($\hat{\phi}_i < \phi_i < 1$) or totally ineffective ($\phi_i = 1$). In most cases the pollutant concentration in urban wastewater would be higher than in domestic wastewater, $q_j^U > q_j^D$. But note that we do not rule out the possibility that concentrations lower than q_j^D can also hamper treatment. An example is a biological treatment with bacteria that need a minimum concentration of a target pollutant to perform optimally. Another example of the sensitivity of a treatment process is that a high concentration of salinity inhibits the biological treatment process which removes other pollutants. We will discuss this case below.

The compliance game

Given these characteristics of the urban wastewater flow, we now present the agents of the compliance game, i.e. firms and the water utility with their strategies and payoffs.

Firms: We assume that each of m firms in the set $M = \{1,...,m\}$ generates a quantity $(1-\alpha)/m$ of raw industrial wastewater, characterized by $q^R = \left(q_1^R,...,q_k^R\right)$ where the concentration of at least one pollutant i is higher than in domestic wastewater, $q_i^R > q_i^D$. A regulation requires firms to decrease the concentrations of these pollutants to domestic wastewater concentrations before discharge. Whether a firm complies with the regulation is private information to the firm and cannot be observed by the water utility without costly

[8] Note that if $\hat{\phi}_i = 1$, then $\phi_i = 1$. This does not represent total breakdown of the process but rather that the treatment process was not designed for this particular pollutant.

[9] We do not consider any other problems, for example weather conditions that potentially influence the effectiveness of the plant.

monitoring. The general characteristics of firms are, however, public information. We assume that firms are identical except for their pre-treatment costs c_M which are assumed to be uniformly distributed over an interval $\left[\underline{c},\overline{c}\right]$.

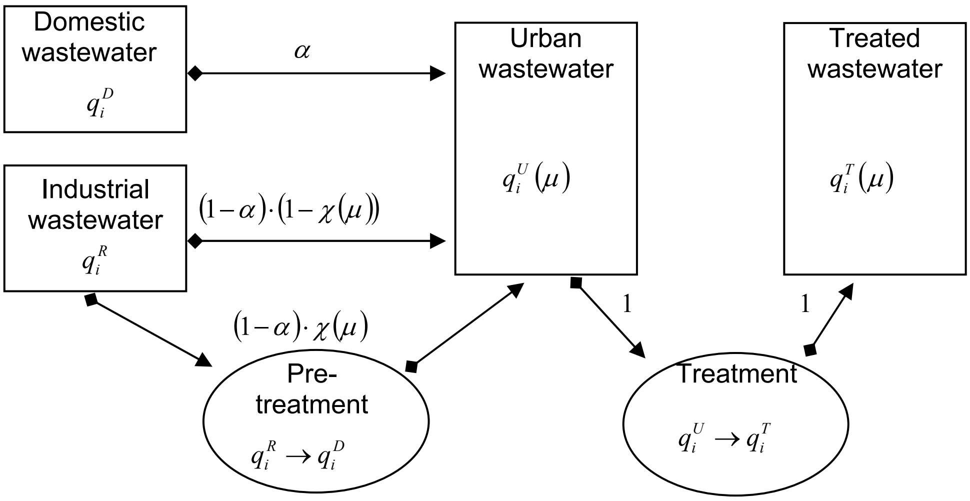

Diagram 3.1: Water composition and quality in the urban water flow.

A firm complies with the regulation if its pre-treatment costs are lower than or equal to the expected value of the fine that it may have to pay if it does not comply. The expected value of the fine is the product of the fine f and the probability of being fined which is the monitoring rate μ. Generally a firm $l \in M$ complies if $c_M^l \leq \mu \cdot f$. We assume that the fine is exogenously given and larger or equal to the highest pre-treatment costs, $f \geq \overline{c}$ which enables to induce full compliance. The compliance rate is zero if the monitoring rate is too low to force the firm with the lowest pre-treatment cost to comply. Otherwise it is $\int_{\underline{c}}^{\mu\cdot f} 1 \ /\left(\overline{c}-\underline{c}\right)dc = \left(\mu\cdot f-\underline{c}\right)/\left(\overline{c}-\underline{c}\right)$. Hence, we have

(3.3)
$$\chi(\mu)=\begin{cases} 0 & \text{if} \quad 0 \leq \mu \leq \underline{c}/f \\ \left(\mu\cdot f-\underline{c}\right)/\left(\overline{c}-\underline{c}\right) & \text{if} \quad \underline{c}/f < \mu < \overline{c}/f \\ 1 & \text{if} \quad \overline{c}/f \leq \mu \leq 1. \end{cases}$$

Substituting Eq.3.1 and Eq.3.3 into Eq.3.2 yields the concentration of the different pollutants in treated wastewater depending on the monitoring rate

(3.4) $$q_i^T(\mu) = \phi_i\left(q_1^U\left(\chi(\mu)\right),...,q_k^U\left(\chi(\mu)\right)\right)\cdot q_i^U\left(\chi(\mu)\right).$$

Diagram 1 sketches our model of the urban water flow.

The water utility: The water utility maximizes net benefits of the water chain by setting the monitoring rate μ. Five items determine net benefits: (i) baseline treatment benefits (ii) monitoring benefits (iii) treatment costs (vi) monitoring costs, and (v) compliance costs. Note, that fines do not add to net benefits because they are revenues for the water utility but costs for firms. Baseline treatment benefits, denoted by $\overline{B}$, capture the benefits of the treatment plant when the monitoring rate is zero which means that pre-treatment is not enforced. $\overline{B}$ is zero if the treatment process breaks down completely in the absence of monitoring; else $\overline{B}$ is positive. The second item is monitoring benefits. Monitoring motivates firms to pre-treat their wastewater which induces a higher effectivity of treatment and therefore reduces pollutant concentrations in treated wastewater. This reduction of pollution generates benefits along the urban water chain. Using (3.4) the monitoring benefits is given by

(3.5) $$B(\mu) = B\left(q_1^T(\mu),...,q_k^T(\mu)\right),$$

with $\partial B(\mu)/\partial\mu > 0$. The third item, treatment costs, is the operation costs of the treatment plant which is given by c_T. The fourth, monitoring costs, are given as the number of firms monitored, $\mu \cdot m$, times the costs of monitoring per firm $c_\mu > 0$. The fifth, compliance costs, are the sum of the individual pre-treatment costs of all complying firms, $\int_0^{f\cdot\mu} \frac{c}{\overline{c}-\underline{c}}\,dc = \frac{(f\cdot\mu)^2}{2(\overline{c}-\underline{c})}$. Putting together (i) – (v) net benefits are

(3.6) $$\pi(\mu) = \overline{B} + B(\mu) - c_T - \mu\cdot m\cdot c_\mu - \frac{\left(f\cdot\mu\right)^2}{2\cdot\left(\overline{c}-\underline{c}\right)}$$

The water utility must recover treatment and monitoring costs, $c_T + \mu\cdot m\cdot c_\mu$ from charges to households p_D, farmers p_F, and firms p_M, and revenues from fines. We model revenues from fines as an expected value. Since the water utility monitors m firms of which $1-\chi(\mu)$ do not comply it expects to collect fines from $m\cdot\left[1-\chi(\mu)\right]\cdot\mu$ firms. The budget constraint is

(3.7) $$c_T + \mu \cdot m \cdot c_\mu \leq p_D + p_F + p_M + m \cdot [1 - \chi(\mu)] \cdot \mu \cdot f \ .$$

Note that, in developing countries the ability to collect charges from households and farms is usually limited. We will address this in the example in section 3.4.

3.3 General Results

We now turn to the optimal monitoring rate in the compliance game. The water utility maximizes net benefits by choosing the monitoring rate μ (Eq.3.6) under the budget constraint (Eq.3.7). The Lagrangian function for this problem is

(3.8) $$L = \overline{B} + B(\mu) - c_T - \mu \cdot m \cdot c_\mu - \frac{1}{2} \cdot (f \cdot \mu)^2 / (\overline{c} - \underline{c})$$
$$+ \lambda \cdot \left(c_T + \mu \cdot m \cdot c_\mu - p_D - p_F - p_M - m \cdot (1 - \chi(\mu)) \cdot \mu \cdot f\right)$$

We have to distinguish two cases. First, the budget constraint is not binding which yields an interior solution where the optimal monitoring rate yields the global optimum. Then, $\lambda = 0$ and we obtain Eq.3.9 by setting the first derivative of the net benefit function (Eq.3.6) equal to zero. Solving Eq.3.9 yields the optimal monitoring rate $\mu*$. Marginal monitoring benefits must be equal to marginal monitoring costs plus marginal compliance costs

(3.9) $$\partial B(\mu) / \partial \mu = m \cdot c_\mu + \mu \cdot f^2 / (\overline{c} - \underline{c})$$

In the second case, the budget constraint is binding. This yields a corner solution where the global optimum cannot be realized. Then, $\lambda > 0$ and the budget constraint (Eq.3.7) must hold with equality. Hence, the optimal monitoring rate $\mu*$ solves Eq.3.10. Costs from treatment and monitoring must be recovered by revenues from water charges and fines

(3.10) $$c_T + \mu * \cdot m \cdot c_\mu = p_D + p_F + p_M + m \cdot [1 - \chi(\mu*)] \cdot \mu * \cdot f \ .$$

The analytical results from the model can be summarized as follows. First, Eq.3.9 shows that high marginal benefits from monitoring yield a high optimal monitoring rate. Second, the budget constraint (Eq.3.7) shows how the monitoring rate determines budget balancing. Monitoring drives two elements in the budget constraint, monitoring costs and revenues from fines. Monitoring costs are zero for zero monitoring and increase linearly with the monitoring rate. Revenues from fines are zero for zero monitoring because no firm is caught. As the monitoring rate increases revenues increase, reach a maximum and fall to zero for a monitoring rate of 1 because all firms comply. For small monitoring rates monitoring costs and revenues from fines are small. This generates only a moderate effect on the budget constraint. For medium monitoring rates revenues from fines are high. This favours budget balancing. For high monitoring rates revenues from fines are low while monitoring costs keep increasing, which renders budget balancing difficult. A third result is obtained from the budget constraint (Eq.3.7). Rewriting yields $(c_T - p_D - p_F - p_M)/m \leq \mu^*\left[\left(1-\chi(\mu^*)\right)\cdot f - c_\mu\right]$. It appears that meeting the budget constraint would be easier for a larger number of firms (larger m) provided that μ^* is constant. The latter, however, does not hold since a change in the number of firms changes the optimal monitoring rate (Eq.3.9) which, in turn, changes revenues from fines. Hence, to be able to draw conclusions we need to establish two relations. The first is the relation between the number of firms and the optimal monitoring rate, $\mu^*(m)$. The second is the relation between the optimal monitoring rate and revenues from fines, $\left(1-\chi(\mu^*)\right)\cdot f$. Because the optimal monitoring rate cannot be determined explicitly without further specifications of the model, it is impossible to obtain more detailed insights. In order to make further progress in the analysis we employ a numerical example where we specify the relevant functions and parameters. We turn to this in the next section.

3.4. The example of small scale leather processing

In this section we illustrate our model with a numerical example about the leather processing industry in developing countries. An example from India is provided by Lefebvre et al. (2006) which motivates the general setting. Tannery wastewater is characterized by high salinity as salt is used to preserve the fresh skins from decomposition after they are stripped off the animal. The salt is removed in the tannery before further processing by soaking which generates a highly saline effluent. Pre-treatment is suggested before the effluent is blended with non-saline domestic wastewaters.

We first stipulate parameters of the physical water flow. All parameter values that we introduce in the following are listed in the Appendix of this chapter for readers' convenience. Water is characterized by the concentrations of nutrients, faecal coliform bacteria, and salinity, $K = \{N, P, S\}$. We normalize concentrations to ranges between zero and one for minimal and maximal concentration, respectively. The concentration of nutrients, faecal coliform bacteria is one for domestic and industrial wastewater. The salinity concentration is low in domestic and high in industrial wastewater. This specification helps to isolate the inhibition of the treatment process due to high salinity. Hence, domestic and industrial wastewater differ only in their salinity concentration and are characterized by $q^D\left(q_N^D, q_P^D, q_S^D\right) = (1,1,0)$ and $q^R\left(q_N^R, q_P^R, q_S^R\right) = (1,1,1)$, respectively. We assume that the share of domestic wastewater to urban wastewater is $\alpha = 0.75$.

To specify the wastewater treatment process we assume that removal rates under optimal conditions of nutrients and faecal coliform bacteria are 80% and 90%, respectively. This implies $\hat{\phi}_N = 0.2$ and $\hat{\phi}_P = 0.1$. Excess nutrient and pathogen concentration does not influence nutrient and pathogen removal, $\partial\phi_N / \partial q_N^U = 0$, $\partial\phi_N / \partial q_P^U = 0$, $\partial\phi_P / \partial q_N^U = 0$, and $\partial\phi_P / \partial q_P^U = 0$. The technology does not remove salt. Hence, $\hat{\phi}_S = 1$, and $\partial\phi_S / \partial q_S^U = \partial\phi_S / \partial q_N^U = \partial\phi_S / \partial q_P^U = 0$. Excess salt, however, inhibits biological processes for nutrient and pathogen removal such that ϕ_N and ϕ_P increase with salt concentrations (Dincer and Kargi 1999 and 2001, Uygur and Kargi 2004). Formally this is reflected in the partial derivatives of the treatment function, $\partial\phi_N / \partial q_S^U = 3$ and $\partial\phi_P / \partial q_S^U = 2$. Substituting these specifications in Eq.3.4 yields the concentration of individual pollutants in treated wastewater depending on compliance and ultimately on the monitoring rate. First notice that pre-treatment only reduces salinity. Therefore, $q_N^U = q_P^U = 1$ which is independent of compliance. Assuming linear treatment functions with slopes as defined above we have $q_N^T = 0.2 + 3 \cdot q_S^U(\chi) \cdot q_N^U$ and $q_P^T = 0.1 + 2 \cdot q_S^U(\chi) \cdot q_P^U$. Using Eq.3.1 we obtain $q_S^U = (0.75 + 0.25 \cdot \chi) \cdot 0 + 0.25 \cdot (1-\chi) \cdot 1 = 0.25 - 0.25 \cdot \chi$ for the salt concentration in untreated wastewater. Hence, concentrations of nutrients, faecal coliform bacteria, and salt are $q_N^T = 0.95 - 0.75 \cdot \chi$, $q_P^T = 0.6 - 0.5 \cdot \chi$, and $q_S^T = 0.25 \cdot \left(1-\chi\right)$, respectively.

We now turn to the treatment and monitoring benefits. We have specified the treatment technology such that the treatment process breaks down only partially for a compliance rate of zero. We have $q_N^T(\chi=0)=0.95$ and $q_P^T(\chi=0)=0.6$. Hence, baseline treatment benefits are positive and we assume $\overline{B}=0.9$. Next, we specify the monitoring benefits (Eq.3.5). We already specified how the compliance rate determines the pollutant concentration in treated wastewater. We now specify how the reduction of pollutant concentration in treated wastewater generates benefits. Two monitoring benefits are relevant when wastewater is reused in agriculture.[10] The first captures how the removal of faecal coliform bacteria in wastewater reduces health costs to the local population. The affected local population comprises for example workers in wastewater irrigated agriculture and consumers of wastewater irrigated food (Gengenbach and Weikard, 2010a). We assume that full compliance brings about effective treatment, $\hat{\phi}_P = q_P^T(\chi=1)$, which reduces health costs to zero, $\underline{C}_P = 0$. By contrast, without monitoring the compliance rate is zero and brings about the highest concentration of bacteria, $\overline{q}_P^T = q_P^T(\chi=0)$, which causes health costs of $\overline{C}_P > 0$. For simplicity, we assume the relation between the concentration of coliform bacteria and health costs to be linear. Hence, health costs are $C_P(\chi)=\overline{C}_P-\overline{C}_P\cdot\left(\overline{q}_P^T-q_P^T(\chi)\right)/\left(\overline{q}_P^T-\hat{\phi}_P\right)$. Monitoring benefits of reduced health costs are $B_P(\chi)=\overline{C}_P-C_P(\chi)$ and consequently $B_P(\chi)=\overline{C}_P\cdot\left(\overline{q}_P^T-q_P^T(\chi)\right)/\left(\overline{q}_P^T-\hat{\phi}_P\right)$. For our base case we consider low health costs of $\overline{C}_P=0.1$. This resembles a setting where the risk of infection is low as in settings with low population density. With increasing density, however, the risk of infection and the related health costs grow. We run two additional numerical simulations with $\overline{C}_P=0.5$, and $\overline{C}_P=1$. The second monitoring benefit captures how the removal of excess nutrients in wastewater generates benefits by increasing soil productivity (Magesan et al. 2000) and preventing negative effects on plant growth (Toze 2006). We capture this in a benefit function assuming the following. When the monitoring rate is zero, nutrient concentration is $\overline{q}_N^T = q_N^T(\chi=0)$ for which costs of excess nutrient concentration are $\underline{C}_N=1$. By contrast, a monitoring rate of one reduces the concentration to $\hat{\phi}_N = q_N^T(\chi=1)$ for which costs are zero, $\overline{C}_N=0$. For simplicity, we assume the

[10] There are, of course, other benefits. To illustrate qualitative results it is sufficient, however, to consider only one type of benefit for nutrient removal and pathogen removal.

relation between costs and the concentration of nutrients to be linear. Hence, costs are $C_N(\chi) = \underline{C}_N - \underline{C}_N \cdot \left(\overline{q}_N^T - q_N^T(\chi)\right) / \left(\overline{q}_N^T - \hat{\phi}_N\right)$ and monitoring benefits are $B_N(\chi) = \underline{C}_N - C_N(\chi)$ and consequently $B_N(\chi) = \left(\overline{q}_N^T - q_N^T(\chi)\right) / \left(\overline{q}_N^T - \hat{\phi}_N\right)$. Total monitoring benefits are $B(\chi) = B_P(\chi) + B_N(\chi)$.

Finally, we stipulate the parameters of the agents in the game. We assume that the number of firms is $m = 10$. Their pre-treatment costs c_M are uniformly distributed in the interval $\left[\underline{c} = 0, \overline{c} = 1\right]$. We assume that charges to households, farms and firms are zero, $p_D = p_F = p_M = 0$. We do so to identify the cases where costs can be recovered by revenues from fines alone. Note that charges can be positive in other settings. The fine per firm for not complying is $f = 1$. Then, using Eq.3.3, the compliance rate is simply $\chi = \mu \cdot f$. The water utility faces treatment costs of, $c_T = 1$. Monitoring costs are $c_\mu = 0.1$ per firm.

First, we illustrate how the optimal monitoring rate depends on the monitoring benefits. We demonstrate this by varying health costs for zero monitoring, $\overline{C}_P$. Increasing this parameter increases the reduction of health costs by monitoring and therefore increases monitoring benefits. We run our numerical example for three parameter values representing small ($\overline{C}_P = 0.1$), medium ($\overline{C}_P = 0.5$) and high monitoring benefits ($\overline{C}_P = 1$). Note that $\overline{C}_P$ does not appear in the budget constraint which makes the budget the same for all three values of $\overline{C}_P$.

The numerical example illustrates our analytical result that the optimal monitoring rate increases with increasing monitoring benefits. Figure 3.1 shows that for $\overline{C}_P = 0.1$, $\overline{C}_P = 0.5$, and $\overline{C}_P = 1$ the optimal monitoring rates are $\mu^* = 0.1$, $\mu^* = 0.5$, and $\mu^* = 1$, respectively. Furthermore, the figure shows an interesting result. Net benefits are negative for $\overline{C}_P = 0.1$ even at the optimal monitoring rate $\mu^* = 0.1$. This means that the benefits of the treatment scheme will never cover its costs. In this case the treatment scheme does not increase welfare. When monitoring benefits increase, however, net benefits of the treatment scheme become positive for the optimal monitoring rate. This case is illustrated for $\overline{C}_P = 0.5$ with the optimal monitoring rate $\mu^* = 0.5$. As monitoring benefits increase further, the net benefits of the treatment scheme also increase further. Our example shows that for $\overline{C}_P = 1$ the optimal monitoring rate is $\mu^* = 1$ which implies full compliance.

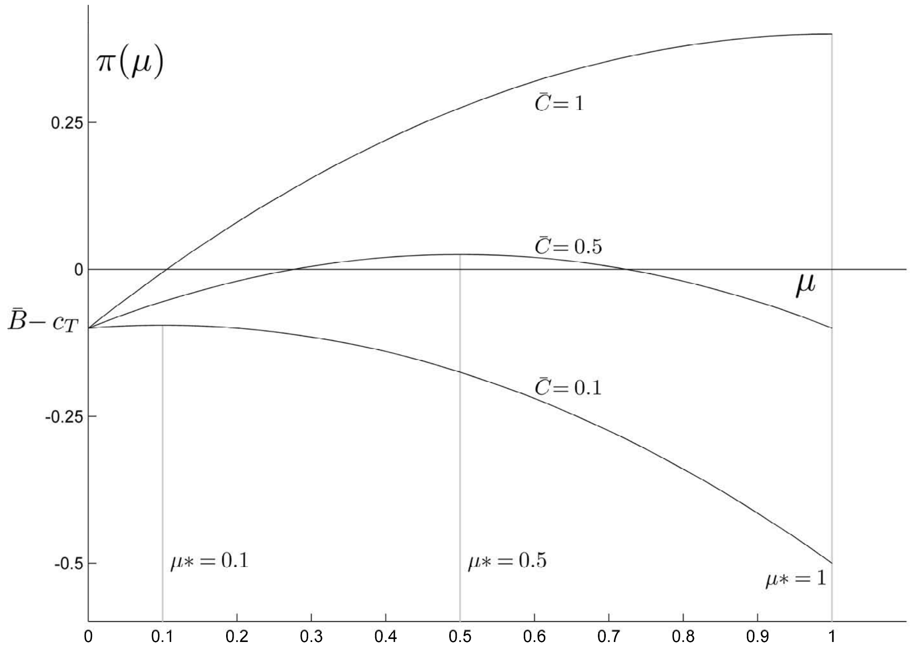

Figure 3.1: Total benefits as a function of the monitoring rate, $\pi(\mu)$, for three different health costs parameters: $\overline{C}_P = 0.1$, $\overline{C}_P = 0.5$, and $\overline{C}_P = 1$. The corresponding optimal monitoring rates are indicated in the graph.

We now illustrate the relation between monitoring benefits and budget recovery for which we could not obtain analytical results. Figure 3.2 shows the domain where the budget constraint is met which is in our case in the interval $[\mu = 0.13, \mu = 0.77]$. The budget balance is positive generating a budget surplus for optimal monitoring rates $0.13 < \mu^* < 0.77$. For $\mu^* = 0.13$ and $\mu^* = 0.77$ the budget is exactly balanced, and for $\mu^* < 0.13$ and $\mu^* > 0.77$ the budget balance is negative generating a deficit. Hence, the water utility cannot recover its costs for both $\overline{C}_P = 0.1$ with $\mu^* = 0.1$, and $\overline{C}_P = 1$ with $\mu^* = 1$. For $\overline{C}_P = 0.5$ with $\mu^* = 0.5$, however, cost recovery is successful.

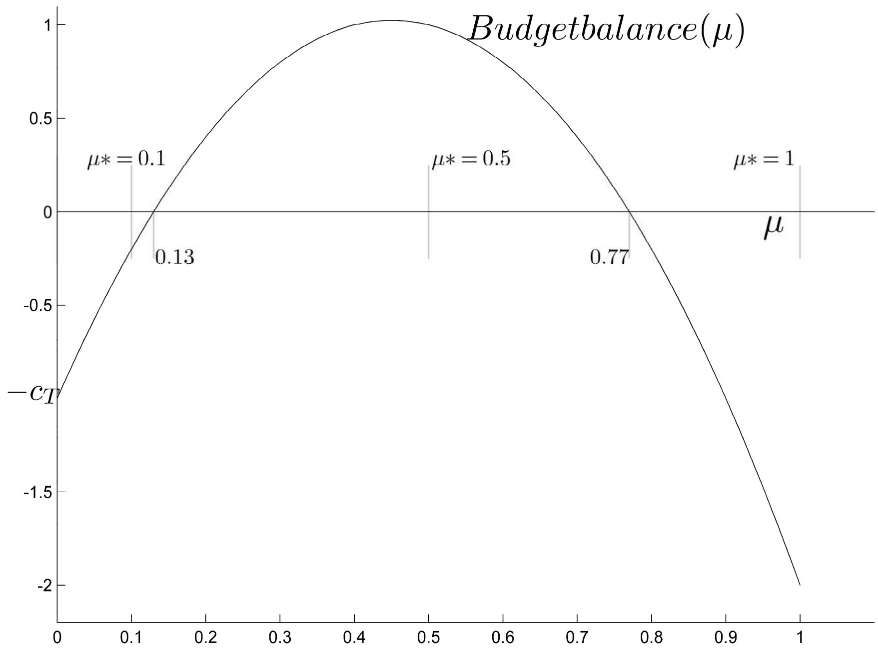

Figure 3.2: Budget surplus as a function of the monitoring rate. The optimal monitoring rates, μ^*, for three different health costs parameters ($\overline{C}_P = 0.1$, $\overline{C}_P = 0.5$, and $\overline{C}_P = 1$) are indicated in the graph.

These numerical results confirm the conjecture of the previous section. For small monitoring rates monitoring costs and revenues from fines are small. Their net effect is too small to recover fixed operation costs. For medium monitoring rates revenues from fines are high which enables the recovery of both monitoring and fixed treatment cost. For high monitoring rates monitoring costs increase, while revenues from fines decrease which renders cost recovery impossible.

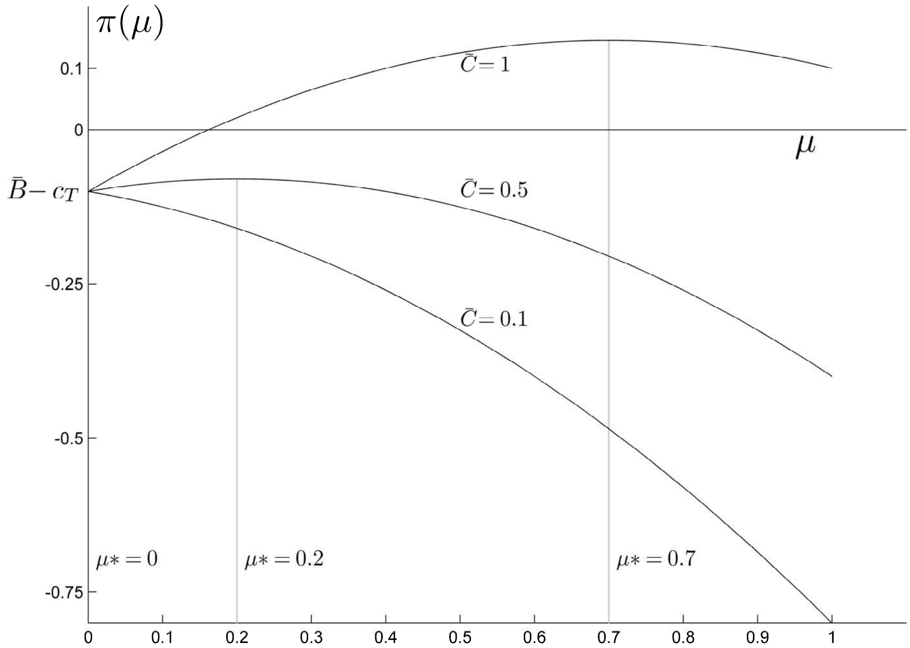

Figure 3.3: Total benefits as a function of the monitoring rate, $\pi(\mu)$, for a 30% increase in firms for three different health costs parameters: $\overline{C}_P = 0.1$, $\overline{C}_P = 0.5$, and $\overline{C}_P = 1$. The corresponding optimal monitoring rates are indicated in the graph.

These results are sensitive to a change in the number of firms. An increase of the number of firms reduces the optimal monitoring rate. Hence, $\partial\mu^* / \partial m < 0$. Figure 3.3 illustrates this for a 30% increase in number of firms where the optimal monitoring rate decreases to $\mu^* = 0$, $\mu^* = 0.2$, and $\mu^* = 0.7$ (compared to $\mu^* = 0.1$, $\mu^* = 0.5$, and $\mu^* = 1$) for low, medium and high health costs, respectively. On the one hand, a lower monitoring rate reduces the effectiveness of the treatment scheme. On the other hand, it facilitates cost recovery because the rates are now in the interval where revenues from fines are sufficiently large. This can be seen in figure 4. Costs can now be recovered for medium and high health costs ($\mu^* = 0.2$, and $\mu^* = 0.7$), not just for medium health cost ($\mu^* = 0.5$) in the case with a smaller number of firms. Note that this is not a general result as it depends on parameters and distribution of pre-treatment costs.

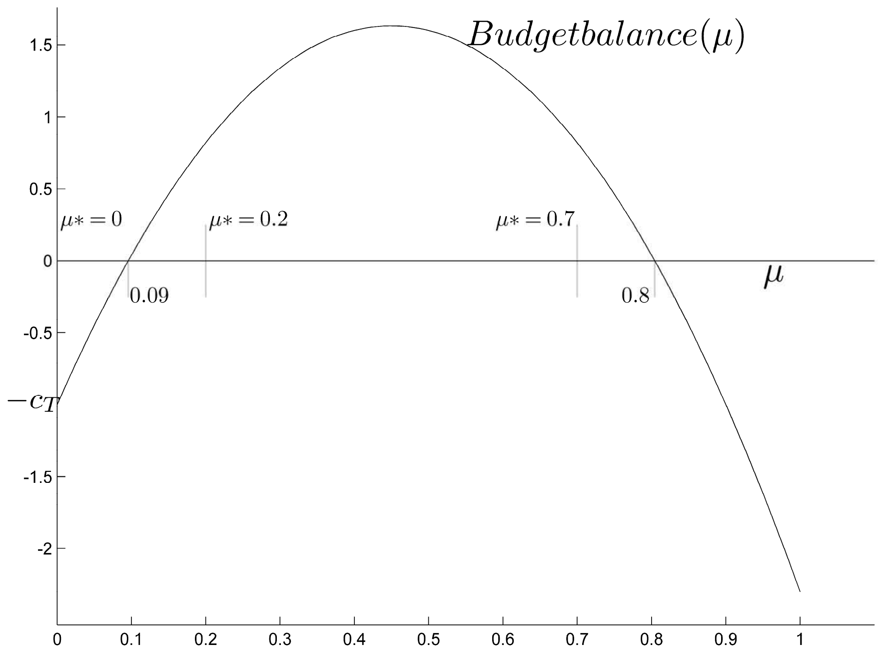

Figure 3.4: Budget surplus as a function of the monitoring rate for a 30% increase of the number of firms. The optimal monitoring rates, $\mu*$, for three different health costs parameters ($\overline{C}_P = 0.1$, $\overline{C}_P = 0.5$, and $\overline{C}_P = 1$) are indicated in the graph.

The following summarizes and discusses our four main findings from the numerical example. The first finding illustrates our analytical result that the optimal monitoring rate increases with monitoring benefits. Second, net benefits for low optimal monitoring rates are negative. Hence, the treatment scheme is worse than having no-treatment. Equation 3.6 illustrates the intuition behind this result. For a low optimal monitoring rate baseline benefits plus variable benefits are too low to cover costs of pre-treatment and treatment. One way to avoid this result is to apply a treatment technology that is more robust against deviations of pollution concentrations from target concentrations. Such a technology would, hence, be less dependent on the monitoring rate. Third, the results are sensitive to the number of firms. An increase in the number of firms reduces the optimal monitoring rate which facilitates cost recovery. The fourth result is most intriguing. For medium optimal monitoring rates fines alone can recover the costs of the treatment scheme and even generate a surplus. This result is driven by the fact that revenues from fines reach their maximum for medium optimal monitoring rates.

3.5 Discussion and Conclusions

This chapter offers insights for policy makers to improve urban wastewater treatment in developing countries. We develop a model to analyze how a regulator can set incentives to maximize net benefits in an urban wastewater treatment scheme and to recover its costs. We illustrate the model with a numerical example on small scale leather processing. The model is a ready to use tool for empirical calibration to provide quantitative output that can inform planners of urban wastewater treatment schemes. On the one hand, the model can be applied to improve the performance of an existing wastewater treatment and monitoring system by identifying the optimal monitoring rate. On the other hand, it can be applied to identify the best suited wastewater treatment technology when new treatment schemes are designed or existing treatment plants are upgraded. The model can be adapted easily to developed country settings.

Our model is sufficiently general to make it applicable in many specific settings. The simplifying assumptions in the numerical example section are adopted for just illustrative purposes. Before drawing final conclusions we want to discuss three of the caveats and limitations of our study. The first concerns the general model. We assume that firms trade off pre-treatment costs against the expected value of fines when deciding whether to comply or not. While this makes the model simple, firms' compliance behaviour might be more complex. Some studies have reported that firms overcomply with environmental regulation (Arora and Gangopadhyay 1995, and Bandyopadhyay and Horowitz 2006). In such a case our model can be adapted in Eq. 3.3. The second and third caveat concern only the numerical example. Second, we assume that wastewater treatment generates value only by reducing health hazards and reducing production losses of farmers. While this is not a complete list of benefits, it is sufficient too illustrate the mechanisms in our numerical example. Any application of the model to a real case must aim at a comprehensive account of benefits and adapt Eq.3.5 accordingly. Benefits from reduced health hazards are particularly difficult to quantify because infections must be shown to be wastewater related and, moreover, the monetary costs per infection are difficult to pin down. Third, we assume that the water utility does not collect regular charges from households, firms and farmers to contribute to its cost recovery. This may seem to be in conflict with our assumption that fines can be collected from firms. However, the collection of charges from polluters, like households and firms, is often not very effective in developing countries. Polluters are numerous and collecting a small charge from each polluter comes at high transaction costs reducing net charges to almost zero. Collecting fines from firms who are caught not complying with regulation will then be more efficient. Collecting charges for treated wastewater from farmers is equally difficult. They are often poor small scale farmers who are not capable of paying charges. Our numerical example illustrates therefore the special case where charges to polluters and reusers are zero.

We start our conclusions by pointing out directions for future research. Our model analyzes the upstream part of the chain. Other studies analyze downstream parts of the chain. Feinerman, Plessner, and DiSegni Eshel (2001) for example analyze bargaining about treatment level and cost sharing between a wastewater producing city and wastewater using farmers. They model the city and farmers as players whereas we model strategic interaction within the city but do not give farmers a strategic role. Extending our model with farmers as players would be a further step to analyze strategic interaction of the entire water chain. Solving such a model by backward induction would provide an economic equivalent to the "Reversed Water Chain Approach" (Van Lier and Huibers 2007).

We have shown that costs of a treatment scheme cannot be fully recovered by revenues from fines alone when the optimal monitoring rate is in the critical intervals at the lower or upper ends of its domain. We therefore conclude that for these cases full cost recovery depends on the ability to charge polluters and downstream users who benefit from improved water quality. Hence, the polluter pays principle that justifies charges to upstream polluters gains importance. Without polluter charges it is hardly possible to cover the costs of an effective treatment scheme, in particular when health costs are high and treatment matters most.

We found that net benefits can be negative for low optimal monitoring rates. This result is driven by treatment costs and the value of treatment without monitoring. Net benefits are negative if the treatment costs are high and the baseline value of treatment without monitoring is low. We conclude that establishing cheap and robust options for wastewater treatment in developing countries is of utmost importance.

Appendix:

Table 3.1A: List of symbols and parameter values

Description	Symbol	Value(s)
share of domestic wastewater	α	0.75
set of pollutants	$K = \{1,..,k\}$	$K = \{ N, P, S\}$
domestic wastewater	$q^D = \left(q_1^D,..,q_k^D\right)$	$q^D = (1,1,0)$
raw industrial wastewater	$q^R = \left(q_1^R,..,q_k^R\right)$	$q^R = (1,1,1)$
urban wastewater	$q^U = \left(q_1^U,..,q_k^U\right)$	
treated wastewater	$q^T = \left(q_1^T,..,q_k^T\right)$	
treated wastewater of pollutant $i \in K$	$q_i^T = \phi_i\left(q_1^U,...,q_k^U\right)\cdot q_i^U$	
treatment function for pollutant $i \in K$	$\phi_i\left(q_1^U,.,q_k^U\right)$	
minimum value of treatment function for pollutant $i \in K$	$\hat{\phi}_i$	$\hat{\phi}_N = 0.2$, $\hat{\phi}_P = 0.1$ and $\hat{\phi}_S = 0$
compliance rate	χ	
concentration of pollutant $i \in K$ in treated wastewater under full monitoring	$\phi*_i = q_i^T\left(\chi = 1\right)$	
concentration of pollutant $i \in K$ in treated wastewater under zero monitoring	$\overline{q}_i^T = q_i^T\left(\chi = 0\right)$	
set of firms	$M = \{1,..,m\}$	$m = 10$
firms' individual pre-treatment costs	c_M	uniformly distributed
interval of pre-treatment costs	$[\underline{c},\overline{c}]$	$[0,1]$
fine	f	1
baseline monitoring benefits	$\overline{B}$	0.9
monitoring benefit function	$B(\mu)$	$B(\mu) = B_P(\mu) + B_N(\mu)$

health costs under zero monitoring	$\overline{C}_P$	0.1, 0.5 and 1
health costs under full monitoring	$\underline{C}_P$	0
costs of excess nutrients under zero monitoring	$\underline{C}_N$	1
costs of excess nutrients under full monitoring	$\overline{C}_N$	0
treatment costs	c_T	1
monitoring costs	c_μ	0.1
wastewater charges to households	p_D	0
wastewater charges to farms	p_F	0
wastewater charges to firms	p_M	0

Chapter 4

Cleaning a river: An analysis of voluntary joint action*

River pollution creates negative externalities to downstream water users. In this chapter we analyze how voluntary joint action of water users can improve pollution abatement when optimal treatment cannot be enforced. We model a transboundary pollution game with a unidirectional pollutant flow. Players are identical except for their location along the river. We find that, surprisingly, the location of coalition members has no impact on coalition stability. Location does, however, affect overall welfare. The more upstream the members of the coalition are, the higher is the overall welfare because the positive externalities of cleaning accrue to a larger number of downstream water users.

* This chapter is based on Gengenbach, Weikard and Ansink (2010) Natural Resource Modeling forthcoming.

4.1. Introduction

In this chapter we study a transboundary river pollution game. Players are cities who, depending on their individual incentives, form coalitions to enhance wastewater treatment. Our objective is to analyze coalition stability in this setting of unidirectional river pollution.

River pollution is excessive in many developing countries due to the discharge of improperly treated wastewater. Scott, Faruqui and Raschid (2004) report that the share of urban wastewater which is treated to secondary level is zero for Africa, 35% for Asia, and 14% for Latin America and the Caribbean. For upstream polluters, wastewater discharge is a cheap way of disposal. Downstream water users, on the other hand, suffer damages. While disposing wastewater cheaply is individually optimal, it is inefficient from a river basin perspective. Downstream damages are negative externalities which a polluter has to take into account when choosing an efficient treatment level. This would lead to additional upstream wastewater treatment which can be achieved in two ways. First, upstream polluters might be forced by a regulating authority to apply optimal treatment. Enforcing optimal treatment is justified by the polluter pays principle which is applied in many developed countries. The second way to increase wastewater treatment is voluntary joint action between the polluters. Hophmayer-Tokich and Kliot (2008), for example, present two case studies from Israel where municipalities who suffer from water pollution initiated cooperation on wastewater treatment with upstream polluters. Since in many developing countries authorities cannot enforce optimal treatment, voluntary joint action seems to be a realistic alternative to organize wastewater treatment in many river basins.

Voluntary joint action yields the welfare optimum only if all cities participate. This is rather straightforward in a setting with two cities that can bargain to solve the externality problem (Mäler, 1990). Obtaining the welfare optimum becomes difficult, however, in a setting with more than two cities. Some cities may decide to free-ride on upstream treatment which is a positive externality to them. Consequently, cities only cooperate when the benefits of voluntary joint action are higher than the benefits from free-riding. Both types of benefits depend on the other cities' decision to cooperate. Hence, we can analyze voluntary joint action in wastewater treatment as a transboundary pollution game.

Mäler (1989) introduced this type of game for the case of acidification in Europe. In his "acid rain game" a supra-national authority to regulate pollution is missing. Players of the game are countries who choose their emission levels in reaction to the choice of the emission levels of all other countries. The resulting Nash equilibrium yields the highest payoff for players in the absence of cooperation and serves therefore as a benchmark for analyzing coalitions in such games. Folmer and von Mouche (2000) generalized this game to a transboundary pollution game. They present analytical results for different assumptions about cost functions, damage functions and the pollution transportation matrix. They compare the non-cooperative Nash equilibrium with full cooperation outcomes. Partial cooperation and the incentives for voluntary joint action, however, are not considered.

In a related strand of literature the stability and formation of international environmental agreements (IEA) has been studied, mainly in the context of a uniformly mixing pollutant where abatement is a pure public good. With few exceptions this literature has applied and adapted models of cartel formation prominent in the literature on industrial organization (cf. d'Aspremont et al., 1983). The stability of coalitions is analyzed by assessing internal stability (no coalition member has an incentive to leave the coalition), and external stability (no singleton has an incentive to join the coalition). Hoel (1992), Carraro and Siniscalco (1993) and Barrett (1994a) were the first to use this approach for the analysis of international environmental agreements. A common result is that there is a wide range of possible voluntary coalitions to control emissions. While full cooperation is stable when the number of players or the gains of cooperation are small, partial cooperation emerges for a larger number of players and if gains from cooperation are large. Carraro and Siniscalco (1993) point out that the number of members in a stable coalition increases when welfare transfers or side payments are introduced.

We apply the coalition stability concept to a transboundary river pollution setting, thereby combining the transboundary pollution game with the international environmental agreements literature. The transportation matrix in our game is an upper-triangular matrix, as pollution can only be transported downstream. The game setting is as follows. Each city uses water from the river and discharges emissions into the river which causes damages to itself and all downstream cities. Each city can abate emissions by, for example, wastewater treatment which generates benefits to itself and all downstream cities by reducing damages. Emission abatement is costly, however, which makes cities trade off abatement benefits against abatement costs when choosing their optimal abatement levels. Since a regulating authority is missing, we assume as a benchmark that cities choose their abatement level maximizing their own net benefits as singletons without taking benefits of downstream cities into account. This defines the non-cooperative Nash equilibrium. We then introduce cooperation in form of a coalition. Cities in the coalition choose their abatement level to maximize coalition benefits which are the sum of the net benefits of all member cities. Hence, members do take abatement benefits of downstream coalition members into account. Coalition members distribute the coalition payoff in order to stabilize the coalition. We adopt the common assumption in the IEA literature that cities are identical with respect to their benefits and costs of pollution abatement. Particularly, we assume that cities have the same linear abatement benefit function and the same strictly convex abatement cost function. These assumptions enable us to analytically derive conditions for cooperation and coalition stability, and illustrate further insights with a numerical example. But note that in our river-basin setting the assumption of identical players is relaxed as cities differ in location.

The existing literature on transboundary pollution in a river basin setting has mainly focused on two-player settings, which is fair given that 176 out of 261 international river basins are shared by only two states (Wolf 1999). Examples are Mäler (1990), Barrett (1994b), Fernandez (2002), and Dinar (2006). Recently, Fernandez (2009) has analyzed water pollution in the Tijuana River, shared by Mexico and the US, using differential game theory and applying various cooperative solution concepts. Not much work has been done, however, on the multi-player river basin setting. A notable exception is the work by Ni and Wang (2007) who apply principles from international water law to determine a cooperative sharing rule for the costs of cleaning a river. These two main principles are *unlimited territorial integrity*, which says that every player has the right to all river water within and upstream of his territory, and *unlimited territorial sovereignty*, which says that every player has exclusive rights to use the water on his territory (Salman, 2007). In this chapter we do not impose such principles, but rather assume that each city maximizes its own payoff or coalition payoff as discussed above.

This chapter contributes to the literature in two domains. First, we add to the literature on transboundary river pollution games by analyzing a multi-player setting. This literature has largely focused on two player games which can be solved by bargaining approaches. Second, we add to the literature on international environmental agreements. This literature has largely focused on uniformly mixing pollutants where the abatement of one player is a public good for all others and the pollution stock is the same for all players. Our case, however, is characterized by unidirectional pollution flow where abatement is a public good for downstream players only and the emission stock varies between players unless all upstream players choose full abatement. Hence, a player's location matters in our game, which distinguishes our work from the literature on international environmental agreements.

We find for interior solutions that all coalitions of a certain size are stable. Hence, location has, surprisingly, no impact on coalition stability in the river basin. Location does, however, affect overall welfare. The more upstream the members of the coalition are, the higher is the overall welfare because downstream singletons benefit from upstream coalition abatement. The welfare maximizing stable coalition is therefore obtained when the coalition consists of the most upstream players. In the standard public goods game, on the other hand, only the number of players determines welfare.

The chapter is organized as follows. The next section introduces the game. Section 4.3 presents two benchmarks: all singletons and full cooperation. Section 4.4 presents analytical results of the coalition game. Section 4.5 presents a numerical example. Section 4.6 concludes.

4.2 The model

Cities along a river

Let $N=\{1,2,\ldots,n\}$ be a finite ordered set of cities along a river with $n \geq 3$. City 1 is the most upstream and n is the most downstream city. In general, $i \in N$ is upstream of $j \in N$ if and only if $i < j$. In absence of any abatement policies, each city $i \in N$ generates $\overline{e}_i$ units of emissions. These emissions are exogenous to the model and reflect a "business as usual" scenario. A city can reduce its emissions by choosing an abatement of a_i units[11]. Its net emissions into the river are then $\overline{e}_i - a_i$. The pollution stock e_i of $i \in N$ is the sum of its own and all upstream cities' net emissions, $e_i\left(a_1,\ldots,a_i\right)=\sum_{h=1}^{i}\left(\overline{e}_h - a_h\right)$. We allow for the possibility that city 1 faces an already polluted river due to upstream pollution (by, for instance, an upstream country in the case of an international river).

Each city $i \in N$ suffers damages from its pollution stock, given by the linear damage function $D_i\left(e_i\right)=d_i e_i$ with $d_i > 0$. This linearity assumption, common in the IEA literature, eases the exposition and allows closed-form solutions to our model. Since abatement reduces the pollution stock, and thereby damages, it generates benefits. We define abatement benefits as damages before abatement minus damages after abatement:

[11] For consistency of the terminology with the literature on environmental agreements we choose abatement, rather than emissions, as the choice variable of the players.

$B_i\left(a_1,...,a_i\right) = D_i\left(\sum_{h=1}^{i}\left(\overline{e}_h\right)\right) - D_i\left(\sum_{h=1}^{i}\left(\overline{e}_h - a_h\right)\right) = d_i \cdot \sum_{h=1}^{i}\left(a_h\right)$. The fact that city i 's benefits depend only on its own and upstream abatement captures the positive unidirectional externality in this game. The marginal benefit due to (upstream) abatement by $j \le i$ equals $B_i'(a_j) = -\partial D_i\left(\sum_{h=1}^{i}\left(\overline{e}_h - a_h\right)\right) / \partial a_j = d_i$. Abatement costs are given by the strictly convex cost function $C_i\left(a_i\right)$ with $C_i\left(0\right) = 0$, $C_i' > 0$, and $C_i'' > 0$. City i 's net benefits are abatement benefits minus abatement costs: $B_i\left(a_1,...,a_i\right) - C_i\left(a_i\right)$.

The coalition game

We model cooperation as a two-stage coalition game like in the IEA literature. At the first stage each city $i \in N$ chooses to become a member of the coalition. Its choice to become a member is denoted by $\sigma_i = 1$ while its choice to be a singleton is denoted by $\sigma_i = 0$. The combined choices of all cities yields the coalition structure which is captured in the vector $\boldsymbol{\sigma} \equiv (\sigma_1,...,\sigma_n) = (\sigma_i)_{i \in N}$. Note that for n cities there are $2^n - n$ possible coalition structures. Each coalition structure induces a unique set of $S \subseteq N$ cities that form the coalition. At the second stage coalition members and singletons choose their abatement levels to maximize coalition payoff and individual singleton payoffs, respectively. For interior solutions (see assumption 4.2, below), the first order condition for coalition members $i \in S$ is (see Appendix 4.1):

(4.1) $$\sum_{k \in S; k \ge i} d_k = C_i'(a_i) .$$

Each coalition member equates its individual marginal abatement costs with the sum of its own marginal abatement benefits and the marginal benefits of downstream members. The first order condition for a singleton city $i \notin S$ is (see Appendix 4.2):

(4.2) $$d_i = C_i'(a_i) .$$

Each singleton equates its individual marginal abatement costs with its individual marginal abatement benefits.

Since the coalition structure defines whether a city is a coalition member or a singleton and since members and singletons have different first order conditions, each coalition structure gives rise to a unique system of first order conditions. The solution to each of these systems of equations is a unique vector of abatements of all cities, $\mathbf{a}^S \equiv (a_i^S)_{i \in N}$. The pollution stocks vector, $\mathbf{e}^S \equiv \left(e_i^S\right)_{i \in N}$ follows with $e_i^S\left(\mathbf{a}^S\right) = \sum_{h=1}^{i}\left(\overline{e}_h - a_h^S\right)$. Note that the coalition structure determines the abatement levels and the abatement levels determine each city's payoff. We, therefore, obtain a partition function $v(S)$ which assigns for each coalition S the coalition payoff $v_S(S) = \sum_{i \in S}\left(B\left(\mathbf{a}^S\right) - C\left(a_i^S\right)\right)$ and to each singleton $j \notin S$ the singleton payoff $v_j(S) = B\left(\mathbf{a}^S\right) - C\left(a_j^S\right)$. While the coalition payoff and the singleton payoffs are precisely determined by the partition function, a coalition is free to choose a sharing rule on how to distribute the coalition payoff among its members. This crucially determines coalition stability.

In order to analyze coalition stability we employ the stability concept introduced by d'Aspremont et al. (1983) who decomposed stability (i.e. Nash equilibrium of the coalition formation game) into internal and external stability. Coalition S is *internally stable* if no member wants to leave the coalition because its member payoff is weakly larger than its outside option payoff: $v_i\left(S\right) \geq v_i\left(S_{-i}\right), \forall i \in S$. Individual payoffs of members are determined by the coalition's sharing rule. Following Weikard (2009) we assume that the sharing rule satisfies the *Claim Rights Condition*. The Claim Rights Condition says that if the coalition payoff is large enough to satisfy the 'claims' (outside option payoffs) of each member then the coalition applies a sharing rule which does so. Consequently, the coalition is internally stable if it applies a sharing rule that satisfies the Claim Rights Condition. Using the partition function it is then sufficient to check internal stability by calculating whether the coalition payoff is at least as large as the sum of the outside option payoffs: $v_S(S) \geq \sum_{i \in S} v_i(S_{-i})$.

Coalition S is *externally stable* if no singleton *j* wants to enter the coalition because its singleton payoff is weakly larger than its member payoff when *j* would enter the coalition: $v_j\left(S\right) \geq v_j\left(S_{+j}\right) \forall j \notin S$. This holds if there does not exist a coalition S_{+j}

($j \notin S$) that is internally stable: $v_i\left(S_{+j}\right) \geq v_i\left(S_{+j-i}\right), \forall i \in S_{+j}$ (cf. Weikard 2009, Lemma 1). Consequently, coalitions $S_{+j}, \forall j \notin S$ are internally unstable because coalition S_{+j} cannot guarantee j 's outside option payoff and all singletons $j \notin S$ prefer to stay out of S. Using the partition function we can check external stability of *S* by checking that S_{+j} is internally unstable for all $j \notin S$.

Note that it is not necessary to know the precise sharing rule for analyzing the stability of coalition S. It is sufficient to know whether the coalition payoff exceeds the sum of the outside option payoffs of all members and given the Claim Rights Condition applies.

To finish the description of the model, we introduce two assumptions, the first of which introduces a restriction on the characteristics of the cities. This restriction allows us to focus our attention on the effects of the river basin setting:

Assumption 4.1. Cities are identical with respect to everything but location: $D_i\left(e_i\right)=D\left(e_i\right)$ with $d_i=d$, $C_i\left(a_i\right)=C\left(a_i\right)$, and $\overline{e}_i=\overline{e}$ for all $i \in N$.

The second assumption concerns the type of solutions that we are interested in:

Assumption 4.2. We consider only interior solutions: $\sum_{k \in S; k \geq i} d_k < C_i'\left(e_{i-1}^S+\overline{e}\right)$ for all $S \in N$.

Assumption 4.2 states that marginal damages of a city[12] plus marginal damages of all downstream members in its coalition are smaller than the marginal abatement costs that it faces if it were to clean the river completely. This implies that its abatement is less than its pollution stock in the river, $a_i^S < e_{i-1}^S+\overline{e}$ and thereby assures that no city has an incentive to clean the river completely. This is a common scenario in many cases, particularly in developing countries, where even joint action in wastewater treatment aims at abating only some fraction of the overall emissions. Still, in section 4.5 we will drop this assumption to illustrate the structure of stable coalitions when one city cleans the river entirely - a case more likely to apply to developed countries.

[12] This holds for members of a coalition as well as for singletons because any singleton can be considered one-member coalition.

Before we analyze stability in section 4.4, we determine the abatement vector and payoffs of two benchmark situations, following Folmer and von Mouche (2000): first the Nash equilibrium for all-singletons, and then the fully cooperative solution. Then we analyze which coalitions are stable and how their payoffs compare to these benchmarks.

4.3 Two benchmark situations

Non-cooperation benchmark

When all cities act as singletons, each city only takes into account its own damage in choosing its abatement level. The coalition structure is $\boldsymbol{\sigma} = (0,...,0) \Leftrightarrow S = \varnothing$ and equation (4.2) applies to all cities. Note that the LHS of equation (4.2) is a constant and because of assumption 4.1 it is also equal for all $i \in N$. Hence, the abatement level chosen by i is insensitive to other cities' abatement levels: each city has a dominant strategy. It follows that there exists a unique strictly dominant equilibrium (Folmer and von Mouche, 2000, proposition 2) which we call the non-cooperation Nash equilibrium. The non-cooperation abatement levels $\mathbf{a}^{\varnothing} = \left(a_i^{\varnothing}\right)_{i \in N}$ of this equilibrium determine the non-cooperation pollution stock $\mathbf{e}^{\varnothing} = \left(e_i^{\varnothing}\right)_{i \in N}$. The non-cooperation Nash equilibrium has two properties as summarized in the following proposition.

Proposition 4.1. *In the non-cooperation Nash equilibrium, individual abatement is equal for all cities:* $a_i^{\varnothing} = a^{\varnothing} < \overline{e} \; \forall i \in N$ *, and the pollution stock increases linearly downstream:* $e_{i+1}^{\varnothing} - e_i^{\varnothing} = \overline{e} - a^{\varnothing} \; \forall i \in N \setminus \{n\}$.

Proof. Given assumption 4.1, the only difference between the cities' abatement decisions is due to their location. Because each city has a dominant strategy the equilibrium abatement level of each city i is insensitive to other cities' abatement levels and therefore insensitive to the pollution stock $e_i^{\varnothing}$. Therefore, using equation (4.2), the abatement decision of each city is equal and we have $a_i^{\varnothing} = a^{\varnothing} \; \forall i \in N$. By assumption 4.2 we have $a_1^{\varnothing} = a^{\varnothing} < \overline{e}_1$, and by assumption 4.1 this can be generalized to $a^{\varnothing} < \overline{e}$. The second part of the proposition follows directly. ■

The presence of dominant strategies is a driving feature of our model. It assures that equilibrium abatement does not depend on the pollution stock. Given identical cities this implies that pollution increases downstream.

Full cooperation benchmark

In the full cooperation case, each city takes into account its own damage and damages to all downstream cities when choosing its abatement level. The coalition structure is the grand coalition, $\boldsymbol{\sigma} = (1,\ldots,1) \Leftrightarrow S = N$, and equation (4.1) applies to all cities. Again, note that the LHS of equation (4.1) is a constant, reflecting the sum of marginal damages of all downstream cities. In contrast to the non-cooperation benchmark, however, it is not equal for all cities, because each city now takes into account the effect of its abatement on the downstream cities. Solving for the optimum gives a unique solution which we call the full cooperation solution. The full cooperation abatement levels $\mathbf{a}^N = \left(a_i^N\right)_{i\in N}$ determine the full cooperation pollution stock $\mathbf{e}^N = \left(e_i^N\right)_{i\in N}$. The full cooperation solution has two properties as summarized in the following proposition.

Proposition 4.2. *In the full cooperation solution, individual abatement decreases downstream:* $a_i^N > a_{i+1}^N \ \forall i \in N \setminus \{n\}$ *, and the pollution stock increases at an increasing rate downstream:* $e_{i+1}^N - e_i^N < e_{i+2}^N - e_{i+1}^N \ \forall i \in N \setminus \{n, n-1\}$.

Proof. Each city takes into account the avoided marginal damage to all downstream cities including itself due to its abatement, see equation (4.1). Given assumption 4.1, any difference between a_i^N and a_j^N , $j \neq i$ is due to this difference in marginal damage, which is entirely driven by the location of i and j . Hence, city $j = i+1$ takes the marginal damage of one city less into account, so that $a_i^N > a_j^N$. The second part of the proposition follows directly from the strict convexity of $C(a_i)$. ■

Other things equal, abatement by city i is more efficient than abatement by city $i+1$ because it brings about benefits to one additional city. This is the reason why abatement is decreasing downstream in the full cooperation benchmark, while this is not the case in the non-cooperation benchmark.

4.4 Coalition game

There is no evident reason why either the non-cooperation or the full cooperation benchmark would be an equilibrium of the game. Cities might want to deviate from non-cooperation because of cooperation gains and from full cooperation because of free-rider incentives. We therefore now turn to analyze which coalitions are stable based on individual payoffs applying the stability concept introduced in section 4.2. As discussed in that section, a city will join the coalition when its payoff as a member is higher than its payoff as a singleton. As a singleton, a city chooses its optimal abatement level by equating its marginal abatement benefits and its marginal abatement costs according to equation (4.2). As a coalition member, a city chooses its optimal abatement level by equating its marginal abatement benefits plus the sum of its downstream coalition members' marginal abatement benefits with its marginal abatement costs according to equation (4.1). Whether it is preferable to be a member or a singleton depends on cost and benefit functions and the city's location. We present some general results related to location in this section and illustrate these in section 4.5.

Proposition 4.3. *Individual abatement by singletons is equal for each city:* $a_j^S = a^S \ \forall j \notin S$.

Proof: The proof is similar to the proof of proposition 4.1. Given assumption 4.1, the only difference between the singletons' abatement decisions is due to their location. Because each city has a dominant strategy the equilibrium abatement level of each singleton $j \notin S$ is insensitive to other cities' abatement levels and therefore insensitive to the pollution stock e_j^S. Therefore, using equation (4.2), the abatement decision of each city is equal and we have $a_j^S = a^S, \ \forall j \notin S$. ■

The result provided by proposition 4.3 is useful in analyzing the stability of any coalition structure. Specifically, it clarifies that leakage does not play a role in the current game setting. Leakage occurs when singletons react on upstream abatement by reducing own abatement. In general, leakage is important for coalition stability because it can destabilize coalitions. Due to dominant strategies, however, this leakage effect does not play a role in our game.

Proposition 4.4. *Individual abatement by coalition members decreases downstream:* $a_i^S > a_j^S, \forall i, j \in S$ *with* $i < j$.

Proof. The proof is similar to the proof of proposition 4.2. Each city takes into account the avoided marginal damage of all downstream coalition members including itself due to its abatement, see equation (4.1). Given assumption 4.1, any difference between a_i^S and a_j^S for $i, j \in S, i \neq j$ is due to this difference in marginal damage, which is entirely driven by the location of i and j. Hence, for $i, j \in S$ and j downstream of i, we have that the marginal damage of at least one city less is taken into account, so that $a_i^S > a_j^S$. ■

It is possible to relate abatement levels of coalition members to those of singletons as follows.

Proposition 4.5. *Individual abatement by coalition members is strictly higher than individual abatement by singletons, except for the individual abatement by the most downstream coalition member which is equal to individual abatement by singletons: for* $k \in S$ *and* $k \geq l, \forall l \in S$ *and* $j \notin S$*, we have* $a_i^S > a_j^S, \ \forall i \in S \setminus \{k\}$ *and* $a_k^S = a_j^S$.

Proof: By proposition 4.4, the most downstream coalition member $k > i \ \forall i \in S$ has the lowest abatement level of all coalition members. Its abatement level a_k^S is determined by equation (4.1), but because k has no downstream coalition members, equation (4.1) reduces to equation (4.2). Hence, we have $a_k^S = a_j^S$ for $j \notin S$ and $a_i^S > a_j^S \ \forall i \in S \setminus \{k\}$ follows by proposition 4.4. ■

Hence, except for the most downstream coalition member, every coalition member abates strictly more than every singleton. This implies that the larger the coalition, the higher is total abatement. A larger coalition does not only allocate abatement more efficiently but also provides more abatement because more externalities are internalized. Propositions 4.3 to 4.5 allow us to derive some results on the size of stable coalitions.

Proposition 4.6. *If some coalition* S *is stable, then every coalition* S' *of size* $|S'| = |S|$ *is stable.*

Proof: We prove the proposition by demonstrating that the location of coalition members along the river does not affect internal nor external stability. The stable coalition S contains $|S|$ cities. We order the $|S|$ coalition members according to their location, and denote city i being in position κ by $i,(\kappa)$, so that city $i,(1)$ denotes city i in the most upstream position of the coalition and $i,(|S|)$ denotes city i in the most downstream position of all coalition members. By proposition 4.3, singletons' abatement levels are not affected by the location of the coalition members along the river: $a_j^S = a^S$, $j \notin S$. By proposition 4.5, the same holds for coalition members' abatement levels: $a_{i,(1)}^S > a_{i,(2)}^S > \ldots > a_{i,(|S|)}^S$. Now consider a stable coalition S. Consider two adjacent cities, one of which is a coalition member and the other is not. Without loss of generality, let city $i \notin S$ be the singleton and city $j = i+1 \in S$ the coalition member.

The next step of our proof is to show that if i and j swap their membership status (i.e. $i \in S'$ and $j \notin S'$) so that a new coalition S' is formed, then coalition S' is stable. Note that this swap does not affect the optimal abatement levels of any city which is located upstream of i and downstream of j because their optimal abatement conditions do not change. All singletons have the same condition (equation (4.2)) while the condition for members (equation (4.1)) does not change since the coalition structure stays the same. The membership swap does, however, change the optimal abatement condition of i and j. In the new coalition structure S' i becomes a member and optimizes according to equation (4.1) while j becomes a singleton and optimizes according to equation (4.2). This membership swap does not, however, change the coalition structure in the sense that all members in $S \cap S'$ retain their position. The new member at location i is at position κ in the coalition which generates the same optimal abatement as if it were a member at location j at position κ as in the original coalition S. Hence, the membership swap merely swaps abatements of i and j in the abatement vector which yields an abatement vector $\mathbf{a}^{S'} = \left(a_i^{S'}\right)_{i\in N}$ given by $a_i^{S'} = a_j^S$, $a_j^{S'} = a_i^S$ and $a_k^{S'} = a_k^S, \forall k \in N \setminus \{i, j\}$. As the membership swap has only an effect on i and j, the new coalition S' is internally and externally stable for cities $k \in N \setminus \{i, j\}$. Consequently it is sufficient to check internal and external stability related to i and j in order to analyze whether the membership swap generates a stable coalition S'.

Internal stability: Recall that internal stability of S' requires $v_i\left(S'\right) \geq v_i\left(S'_{-i}\right), \forall i \in S'$. The membership swap can be interpreted as one coalition member moving one place upstream. This induces an increase in coalition payoff $v_{S'}\left(S'\right) - v_S\left(S\right) > 0$ because city *i*'s payoff increases as its pollution stock decreases by one singleton's emissions. Its outside option payoff $v_i\left(S'_{-i}\right)$ also increases for the same reason by exactly the same amount. Considering that S is internally stable and the coalition payoff of S' increases by the same amount as *i*'s outside option, it follows that the coalition payoff of S' is larger or equal to the sum of outside options of its members. Therfore, S' is internally stable.

External stability: Recall that external stability of S' requires $v_j\left(S'\right) \geq v_j\left(S'_{+j}\right) \forall j \notin S'$. Because S is externally stable, S_{+i} is not internally stable (Weikard, 2009, lemma 1). Because of the membership swap, coalition S'_{+j} is equivalent to coalition S_{+i}, so that S'_{+j} is not internally stable. The converse relation between external and internal stability also holds: if S'_{+j} is not internally stable, then S' is externally stable.

The inductive step is to show that this is true for any two arbitrary coalitions S and S' with the same size $\left|S\right| = \left|S'\right|$. This follows directly from the transitivity of the order of cities. ■

To link our paper with one of the workhorse specifications in public goods games, we introduce one additional assumption on the abatement cost function:

Assumption 4.3. Quadratic costs: $C(a_i) = \frac{1}{2}ca_i^2$.

Barrett (1994a) showed that in a public good game with identical players under a linear benefits – quadratic costs specification, only coalitions with three players are stable. Although, in principle, location matters, the same result holds here as shown in the following proposition:

Proposition 4.7. *With quadratic costs, a coalition is stable if and only if it has size* $|S| = 3$.

Proof: See Appendix 4.3.■

Proposition 4.6 tells us that if some coalition of size $|S|$ is stable, then all coalitions of this size are stable. Hence, the location of cities has little impact on coalition stability in the river basin. This shows that coalition formation in river basins is indeed similar to coalition formation in the standard public goods games with symmetric players (cf. Barrett, 1994a), as demonstrated by proposition 4.7. In the next section we employ a numerical example to further illustrate our case.

4.5 Numerical example

In this section we employ a numerical example in order to illustrate some features of our model. First, we illustrate propositions 4.6 and 4.7, the two main analytical results. Second, we relax the interior solution condition (assumption 4.2) in order to give some intuition on the mechanisms at work in the case of corner solutions. The numerical example is programmed in Matlab and works in two steps. First, it calculates the cities' optimal abatements and resulting payoffs for every possible coalition structure $\boldsymbol{\sigma}$ by solving the corresponding system of first-order-conditions. Second, it checks the stability of each coalition. Note that if the coalition payoff is larger than the sum of the outside options—generating a coalition surplus—the coalition chooses a sharing rule that distributes this excess equally among the coalition members.

The parameters that need to be specified are number of cities n, their emissions $\bar{e}$, their marginal damages d, and cost function parameters c and δ of the strictly convex abatement cost function $C(a_i) = \frac{1}{2} c a_i^{\delta}$. The condition to obtain an interior solution is given by $\left(|S| - \kappa + 1\right) \cdot d \leq \frac{1}{2} \delta \cdot c \cdot a_i^{\delta - 1}$ where $|S|$ is the number of coalition members and κ is the position of city i in the coalition. The interior solution condition is strictest for the first member in the grand coalition, when $i = 1$, $|S| = n$, and $\kappa = 1$. Obviously, for the linear benefits - quadratic costs case ($\delta = 2$) the requirement posed by the interior solution condition is weaker because the only stable coalition size is $|S| = 3$ (see proposition 4.7).

Table 4.1: Stability of coalitions if the interior solution conditions hold and abatement costs are quadratic. Coalition structure $\boldsymbol{\sigma}$, size of coalition $|S|$, internal stability (ISt), external stability (ESt), stability (St), total welfare (TW), and individual payoffs for all cities (P1-P5) for parameter values $n=5$, $\bar{e}=1$, $d=0.25$, $c=1$, and $\delta=2$. Stable coalitions are shown in bold. We use a sharing rule that distributes any coalition surplus equally among members.

#	$\boldsymbol{\sigma}$	$\lvert S \rvert$	I St	E St	St	TW	P1	P2	P3	P4	P5
1	(0,0,0,0,0)	1	1			0.78	0.031	0.094	0.156	0.219	0.281
2	(1,1,0,0,0)	2	1			1.00	0.047	0.109	0.219	0.281	0.344
3	(1,0,1,0,0)	2	1			1.00	0.047	0.156	0.172	0.281	0.344
4	(1,0,0,1,0)	2	1			1.00	0.047	0.156	0.219	0.234	0.344
5	(1,0,0,0,1)	2	1			1.00	0.047	0.156	0.219	0.281	0.297
6	(0,1,1,0,0)	2	1			0.94	0.031	0.109	0.172	0.281	0.344
7	(0,1,0,1,0)	2	1			0.94	0.031	0.109	0.219	0.234	0.344
8	(0,1,0,0,1)	2	1			0.94	0.031	0.109	0.219	0.281	0.297
9	(0,0,1,1,0)	2	1			0.88	0.031	0.094	0.172	0.234	0.344
10	(0,0,1,0,1)	2	1			0.88	0.031	0.094	0.172	0.281	0.297
11	(0,0,0,1,1)	2	1			0.81	0.031	0.094	0.156	0.234	0.297
12	**(1,1,1,0,0)**	**3**	**1**	**1**	**1**	**1.31**	**0.042**	**0.167**	**0.229**	**0.406**	**0.469**
13	**(1,1,0,1,0)**	**3**	**1**	**1**	**1**	**1.31**	**0.042**	**0.167**	**0.344**	**0.292**	**0.469**
14	**(1,1,0,0,1)**	**3**	**1**	**1**	**1**	**1.31**	**0.042**	**0.167**	**0.344**	**0.406**	**0.354**
15	**(1,0,1,1,0)**	**3**	**1**	**1**	**1**	**1.25**	**0.042**	**0.219**	**0.229**	**0.292**	**0.469**
16	**(1,0,1,0,1)**	**3**	**1**	**1**	**1**	**1.25**	**0.042**	**0.219**	**0.229**	**0.406**	**0.354**
17	**(1,0,0,1,1)**	**3**	**1**	**1**	**1**	**1.19**	**0.042**	**0.219**	**0.281**	**0.292**	**0.354**
18	**(0,1,1,1,0)**	**3**	**1**	**1**	**1**	**1.13**	**0.031**	**0.104**	**0.229**	**0.292**	**0.469**
19	**(0,1,1,0,1)**	**3**	**1**	**1**	**1**	**1.13**	**0.031**	**0.104**	**0.229**	**0.406**	**0.354**
20	**(0,1,0,1,1)**	**3**	**1**	**1**	**1**	**1.06**	**0.031**	**0.104**	**0.281**	**0.292**	**0.354**
21	**(0,0,1,1,1)**	**3**	**1**	**1**	**1**	**0.94**	**0.031**	**0.094**	**0.167**	**0.292**	**0.354**
22	(1,1,1,1,0)	4		1		1.59	0.016	0.203	0.328	0.391	0.656
23	(1,1,1,0,1)	4		1		1.59	0.016	0.203	0.328	0.594	0.453
24	(1,1,0,1,1)	4		1		1.53	0.016	0.203	0.469	0.391	0.453
25	(1,0,1,1,1)	4		1		1.41	0.016	0.281	0.266	0.391	0.453
26	(0,1,1,1,1)	4		1		1.22	0.031	0.078	0.266	0.391	0.453
27	(1,1,1,1,1)	5		1		1.69	-0.038[13]	0.213	0.400	0.525	0.588

[13] Note that the payoff to city 1 in the grand coalition (# 27) is negative. This is a result of the excess coalition payoff being distributed equally among the coalition members. An alternative distribution rule would solve this.

In table 4.1 we demonstrate the stability of coalitions for the case where $n = 5$, $\bar{e} = 1$, $d = 0.25$, $c = 1$, and $\delta = 2$. Because of the quadratic cost function ($\delta = 2$), we know that $|S| = 3$ and it can be verified that the condition for interior solutions holds ($0.75 \le 1$). Table 1 illustrates three features. First, all coalitions with the same number of members are stable (proposition 4.6). Stability is indicated by "1" in the "Stab" column and is the result of the coalitions being both internally and externally stable (stable coalitions are presented in bold). All other coalitions are not stable. Coalitions with less than three members are internally stable but externally unstable. While no member wants to leave the coalition, at least one singleton wants to join. Coalitions with more than three members are externally stable but not internally stable. While no singleton wants to enter the coalition, at least one member wants to leave.

Second, in the quadratic abatement cost case, stable coalitions have three members (# 12-21 in table 4.1, see proposition 4.7). To further illustrate the stability of coalitions, we highlight the individual incentives of cities to deviate (members leave and singletons join the coalition) from a stable coalition. Consider coalition # 12 (1,1,1,0,0). Individual payoffs are given in the last 5 columns. If city 1, 2, or 3 (members) leaves the coalition, the new coalition structure is # 2, 3, or 6, respectively. The individual payoff of the deviant is shown shaded in the table. One can see that for each member the payoff in the new coalition is lower than the payoff in the original coalition (# 12). The same happens for singletons. If cities 4 or 5 (as singletons) enter the coalition, the new coalition structure is # 22 or 23, respectively, and a similar observation regarding payoffs can be made.

Third, table 4.1 illustrates two effects of the coalition structure on total welfare. First, total welfare increases when more cities are in the coalition. This is a common finding in public good games. Second, total welfare increases when coalition members are located more upstream for a given coalition size. This result is intuitive since the more upstream coalition abatement is conducted the more cities benefit from it.

We now proceed to illustrate proposition 4.6 by changing the convexity of the abatement cost function using different values for δ. We only consider $\delta \ge 1$ which yields linearity for $\delta = 1$ and convexity otherwise. It can be verified that the condition for internal solutions holds for these values. Table 4.2 shows the size of stable coalitions for intervals of δ. All simulations for $\delta \ge 1.22$ yield a stable coalition size of 3. Lower values of δ, implying less convexity, increase the size of stable coalitions. Switching points occur at $\delta = 1.22$, below which the size of stable coalitions increases to 4, and

$\delta = 1.11$, below which the size of stable coalitions increases to 5 (grand coalition). For $\delta = 1$ the grand coalition is stable. This solution is, however, trivial. Not even the first city abates any emissions because marginal abatement costs are too high relative to the sum of the members' abatement benefits.

Table 4.2: Size of stable coalitions depending on the exponent of the abatement cost function for parameter values $n = 5$, $\bar{e} = 1$, $d = 0.09$, and $c = 1$.

δ	Size $\lvert S \rvert$ of stable coalitions
$\delta \geq 1.22$	3
$1.22 > \delta \geq 1.11$	4
$1.11 > \delta \geq 1$	5

To finish this section we now present a case that violates the interior solution condition (assumption 4.2) in order to present corner solutions and discuss their impact on the size of stable coalitions. We use parameter values $n = 5$, $\bar{e} = 1$, $d = 0.59$, $c = 1$, and $\delta = 2$, so that the condition for interior solutions is violated for the most upstream coalition member. Table 4.3 illustrates two features. First, the table shows the co-existence of stable coalitions of different sizes, namely $\lvert S \rvert = 3$ and $\lvert S \rvert = 4$. This co-existence result is a standard feature that occurs for a wide range of parameter values. Second, there may exist cities that clean up all pollution in the river. Consider, for instance, the abatement vector of coalition structure # 25, where only city 2 is a singleton. This vector is $\mathbf{a}^{\boldsymbol{\sigma}=(1,0,1,1,1)} = \left(1.00, 0.59, 1.41, 1.00, 0.59\right)$. The first coalition member, city 1, abates all its emissions. The following city, a singleton, abates less than its emissions. The subsequent city, a member, cleans the river entirely, abating its own emissions and cleaning the emissions of the upstream singleton.

Table 4.3: Stability of coalitions if the interior solution condition does not hold. Coalition structure $\boldsymbol{\sigma}$, size of coalition $|S|$, internal stability (ISt), external stability (ESt), stability (St), total welfare (TW), and individual payoffs for all cities (P1-P5) for parameter values $n = 5$, $\bar{e} = 1$, $d = 0.59$, $c = 1$, and $\delta = 2$. Stable coalitions are shown in bold.

#	$\boldsymbol{\sigma}$	$\lvert S \rvert$	I St	E St	St	TW	P1	P2	P3	P4	P5
1	(0,0,0,0,0)	1	1			4.35	0.174	0.522	0.870	1.218	1.566
2	(1,1,0,0,0)	2	1			5.23	0.253	0.601	1.112	1.460	1.808
3	(1,0,1,0,0)	2	1			5.23	0.253	0.764	0.949	1.460	1.808
4	(1,0,0,1,0)	2	1			5.23	0.253	0.764	1.112	1.297	1.808
5	(1,0,0,0,1)	2	1			5.23	0.253	0.764	1.112	1.460	1.645
6	(0,1,1,0,0)	2	1			5.22	0.174	0.609	0.957	1.566	1.915
7	(0,1,0,1,0)	2	1			5.22	0.174	0.609	1.218	1.305	1.915
8	(0,1,0,0,1)	2	1			5.22	0.174	0.609	1.218	1.566	1.653
9	(0,0,1,1,0)	2	1			4.87	0.174	0.522	0.957	1.305	1.915
10	(0,0,1,0,1)	2	1			4.87	0.174	0.522	0.957	1.566	1.653
11	(0,0,0,1,1)	2	1			4.53	0.174	0.522	0.870	1.305	1.653
12	**(1,1,1,0,0)**	**3**	**1**	**1**	**1**	**5.88**	**0.199**	**0.789**	**1.137**	**1.702**	**2.050**
13	(1,1,0,1,0)	3	1			5.88	0.199	0.789	1.354	1.485	2.050
14	(1,1,0,0,1)	3	1			5.88	0.199	0.789	1.354	1.702	1.833
15	(1,0,1,1,0)	3	1			5.76	0.204	0.764	1.142	1.490	2.156
16	(1,0,1,0,1)	3	1			5.76	0.204	0.764	1.142	1.808	1.838
17	(1,0,0,1,1)	3	1			5.41	0.204	0.764	1.112	1.490	1.838
18	**(0,1,1,1,0)**	**3**	**1**	**1**	**1**	**5.87**	**0.174**	**0.553**	**1.249**	**1.597**	**2.292**
19	**(0,1,1,0,1)**	**3**	**1**	**1**	**1**	**5.87**	**0.174**	**0.553**	**1.249**	**1.944**	**1.946**
20	(0,1,0,1,1)	3	1			5.64	0.174	0.559	1.354	1.603	1.951
21	(0,0,1,1,1)	3	1			5.21	0.174	0.522	0.925	1.622	1.970
22	(1,1,1,1,0)	4		1		6.28	0.171	0.761	1.351	1.700	2.292
23	(1,1,1,0,1)	4		1		6.28	0.171	0.761	1.351	1.944	2.048
24	**(1,1,0,1,1)**	**4**	**1**	**1**	**1**	**6.05**	**0.176**	**0.766**	**1.354**	**1.704**	**2.052**
25	**(1,0,1,1,1)**	**4**	**1**	**1**	**1**	**6.02**	**0.176**	**0.764**	**1.114**	**1.811**	**2.159**
26	(0,1,1,1,1)	4		1		6.02	0.174	0.457	1.288	1.878	2.227
27	(1,1,1,1,1)	5		1		6.43	0.155	0.745	1.335	1.925	2.273

4.6 Conclusions

Excessive river pollution is widespread in developing countries. Providing improved wastewater treatment remains therefore a big challenge. In this article we analyze whether and how cities along a river can improve wastewater treatment by voluntary joint action, using a transboundary pollution game with a unidirectional pollutant flow. We adopt the common assumption in the IEA literature that cities are identical with respect to their benefits and costs of pollution abatement. Particularly, we assume that cities have the same linear abatement benefit function and the same strictly convex abatement cost function. Our model displays some typical features of standard public goods games with symmetric players (cf. Barrett, 1994a). First, stable coalitions consist of three members in the linear benefit – quadratic costs specification. Second, the size of stable coalitions increases if the convexity of the abatement cost function decreases. Third, with sufficiently low convexity, even the grand coalition becomes stable.

There are also differences, however. While in the standard game (e.g. Folmer and von Mouche, 2000) emission abatement is a pure public good to all players, in our river setting it is a positive externality only to downstream cities. Hence, we introduce location of a player as a new element in such games and expect that it changes coalition stability. We find, however, for interior solutions that if a coalition of a certain size is stable, all coalitions of that size are stable. Hence, location has, surprisingly, no impact on coalition stability in the river basin. Location does, however, have an impact on overall welfare. The more upstream the members of the coalition are the higher is the overall welfare because downstream singletons benefit from upstream coalition abatement. The welfare maximum is therefore obtained when the coalition consists of the most upstream cities. In the standard public goods game, on the other hand, only the number of members determines welfare.

Assumption 4.1 states that cities in our game are identical with respect to emissions, abatement costs and abatement benefits. This allows for some interesting analytical findings. Real cases generally differ from this assumption which introduces considerable complexity to the analysis. Due to this complexity further analytical findings are most likely restricted to equally strong assumptions on the characteristics of cities. Without such restricting assumptions one is left with calculating the equilibria for calibrated cases in numerical applications, much like we have done in section 4.5. The following example gives some intuition on how our main analytical finding would break down if we allow for differences among the cities. Recall our proposition 4.6 in which we show that if a coalition of a certain size is stable, all coalitions of that size are stable. Now, consider the case where only one city discharges emissions, reflecting a violation of assumption 4.1 such that cities are not identical anymore. Then, by construction, any stable coalition must contain this city and at least one downstream city in order to generate a coalition surplus. When the emitting city is the most downstream city this is not possible. Hence, location affects stability when assumption 4.1 is relaxed.

Our analysis is based on the assumption that optimal treatment cannot be enforced. Most, if not all, countries have laws and regulations on wastewater quality discharge. In developing countries, however, the relevant authorities often lack the power to monitor pollution levels and enforce treatment. As our analysis shows that voluntary cooperation improves the total welfare in the basin, weak governments could rather facilitate voluntary cooperation in form of self-enforcing coalitions. Additionally, we show that the location of coalition members matters for the total welfare in the river basin. We recommend that authorities should facilitate the formation of upstream coalitions. This will indeed induce larger free-riding benefits, because more singletons are located downstream of the coalition and benefit from coalition abatement without contributing to its costs. An interesting way of looking at this situation is that authorities maximize welfare – given the size of a stable coalition – when they maximize free-riders' gains. Note that this only holds under a unidirectional pollution flow where all coalitions with the same number of members are stable. Finally, we do find the well-known negative effects of free-riding on coalition formation which prevents the formation of large coalitions. Hence, we do not expect that full cooperation in the form of grand coalitions will easily emerge. In our stylized numerical example, the grand coalition appears only for low convexity of the abatement cost function. This feature is not likely to hold in reality, except perhaps in early stages of development when advanced treatment technologies are not yet required. In such cases, however, the gains from cooperation are typically small.

Appendix

Appendix 4.1: Derivation of first order conditions for coalition members

The coalition maximizes joint welfare, denoted π_S:

$$\pi_S(a_1,...,a_n)=\sum_{i\in S}\left(B_i(a_1,...,a_i)-C_i(a_i)\right).$$

Using the definition for individual benefits (avoided damage minus abatement costs), we obtain $\pi_i(a_1,...,a_i)=D_i\left(\sum_{j=1}^{i}\overline{e}_j\right)-D_i\left(\sum_{j=1}^{i}\left(\overline{e}_j-a_j\right)\right)-C_i(a_i)$.

Assuming non-signatories' abatement as given, we obtain the following maximization problem $\max_{(a_i)_{i\in S}}\left[\pi_S(a_1,...,a_n)=\sum_{i\in S}\left(D_i\left(\sum_{j=1}^{i}\overline{e}_j\right)-D_i\left(\sum_{j=1}^{i}\left(\overline{e}_j-a_j\right)\right)-C_i(a_i)\right)\right]$.

For interior solutions, using the linear damage function, we obtain the following first order condition for coalition member i's abatement:

$$\sum_{k\in S;k\geq i} d_k = C_i'(a_i) \,.$$

Appendix 4.2: Derivation of first order conditions for singletons

Singletons maximize individual welfare, denoted π_i :

$$\pi_i\left(a_1,..,a_i\right) = B_i\left(a_1,..,a_i\right) - C_i\left(a_i\right).$$

Assuming both other non-signatories' abatement and coalition abatement as given, we obtain the following maximization problem

$$\max_{(a_i)}\left[\pi_i(a_1,...,a_n) = D_i\left(\sum_{j=1}^{i}\overline{e}_j\right) - D_i\left(\sum_{j=1}^{i}\left(\overline{e}_j - a_j\right)\right) - C_i(a_i)\right]$$

Using the linear damage function, we obtain the following first order condition for singleton i 's abatement:

$$d_i = C_i'\left(a_i\right).$$

Appendix 4.3: Proof of Proposition 4.7

From the first order conditions for a linear benefits - quadratic costs specification (Assumptions 4.2 and 4.3) we have that singletons abate

(A4.1) $$a_i = \frac{d}{c}\,.$$

Coalition members take the positive externalities towards coalition partners into account. Hence a coalition member's abatement depends on its position in the coalition. Member i in position κ abates

(A4.2) $$a_{i,(\kappa)} = \frac{d(\left|S\right| - \kappa + 1)}{c}\,.$$

In order to prove the proposition we show that the coalition payoff exceeds the sum of the outside option payoffs for a coalition of size 3; but the coalition payoff falls short of the sum of the outside option payoffs for every larger coalition. We proceed in four steps. (i) We calculate the before-transfers payoff and (ii) the outside option payoff of each member. (iii) We calculate the sum of the differences between (i) and (ii) for all coalition members and show that it is positive for $\left|S\right| \leq 3$ and negative for $\left|S\right| > 3$. This establishes internal stability for all coalitions with 3 members or less and internal instability for all coalitions with more than 3 members. Finally, (iv) we show that all 2-city coalitions are externally unstable.

(i) Given the abatement levels specified in (A4.1) and (A4.2) the payoff of coalition member i in position (κ) is

(A4.3)
$$\begin{aligned} v_{i,(\kappa)} &= d\sum_{h=1}^{i}\left(a_h\right)-\tfrac{1}{2}ca_i^2 \\ &= d\left(\sum_{\rho=1}^{\kappa}\frac{d(|S|-\rho+1)}{c}+(i-k)\frac{d}{c}\right)-\tfrac{1}{2}c\frac{d^2(|S|-\kappa+1)^2}{c^2} \\ &= \frac{d^2}{c}\left(\sum_{i=1}^{|S|}(i)-\sum_{i=1}^{|S|-\kappa}(i)+i-\kappa-\tfrac{1}{2}(|S|-\kappa+1)^2\right) \\ &= \frac{d^2}{c}\left(i-\kappa^2+2\kappa|S|+\tfrac{1}{2}\left(\kappa-|S|^2-2|S|-1\right)\right). \end{aligned}$$

(ii) The outside option payoff of coalition member i in position (κ) can be calculated as

(A4.4)
$$\begin{aligned} \varpi_{\mathrm{i},(\kappa)} &= d\sum_{h=1}^{i}\left(a_h\right)-\frac{1}{2}ca_i^2 \\ &= d\left(\sum_{\rho=1}^{\kappa-1}\frac{d\ \left(|S|-\rho\right)}{c}+\left(i-\kappa+1\right)\frac{d}{c}\right)-\tfrac{1}{2}c\frac{d^2}{c^2} \\ &= \frac{d^2}{c}\left(\sum_{i=1}^{|S|-1}\left(i\right)-\sum_{i=1}^{|S|-\kappa}\left(i\right)+i-\kappa+1-\tfrac{1}{2}\right) \\ &= \frac{d^2}{c}\left(i-\tfrac{1}{2}\kappa^2+\kappa|S|-\tfrac{1}{2}\kappa-|S|+\tfrac{1}{2}\right) \quad . \end{aligned}$$

(iii) To calculate the coalition surplus we calculate the difference between before-transfer coalition payoffs and outside option payoffs:

(A4.5)
$$\mathscr{S}_{i,(\kappa)} \equiv v_{i,(\kappa)}-\omega_{i,(\kappa)} = \frac{d^2}{c}\left(-\tfrac{1}{2}\kappa^2+\kappa(|S|+1)-\tfrac{1}{2}|S|^2-1\right).$$

Eq. (A4.5) shows that a member's surplus only depends on its position in the coalition κ, not on its location in the river *i*. Next, we calculate the sum of all coalition members' surplus:

(A4.6)

$$\begin{aligned}\mathscr{S} &\equiv \sum_{\kappa=1}^{|S|} \mathscr{S}_{i,(\kappa)} \\ &= \frac{d^2}{c}\sum_{\kappa=1}^{|S|}\left(-\tfrac{1}{2}\kappa^2+\kappa(|S|+1)-\tfrac{|S|^2}{2}-1\right) \\ &= \frac{d^2}{c}\left(-\tfrac{1}{2}\sum_{\kappa=1}^{|S|}\left(\kappa^2\right)+(|S|+1)\sum_{\kappa=1}^{|S|}\left(\kappa\right)-\tfrac{1}{2}|S|^3-|S|\right). \\ &= \frac{d^2}{c}\left(-\tfrac{1}{2}\tfrac{|S|(|S|+1)(2|S|+1)}{6}+\tfrac{|S|(|S|+1)^2}{2}-\tfrac{1}{2}|S|^3-|S|\right) \\ &= \frac{d^2}{c}\left(-\tfrac{1}{6}|S|^3+\tfrac{3}{4}|S|^2-\tfrac{7}{12}|S|\right).\end{aligned}$$

It is clear from (A4.6) that the coalition surplus depends only on the size of the coalition and is independent of members' location. The sign of the coalition surplus depends on the expression in brackets of (A4.6). We simplify this expression to

(A4.7)

$$\tfrac{1}{12}\left(-2|S|^3+9|S|^2-7|S|\right).$$

It is easy to check that (A4.7) is non-negative if and only if $1 \le |S| \le 3$. This proves internal stability of all coalitions with three and two (and trivially one) cities. Larger coalitions are internally unstable.

(iv) Finally, because all 3-city coalitions are internally stable, every member of a 3-city coalition receives at least its outside option payoff. Hence, there exists for every 2-city coalition *S* a city $j \notin S$ such that *j* prefers to join *S*. Therefore all 2-city coalitions are externally unstable. All 3-city coalitions are externally stable, because there does not exist a singleton who would join the coalition because all 4-city coalitions are internally unstable, i.e. their members receive less than their outside option payoffs.

This completes the proof that all 3-city coalitions are stable and that there is no other stable coalition.

Chapter 5

Exploring the scope for voluntary joint action to clean the Upper Citarum River Basin in Indonesia

The Citarum River in Indonesia is severely polluted because regulation on wastewater treatment is not enforced. This chapter examines whether voluntary joint action – where downstream regions suffering from pollution compensate upstream regions for pollution control measures – is an option to increase welfare in the Upper Citarum River Basin. The problem is approached by a model of transboundary pollution. We study a coalition formation game for asymmetric players and calibrate the game with data for the Upper Citarum River Basin. We find that in the benchmark calibration no coalition with positive abatement is stable because abatement benefits are too small compared to abatement costs to motivate any coalition to provide abatement. In the sensitivity analysis, however, we find for higher benefits that coalitions with four or five members are stable where only the most upstream members abate emissions.

5.1. Introduction

The Citarum River in Indonesia is severely polluted because regulation on wastewater treatment is not enforced. Improperly treated wastewater is discharged into the river as the cheapest way of disposal. While disposing wastewater cheaply is individually optimal, it is generally inefficient from a river basin perspective as it generates negative externalities to the downstream population. These negative externalities need to be internalized to obtain the welfare optimal treatment levels which are higher than the ones individually chosen. The Indonesian government has tried to regulate river pollution by establishing guidelines for the discharge of wastewater. Their enforcement, however, is weak (ADB 2007) which renders regulation in the Citarum River Basin ineffective. This situation calls for exploring alternative options instead of relying on official regulation. One such option might be voluntary joint action where downstream regions who suffer most from river pollution compensate upstream polluters for reducing pollution. "Voluntary" means that a region only cooperates if its cooperation payoff is at least as high as its non-cooperation payoff. Voluntary joint action even yields the welfare optimum if all regions join. Free riding incentives are, however, an obstacle to cooperation. Downstream regions that do not cooperate and therefore do not contribute to the cost of wastewater treatment of the coalition would still enjoy benefits. In this study we analyze whether cooperation between upstream and downstream regions in the Upper Citarum River Basin can provide wastewater treatment and thereby improve welfare.

Our case is a transboundary pollution problem with more than two players[14]. Such problems have been analyzed as coalition formation games based on a stability concept from the theory of industrial cartel formation (d'Aspremont et al., 1983). A coalition is stable if no member has the incentive to leave the coalition (internal stability) and no non-member has the incentive to enter the coalition (external stability). Coalition games have been extensively applied to the global transboundary pollution problems. Among the first were Hoel (1992), Carraro and Siniscalco (1993) and Barrett (1994a). More recent contributions include e.g. Weikard, Finus and Altamirano-Cabrera (2006) and Nagashima et al. (2009). In Chapter 4, I applied a coalition formation game to a transboundary river pollution problem with symmetric players. The Upper Citarum River Basin consists, however, of asymmetric rural and densely populated urban regions. One common difficulty with coalition formation games is that analytical results are difficult to obtain for asymmetric players. One way to obtain further insights for settings with asymmetric players

[14] For two players the externality problem can be solved by bargain (Mäler, 1990).

is to calibrate a model to obtain numerical solutions. Nagashima et al. (2009) use this approach for an application to the climate change problem.

This chapter continues the analysis of transboundary river pollution games in a multi-agent setting started in chapter 4 by calibrating a coalition formation game with asymmetric players for the Upper Citarum River Basin and computing its equilibria. This contributes to the literature in three ways. First, it is a case study which provides insights into the scope and structure of voluntary cooperation in wastewater treatment in the Upper Citarum River Basin. Second, it illustrates the applicability of the approach developed in Chapter 4. Third, its findings contribute to the theoretical literature on coalition formation games for transboundary river pollution. As analytical results of the asymmetric player game can only be obtained under very restrictive assumptions the findings of this chapter give an intuition on which assumptions should be made and how to proceed in the analytical analysis of these games.

To specify the game we identify regions that will act as players in the game and quantify the parameters that describe emissions, abatement cost functions and abatement benefit functions. This allows computing the equilibria of the game. The following specific research questions will be studied in this chapter. Is there scope for stable coalition(s) in wastewater treatment in the Upper Citarum River Basin? What are general characteristics of the structure of the stable coalitions in transboundary river pollution games with asymmetric players?

For a benchmark calibration we find that no coalition with positive coalition abatement is stable because abatement benefits are too small compared to abatement costs to motivate any coalition to provide additional abatement. As the calculation of abatement benefits contains considerable uncertainty we also conduct a sensitivity analysis in order to check which coalitions would be stable for higher abatement benefits. In the sensitivity analysis we find that coalitions with four or five members are stable. Only the most upstream members abate emissions. Regarding membership of particular regions we find two results. First, the most upstream region is a member in all cases except one. Second, the region with the highest abatement benefits is a member in all cases except one which indicates that the region with the highest abatement benefits is the key region in the river basin. Lastly, we find that total welfare is the highest for the coalition consisting of the regions that have the highest marginal abatement benefits.

The chapter is structured as follows. The following section characterizes the Upper Citarum River Basin with its regulatory setting concerning river pollution. Section 5.3

presents the theoretical framework - the coalition formation game in wastewater treatment along a river with asymmetric players. Section 5.4 presents the calibration of the game for the Upper Citarum River Basin. Section 5.5 presents the results. Section 5.6 conducts a sensitivity analysis while section 5.7 concludes.

5.2. The Upper Citarum River Basin

General characteristics

The Upper Citarum River Basin comprises the part of the Citaraum River from its spring at Wayang Mountain in the centre of West Java Province to the first of three reservoirs, Waduk Saguling. It is inhabited by approximately 5.7 million people and covers an area of 234 088 ha including the city of Bandung, which is the provincial capital of West Java, the city of Cimahi, Bandung Regency, parts of Sumedang Regency and parts of Garut Regency.[15] The Citarum River plays a significant role for the local economy. It is a main source for drinking water, a major supporter of agriculture, fishery and industrial production. Several contributories feed the Citarum River. The Upper Citraum River Basin is therefore divided into seven sub basins, namley Sub Das Citarum Hulu, Sub Das Citarik, Sub Das Cikapundung, Sub Das Cisangkuy, Sub Das Ciwidei, Sub Das Ciminyak, and Sub Das Cimeta.

Water Pollution

Water pollution is mainly caused by emissions from domestic water use, dryland agriculture, livestock breeding and industrial production. Emissions from domestic use are mainly coliforms from the discharge of untreated domestic wastewater. Emissions from dryland agriculture are pesticides and fertilizers. Emissions from livestock breeding are mostly dung. Emissions from industrial production are discharged from seven industrial clusters in the basin. The industrial clusters are Majalaya, Rancaekek, Ujung Berung, Banjaran, Dayeh Kolot, Cimahi and Batujajar. Biological Oxygen Demand (BOD) serves as a general indicator for water pollution. It reached 130 mg/l at the inlet to the Saguling Reservoir during the dry season in 2004 (ADB 2007, p.21) [16].

Institutional setup

A general framework for integrated water resource management (IWRM) is provided by Indonesia’s 2004 Water Law (Al’Afghani 2006). Implementation of IWRM within a river basin context is being promoted through establishment of river basin management units

[15] It is located between 7°19' - 6°24' South and 106°51' - 107°51' East.

[16] River water quality is classified as bad for a BOD value of more than 15mg/l. (Tebbutt 1998, p.96)

called *Balai Besar*. Recently, a range of water management responsibilities (such as water quality management) have been delegated from the central government to the *kabupaten* (district government bodies), to devolve decision-making closer to the "grass roots". The local Environmental Protection Agencies are the authorities to enforce these regulations. "Despite attempts to improve the institutional framework for river basin and water resource management, there appears to be general agreement that (i) current institutional arrangements are highly sectoral with limited effective coordination and (ii) although regulatory frameworks and standards are generally in place (e.g. for water quality or licensing), enforcement is weak." (ADB 2007, p.16) This indicates that the institutional scenario is similar to international cases where a country has exclusive rights to use the water in its territory which is described in the doctrine of *unlimited territorial sovereignty* (Barrett 1994b).

5.3. The coalition game

In this section we develop a coalition formation game between asymmetric players that might cooperate in wastewater treatment along a river. The game is characterised by its players, their strategies, their payoffs and the coalition stability concept.

Players

Let $N = \{1, 2, \ldots, n\}$ be a finite ordered set of players– referred to as regions – along a river where 1 is the most upstream and n is the most downstream one. In general, $i \in N$ is upstream of $j \in N$ if and only if $i < j$. In absence of any abatement policies, each region $i \in N$ generates $\overline{e}_i$ units of emissions. These emissions are exogenous to the model and reflect a "business as usual" scenario. A region can reduce its emissions by choosing an abatement of a_i units.[17] Its net emissions into the river are then $\overline{e}_i - a_i$. The pollution stock of $i \in N$ is the sum of its own and all upstream region's net emissions[18], $e_i\left(a_1, ..., a_i\right) = \sum_{h=1}^{i}\left(\overline{e}_h - a_h\right)$. Each region $i \in N$ suffers damages from its pollution

[17] For consistency of the terminology with the literature on environmental agreements we choose abatement, rather than emissions, as the choice variable of the players.

[18] The fact that player i 's pollution stock depends only on its own and upstream emissions and abatement captures the positive unidirectional externality in this game.

stock, given by $D_i\left(\sum_{h=1}^{i}\bar{e}_h\right)$. Abatement generates benefits by reducing these damages. Abatement benefits are damages before abatement minus damages after abatement given with $B_i\left(a_1,..,a_i\right)=D_i\left(\sum_{h=1}^{i}\bar{e}_h\right)-D_i\left(\sum_{h=1}^{i}\bar{e}_h-a_h\right)$. Abatement costs are given by the cost function $C_i\left(a_i\right)$. Region i's net benefits are abatement benefits minus abatement costs: $B_i\left(a_1,..,a_i\right)-C_i\left(a_i\right)$.

Strategies

We model cooperation as a two-stage coalition game like in the literature on international environmental agreements. At the first stage each region $i\in N$ chooses to become a member of the coalition or not. Its choice to become a member is denoted by $\sigma_i=1$ while its choice to be a singleton is denoted by $\sigma_i=0$. The combined choices of all players yields the coalition structure which is described by a vector $\boldsymbol{\sigma}\equiv(\sigma_1,...,\sigma_n)=(\sigma_i)_{i\in N}$. Note that for n players there are 2^n-n possible coalition structures. Each coalition structure induces a unique set of $S\subseteq N$ players that form the coalition. At the second stage coalition members and singletons choose their abatement levels to maximize coalition payoff and individual singleton payoffs, respectively. The first order condition for coalition members $i\in S$ is (see Appendix 4.1 in chapter 4):

(5.1)
$$\sum_{i\in S;k\geq i}D_k'\left(a_i\right)=C_i'\left(a_i\right).$$

Each coalition member equates its individual marginal abatement costs with the sum of its own marginal abatement benefits and the marginal benefits of downstream members. The first order condition for a singleton player $i\notin S$ is (see Appendix 4.2 in chapter 4):

(5.2)
$$D_i'\left(a_i\right)=C_i'\left(a_i\right).$$

Each singleton equates its individual marginal abatement costs with its individual marginal abatement benefits.

Since the coalition structure defines whether a player is a coalition member or a singleton and since members and singletons have different first order conditions, each coalition structure gives rise to a unique system of first order conditions. The solution to each of these systems of equations is a unique vector of abatements of all players,

$\mathbf{a}^S \equiv (a_i^S)_{i \in N}$. The pollution stocks vector, $\mathbf{e}^S \equiv \left(e_i^S\right)_{i \in N}$ follows with $e_i^S\left(\mathbf{a}^S\right) = \sum_{h=1}^{i}\left(\overline{e}_h - a_h^S\right)$.

Payoffs

Since the coalition structure determines the abatement levels and the abatement levels determine the coalition payoff and the singletons' payoffs, the coalition structure defines a partition function $v(S)$ which gives the payoff of each singleton $i \notin S$ by $v_i\left(S\right) = B\left(\mathbf{a}^S\right) - C\left(a_i^S\right)$ and the coalition payoff by $v_S\left(S\right) = \sum_{i \in S}\left(B\left(\mathbf{a}^S\right) - C\left(a_i^S\right)\right)$.

While the partition function is fully determined by the coalition structure and exogenous parameters, the coalition is free to set a sharing rule to distribute its payoff between members.

Coalition stability concept

We employ a stability concept (d'Aspremont et al. 1983) which decomposes overall stability into internal and external stability. Internal stability means that no member wants to leave the coalition. It is satisfied if the payoff of each coalition member $i \in S$ is weakly larger than its outside option payoff when it leaves the coalition: $v_i\left(S\right) \geq v_i\left(S_{-i}\right) \forall i \in S$. External stability means that no singleton wants to enter the coalition. It is satisfied if the payoff of each singleton $j \notin S$ is weakly larger than its payoff if it would join the coalition: $v_j\left(S\right) \geq v_j\left(S_{+j}\right) \forall j \notin S$. This holds for coalition S if all coalitions $S_{+j} \forall j \notin S$ are not internally stable. Section 4.2.2 in chapter 4 provides a detailed description of this stability concept applied to a river pollution game with symmetrical players.

5.4. Calibration of the coalition game in the Upper Citarum River Basin

In this section we calibrate our coalition formation game for the Upper Citarum River Basin. This includes identifying players and calibrating their emissions, abatement cost functions and abatement benefit functions. The calibration is summarized in Table 5.1 at the end of this section.

Regions

We define $n = 6$ regions as players. The most upstream region comprises of the area around the spring of the Citarum River and along the first two tributaries (Citarik and Cikeruh). We combine this area to one region because emissions from these tributaries do only add to the emission stock of downstream regions. The second region consists of Bandung City with the main tributary Cikapundung and the area along the main river south of Bandung. The third region consists of the area located along the tributary, Cisangkuy. The fourth region consists of the City of Cimahi, the tributary Cimahi and a small area around the main river. The fifth region consists of the area along the most downstream tributary, Ciwidey. Downstream of the fifth region the Citarum River enters into the Saguling reservoir. The sixth region consists of the area around the reservoir. Figure 5.1 presents the Upper Citarum River Basin with its regions. We obtain data for the regions from the 2006 Indonesian Economic Census (BPS 2006). The Census provides data on village level. Regions 1-6 comprise 120, 161, 51, 44, 36 and 44 villages, respectively.

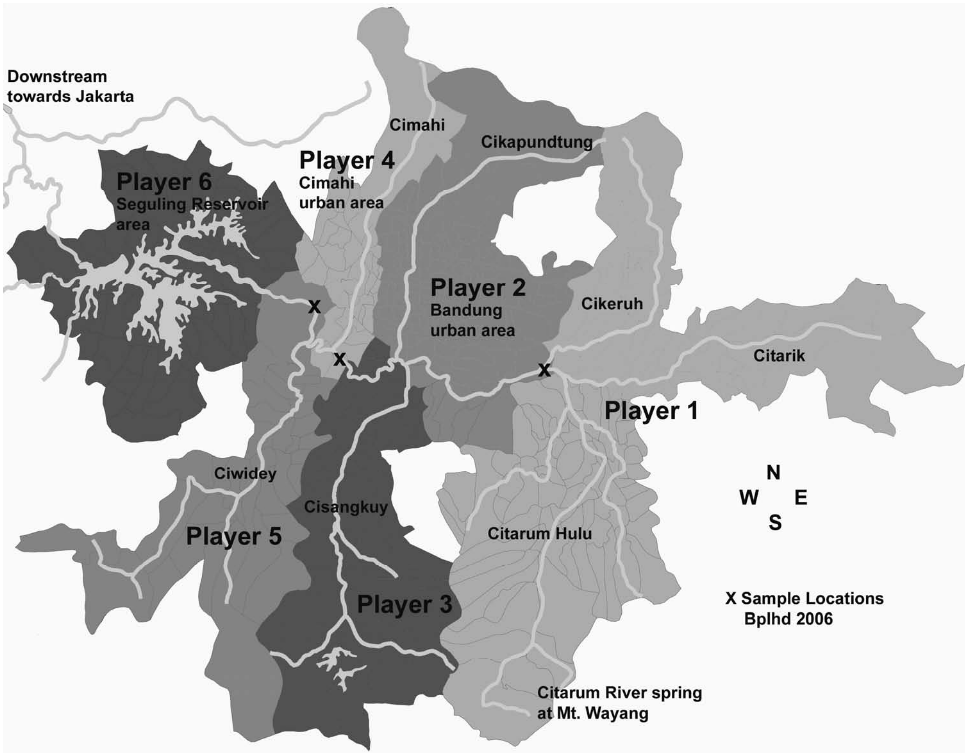

Figure 5.1: The Upper Citarum River Basin with its players

Emissions:

Domestic, industrial and agricultural wastewater is discharged into the Citarum River each comprising a variety of emissions. Calibrating the model for the entire range of emissions requires data on emissions, abatement costs and benefits for each region and for each pollutant. Gathering such a wide range of data was outside the scope of this study. We therefore confine our analysis to faecal coliform emissions from domestic wastewater the only data of which we have sufficient data.

Data from the West Java Environmental Protection Agency (WJEPA) for the year 2006 (WJEPA 2006) show that the concentration of faecal coliforms steadily increases from around 10 000 MPN (most probable number) per 100mL at the most upstream sampling station to 17 000 MPN/100mL at the most downstream sampling location in the Upper Citarum River Basin. All concentrations exceed 1000 MPN/100mL which is the guideline of the WHO (1989) and the Government of Indonesia (2001) for safe use in unrestricted irrigation. From WJEPA (2006) we derive the regions' current emissions, $\overline{e}_i$, and present them in Table 5.1. These emissions are gross emissions because no considerable abatement is currently done. The centralized treatment plant in Bandung does not operate effectively (Sukarama and Pollard 2001). In the dry season it does not receive enough wastewater and in the rainy season it receives too much wastewater to operate effectively. Septic tanks are the alternative. In rural areas, however, the coverage of septic tanks is practically zero. In urban areas on the other hand some households are equipped with private septic tanks. This, however, does not result in effective treatment. Lasut, Jensen and Shivakoti (2008) report that in another major Indonesian city, Manado, less than 30% of the residential septic tanks are in very good condition and that the condition and capacity of the majority of tanks was inadequate which causes leakage.

Emission per household of a region is $\overline{e}_i \,/\, h_i$ where h_i is the number of households of region *i*. The data show that emissions per household in region 1 are almost five times higher then in the other regions. As the structure of households is similar across regions the excess emissions of region 1 are likely due to external effects from livestock breeding. We assume that the emissions per household of region 1 are equal to other regions' emissions per household which yields an initial emission stock of $\overline{e}_0 = 8003$ (see Table 5.1).

Abatement costs:

The abatement strategies adopted by different regions consist of the choice of villages where abatement facilities are installed and the choice of facilities in each village. Two types of abatement facilities are available. Individual and communal septic tanks. The former type of tanks serves one household at 250 000 Rupias annually. The latter serves 200 households. Costs per household are 80 000 Rupias fix costs plus 10 000 Rupias per ha that is covered by the septic tank. We use population density data on the village level to estimate each region's abatement costs function based on the assumption that the most densely populated villages offer the cheapest abatement options. The area (in ha) covered by one communal septic tank in village *j* of region *i* is $200 \cdot g_{i,j} / h_{i,j}$ where $g_{i,j}$ is the residential area in ha, $h_{i,j}$ is the number of households and 200 is the number of households served by one communal septic tank[19]. It is easy to calculate that for a village with a population density lower than 11.8 households per ha an individual septic tank is the cheaper option. The cost to connect 1 household to a communal or individual septic tank in village *j* in region *i* is therefore

$$c\left(g_{i,j}, h_{i,j}\right) = \begin{cases} 80\,000 + 2\,000\,000 \cdot g_{i,j} / h_{i,j} & \text{if} \quad h_{i,j} / g_{i,j} \geq 11.8 \\ 250\,000 & \text{if} \quad h_{i,j} / g_{i,j} < 11.8 \end{cases}.$$

Multiplying the costs per household with the number of households yields the total abatement costs of a village, $C_{i,j}\left(g_{i,j}, h_{i,j}\right) = c\left(g_{i,j}, h_{i,j}\right) \cdot h_{i,j}$. As an effectively operating septic tank removes 80% of the faecal coliforms the village's emission abatement is given by $a_{i,j} = 0.8 \cdot \bar{e}_i / h_i \cdot h_{i,j}$. Ordering the villages according to the abatement costs per unit of abatement ($C_{i,j} / a_{i,j}$) starting with the lowest yields a convex relation, $C_i\left(a_i\right)$, which represents that abatement becomes increasingly expensive for a region. We estimate the coefficients of the following function

[19] Data was obtained in an interview with the head of the Programming and Planning Subdivision of the Housing and Settlement Agency of the West Java Provincial Government, Mr. Iendra Sofyan, on September 3rd 2009. A Communal septic tank serves 200 households spread over 1ha. Costs for planning and construction are 275 Million Rupiah. Annual costs for operation and maintenance amount to 3.6 Million Rupias. 20% of the costs are related to the covered area (2ha). Average lifetime is 15 years. Discount rate: 10%. Individual septic tank: Costs for planning and construction are 3 Million Rupiah. Annual costs for operation and maintenance amount to 100.000 Rupias. Average lifetime is 15 years. Discount rate: 10%.

$C_i(a_i) = -\alpha_i \cdot (-\beta_i)^{\chi_i} + \alpha_i \cdot (a_i - \beta_i)^{\chi_i}$ using least squares. [20] The estimated coefficients of the abatement cost functions for all six regions are given in Table 5.1.

Abatement benefits:
An elevated concentration of faecal coliforms causes health risks to the local population. Abating faecal coliforms reduces these health risks and therefore generates benefits. Abatement benefits are damages before abatement minus damages after abatement as introduced in the Section 5.3. The Stockholm Framework (WHO 2006b) provides a general approach to identify, quantify and manage health risks related to wastewater irrigation. To quantify health risks it suggests using disability-adjusted life years (DALYs) which is calculated by multiplying the number of cases of a disease with their average duration and with their severity factor. Since the DALY concept does not generate a monetary value it does not serve the purpose of this study. We therefore follow the Stockholm Framework by calculating the expected number of infections. But we amend the approach by calculating a monetary measure of damage instead of DALYs.

There are several studies which quantify health risks for a certain disease and a certain target group. An example is Seidu et al. (2008) who conduct a quantitative microbial risk assessment associated with wastewater reuse in Accra, Ghana. They limit their study to rotavirus and Ascaris infections and consider only transmission to farm workers and consumers. Quantifying the health risks for the general population is a very complex issue because of the large variety of diseases (Feachem et al. 1983) and the complexity of their transmission (Carr 2001, Ensink, Mahmood and Dalsgraad 2007). Hence, we rely on the following simplifying assumptions. First, we limit the variety of diseases by considering only rotavirus infection which is one of the main diseases related to faecal coliforms in domestic wastewater. Rotavirus infection causes severe diarrhea which can be lethal for children. Second, we assume that the concentration of faecal coliforms in the Citarum River poses a general risk of infection to the local population instead of distinguishing between different groups like farm workers, local residents or consumers of wastewater irrigated vegetables. This is motivated by findings that diarrhoeal diseases are strongly correlated with faecal coliform contamination in water networks (Abu Amr and Yssim 2008) which generates a risk to the population living around these water networks.

We derive the relation between concentration of E.coli in water and the risk of rotavirus infection from Mara et al. (2007) who analyze the risk of infection for different

[20] Note, that the first term, $-\alpha_i \cdot (-\beta_i)^{\chi_i}$, assures that $C_i(0) = 0$.

concentration levels. Note that the unit of our emission data is MPN of faecal coliforms while the unit in Mara et al. (2007) is MPN of E.coli. Since faecal coliform counts and E.coli counts may be used interchangeably (Dogan-Halkman et al. 2003) we use MPN for the rest of this study. From Mara et al. (2007) we obtain that the number of infections depend on the emissions according to the function $\psi(e_i) = 4.4 \cdot 10^{-7} \cdot e_i$ for the interval of $0 \le e_i \le 20000$ MPN/ 100 mL. This interval is sufficient for our study since the maximum FC concentration is 17 000 MPN/ 100 mL. Multiplying this with the relevant population of region i, p_i, gives the expected number of infections. From Jeuland and Whittington (2009) we obtain the costs of $c_B = 57000$ Indonesian Rupiah per infection.[21] With this specification region i's abatement benefit function is

(5.3)
$$B_i(a_1,..,a_i) = p_i \cdot c_B \cdot 4.4 \cdot 10^{-7} \cdot \sum_{h=1}^{i} a_h .$$

Region i's marginal abatement benefits are then $B_i' = p_i \cdot c_B \cdot 4.4 \cdot 10^{-7}$.

Table 5.1: Region dependent parameters: Emissions $\overline{e}_i$ in MPL/100mL, number of households h_i, population p_i and emissions per household $\overline{e}_i / h_i$, abatement cost function parameters, α_i, β_i, χ_i, and constant marginal benefits, B_i' in Rupiah.

i	$\overline{e}_i$	h_i	p_i	$\overline{e}_i / h_i$	α_i	β_i	χ_i	B_i'
1	1997	263 493	1 010 517	0.038*	1 894.28	-1 490.2	2.12	25 344
2	3971	524 038	2 198 924	0.008	1 600.34	-2 628.73	2.07	54 904
3	1029	135 772	528 224	0.008	1 826.83	-907.72	2.2	13 493
4	1474	195 299	785 532	0.008	5 235.8	-1327.45	2.02	19 516
5	526	69 643	273 210	0.008	1 159.82	-359.7	2.44	7 037
6	726	96 110	349 373	0.008	11 746.25	-437.66	2.35	8 762

*Assumed to be 0.008 in the numerical model analysis.

[21] Jeuland and Whittington (2009) report costs per infection ranging from 2 to 10 US Dollars. We use the expected value of 6 US Dollars with an exchange rate of 9496 Indonesian Rupiah for 1 US Dollar (9 February, 2010).We obtain costs per infection of 56976Rupiah which we round to 57000 Rupiah.

5.5. Results

The coalition game with 6 regions gives rise to 58 distinct coalitions. Computing their stability we find that no coalition with positive coalition abatement is stable.[22] The reason for this is that given our calibration abatement benefits are too small compared to abatement costs to motivate any coalition to provide additional abatement. Abatement levels, marginal costs, individual marginal benefits and coalition marginal benefits of the grand coalition are given in Table 5.2. This result indicates that no welfare gains can be achieved by voluntary joint action among regions along the Upper Citarum River Basin. As the calculation of abatement benefits contains considerable uncertainty we conduct a sensitivity analysis in the next section in order to check whether we find stable coalitions for higher abatement benefits.

Table 5.2. Region *i*, abatement a_i^S, marginal costs $C_i'\left(a_i^S\right)$, marginal benefits $B_i'\left(a_i^S\right)$ and coalition marginal benefits of each region for the grand coalition, $\sum_{j\geq i} B_j'\left(a_j^S\right)$.

i	a_i^S	$C_i'\left(a_i^S\right)$ (thousand Rupiah)	$B_i'\left(a_i^S\right)$ (thousand Rupiah)	$\sum_{j\geq i} B_j'\left(a_j^S\right)$ (thousand Rupiah)
1	0	14 733.5	25.3	129.1
2	0	14 869.5	54.9	103.7
3	0	14 736.2	13.5	48.8
4	0	16 359.4	19.5	35.3
5	0	13 627.1	7	15.8
6	0	14 621	8.8	8.8

5.6. Sensitivity Analysis

The calibration of the parameters in the previous section is subject to considerable uncertainty. This holds particularly for quantifying the monetary abatement benefits. We calculate these benefits as a reduction of heath risks related to a reduction of faecal coliform concentration in discharged domestic wastewater. This calibration introduces two main sources of uncertainty. First, the transmission from a certain concentration of faecal

[22] The calculation was programmed with the software package Matlab 7.1.

coliforms to an infection of a human is highly complex and therefore subject to large uncertainties. Second, we do only consider health risk from faecal coliforms as this is the main health risk. We do not consider other types of risks, e.g. environmental risks. Neither do we consider the local population's amenity value of the Citarum River being less polluted. It is therefore likely that we underestimate the true abatement benefits. The purpose of the sensitivity analysis in this section is to identify stable coalitions for alternative calibrations of higher abatement benefits

We analyze two scenarios. The first scenario analyzes what happens if abatement benefits are higher than in the base case for all regions in the river basin. This captures the case where the true abatement benefits are (proportionally) underestimated in the benchmark calibration. It can also be interpreted as a future scenario when the local population's amenity value of a less polluted river increases due to higher standards of living. For this scenario we introduce the sensitivity parameter δ_B which scales up the individual abatement benefits of each region. The second scenario analyzes what happens if the abatement benefits increase for all regions but increase at a higher rate in the urban regions, Bandung and Chimahi City. An example is when the standard of living increases and the rural population migrates to urban regions which increases the probability of infection there. Besides δ_B we introduce an additional sensitivity parameter, δ_{B2} with $\delta_{B2} > \delta_B$. While δ_B is a scaling factor for the abatement benefits of regions 1, 3, 5 and 6, δ_{B2} is a scaling factor for the abatement benefits of region 2 (Bandung City) and region 4 (Chimahi City).

In scenario 1 we increase the abatement benefits of all regions by the factor $\delta_B = 140$. The computation yields 4 stable coalitions with 5 members where the two most upstream regions are always members. Only the most upstream member abates a fraction of his emissions while all other regions, members and singletons, do not abate. This can be explained by the heterogeneity of the regions. Region 2 has by far the highest individual abatement benefits. Only if region 2 is a member marginal coalition benefits are high enough for region 1 to exceed its marginal abatement costs which renders coalition abatement profitable. Abatement is the highest in coalition (1,1,1,1,0,1) when the region with the lowest marginal benefits is the only singleton. This coalition structure also generates the highest total welfare in the river basin (Table 5.3). This result is different from the case with identical regions of chapter 4, where we find that welfare is the higher the more upstream coalition members are located. Another result is surprisingly similar to the case with identical regions. Proposition 4.6 in chapter 4 states that if some coalition S

is stable, then every coalition S' of size $|S'| = |S|$ is stable. Although in this chapter regions are not identical the sensitivity analysis yields only stable coalitions with the same number of members. As marginal abatement costs are fairly similar among regions (Table 5.4) while marginal benefits are quite different (Table 5.4), proposition 4.6 in chapter 4 might be driven by identical abatement cost functions rather than identical abatement benefit functions. Another proposition of chapter 4, proposition 4.7, does not apply, however, for non-identical regions. It says that if the abatement cost functions are quadratic three members form a stable coalition. Although exponents are close to 2, $2.02 \leq \chi_i \leq 2.44$ a stable coalition is formed by 5 members in this sensitivity analysis. This indicates that the number of coalition members is sensitive to changes in the exponent of the abatement costs function.

Table 5.3. Coalition structure, $\boldsymbol{\sigma}$, number of members, $|S|$, abatement levels, a_i^S, and total welfare of stable coalitions for $\delta_B = 140$.

$\boldsymbol{\sigma}$	$\lvert S\rvert$	$\mathbf{a}^S$	Total Welfare (million Rupiah)
1,1,1,1,1,0	5	188,0,0,0,0,0	430.1
1,1,1,1,0,1	5	210,0,0,0,0,0	453.8
1,1,1,0,1,1	5	54,0,0,0,0,0	164.1
1,1,0,1,1,1	5	129,0,0,0,0,0	338.3

As benefits further increase the structure of stable coalitions changes. Increasing marginal benefits with the factor $\delta_B = 220$ yields one stable coalition with five members and six stable coalitions with four members where the first two regions are always members (see Table 5.5). While only the most upstream member abates emissions in the 5-member coalition the two most upstream members abate emissions in the 4-member coalitions. The reason for that is regions 2's membership in the 4-member coalitions and its non-membership in the 5-member coalition. Region 2 is the main driving force for abatement because it has the highest marginal abatement benefits. Its high marginal abetment benefits are still too low, however, to lead to abatement as a singleton. Only together with other downstream members, their sum of marginal benefits is sufficient to induce abatement in region 1 and 2. The structure of stable coalitions is similar to the previous simulation besides the 5-member coalition. Given the first two upstream regions are members all coalitions with 4 members are stable. The difference to the previous simulation is one member less in the stable coalitions. This indicates that increasing benefits increase free-riding incentives and reduce the number of members in a stable coalition.

Table 5.4. Region *i*, abatement a_i^S, marginal costs $C_i'\left(a_i^S\right)$, marginal benefits $B_i'\left(a_i^S\right)$ and coalition marginal benefits of each region, $\sum_{j \geq i} B_j'\left(a_j^S\right)$, for stable coalition (1,1,1,1,0,1).

i	a_i^S	$C_i'\left(a_i^S\right)$ (million Rupiah)	$B_i'\left(a_i^S\right)$ (million Rupiah)	$\sum_{j \geq i} B_j'\left(a_j^S\right)$ (million Rupiah)
1	210	17.1	3.5	17.1
2	0	14.9	7.7	13.5
3	0	14.7	1.9	5.8
4	0	16.4	2.7	3.9
5	0	13.6	1	-
6	0	14.6	1.2	1.2

Table 5.5. Coalition structure, $\boldsymbol{\sigma}$, number of members, $\left|S\right|$, abatement levels a_i^S, and total welfare of stable coalitions for $\delta_B = 220$.

$\boldsymbol{\sigma}$	$\left\|S\right\|$	$\mathbf{a}^S$	Total Welfare (million Rupiah)
1,1,1,1,0,0	4	889,734,0,0,0,0	11 853.6
1,1,1,0,1,0	4	654,285,0,0,0,0	8 536
1,1,0,1,1,0	4	768,502,0,0,0,0	10 376.3
1,1,1,0,0,1	4	687,347,0,0,0,0	9 109
1,1,0,1,0,1	4	800,564,0,0,0,0	10 820.9
1,1,0,0,1,1	4	564,113,0,0,0,0	6 774.6
1,0,1,1,1,1	5	141,0,0,0,0,0	1 820.9

We now turn to the second scenario in which the abatement benefits of the urban regions increase more than the benefits of the rural regions. We increase benefits of regions 1,3,5 and 6 by the factor $\delta_B = 75$ and the benefits of the urban regions 2 and 4 by the factor $\delta_{B2} = 180$. Four coalitions with five members each are stable (Table 5.6). Coalition abatement is realized either by the first member alone or by the first two members.

Both urban regions are always members. Concerning the coalition structure we again obtain a very similar result as in the previous scenario. Only coalitions of one size are stable. Here the size is five members. This is intriguing because the result of the identical player case persists although the heterogeneity among regions increases since the marginal benefits of two regions are raised more than for the remaining ones. As abatement costs did not change this indicates that abatement benefits do not crucially influence the structure of stable coalitions as conjectured in the first scenario. The highest abatement is realized by the coalition where the second most downstream region is singleton because it has the lowest marginal abatement benefits.

Table 5.6. Coalition structure, $\boldsymbol{\sigma}$, number of members, $|S|$, abatement levels a_i^S, and total welfare of stable coalitions for $\delta_B = 75$ and $\delta_{B2} = 180$.

$\boldsymbol{\sigma}$	$\lvert S \rvert$	$\mathbf{a}^S$	Total Welfare (million Rupiah)
1,1,1,1,1,0	5	188,11,0,0,0,0	329.1
1,1,1,1,0,1	5	199,32,0,0,0,0	348.6
1,1,0,1,1,1	5	156,0,0,0,0,0	295.2
0,1,1,1,1,1	5	0,120,0,0,0,0	43.2

The following summarizes the common results of the two scenarios of the sensitivity analysis. Regarding coalition size we find that coalitions with four or five members are stable. As the exponents of the abatement costs functions are higher than 2 this result is different from the result in Chapter 4 which finds stable coalitions with three members for symmetrical players. Regarding abatement we find that only the most upstream member(s) abate emissions. The reason for this is that the sum of marginal benefits of the members is the highest for the most upstream members while marginal abatement costs are fairly equal among members. This only changes when downstream members have substantially lower marginal abatement costs. Regarding the membership of particular regions we find two common results. First, the most upstream region is a member providing coalition abatement in all cases except one (Table 5.6). Second, the region with the highest abatement benefits is a member in all cases but one (Table 5.5). This indicates that the region with the highest abatement benefits is the key region in the river basin. Without it no abatement is provided. Regarding welfare we find that total welfare is the highest for the coalition consisting of the regions that have the highest marginal abatement benefits. This might not hold in general, however, because of the following trade off. If the most upstream region is a member but a downstream singleton has higher marginal benefits abatement is lower but all regions benefit from it. If on the other hand the two regions swap membership coalition abatement becomes higher but fewer regions benefit from it because it is done by a more downstream region. Hence, location does matter when marginal benefits of the regions are similar.

5.7. Discussion and Conclusions

We analyze whether cooperation in wastewater treatment along the Citarum River in the Upper Citarum River Basin might be an option to improve welfare. Before we draw final conclusions, the following limitations of our study need to be mentioned. A general limitation is the availability of data in the Upper Citarum River Basin which we try to overcome by filling the gaps with data from the literature. This might lead to inconsistencies in the data. More specifically we face limitations about the calibration of emissions, abatement costs and benefits. Emissions per household are very similar for players 2 to 6 but were almost 5 times higher for region 1. As household characteristics are not different among regions, we assumed that emissions per household are equal in all regions. This leaves an initial emission stock which cannot be abated in our model. As abatement benefits are linear this does not fundamentally affect our results. Nevertheless, the source of the initial emissions should be identified and an abatement cost function should be calibrated. Two limitations are related to abatement benefits. First, we confine our analysis to health risks from rotavirus infection to calculate abatement benefits. A variety of diseases can potentially be contracted, however, by getting in contact with wastewater (Feachem et al. 1983). Hence, the abatement benefits might be underestimated in this respect. Second, we calculated each region's health risks as a general risk to its entire population. Since the health risks depend on the pollutant concentration in the main river and the area of a region stretches some distance from it the risk of infection might be lower for a fraction of the population in each region. The risks of infection might therefore be overestimated.

The following concluding remarks are divided into three parts. First, I reflect the results of the benchmark calibration. One central finding is that that neither individual nor aggregate abatement benefits are sufficient to motivate abatement in the base case. Similar results can be found in the literature even for developed countries. Shuval, Lampert and Fattal (1997) estimate health risks from eating vegetables which are irrigated with wastewater and relate these risks to costs to prevent them. They find that meeting USEPA guidelines would result in an extra expenditure of 3-30 million US$ per case of disease prevented. The USEPA guidelines are stricter, however, than the WHO guidelines which apply to developing countries. Fattal, Lampert and Shuval (2004) find that treatment to meet the WHO guidelines would cost 125 US$ per case prevented. This, however, still exceeds the 6 US$ which we use in this study.

As long as emission abatement benefits are low, the installation of wastewater treatment facilities might be questioned in the Upper Citarum River Basin and cheaper options to reduce health risks need to be applied. Raising the local public's awareness of the health risks such that people take individual measures to reduce these risks are likely to be more cost efficient in the short run. This was also suggested in the literature. Keratia, Drechsel and Amoah (2003) recommend for example a balanced approach which considers both health care and livelihoods and which focuses on low-cost options for risk reduction on farms and in markets. Haller, Hutton and Bartram (2007) estimate the costs and health benefits of water sanitation improvements. They suggest a better water management at household level which complements the improvement of water services to be a cost effective health intervention in many developing countries.

The second part of the conclusions reflects on the results of the sensitivity analysis. When guidelines cannot be enforced it is important for a local authority like the West Java Environmental Protection Agency to know which coalition structure maximizes welfare in the river basin. Coalitions should be facilitated according to the following guidelines. First, the region with the highest marginal benefits is the key region for providing abatement and stabilizing a coalition. Second, coalitions of regions with the highest marginal abatement benefits maximize abatement in the Upper Citarum River Basin. This also maximizes total welfare. Note, however, that this might not hold in general. We provide the intuition that location might matter besides the size of marginal benefits at the end of section 5.6.

The third part of the conclusions we point out some directions for future research. Our case generates similar results to the identical player case. Almost all coalitions with the same number of players are stable with the additional condition that the most upstream region and the region with the highest marginal benefits are members. Our case also generates different results to the identical player case. Stable coalitions have more members than in the identical player case. Further analytical research might lead to interesting insights how the characteristics of the abatement costs and abatement benefit functions determine coalition stability for heterogeneous agents. This holds particularly for the interrelation between different parameters, for example the exponents of the abatement cost function and marginal abatement benefits. Besides theoretical research the further application of the model will generate more case studies to compare with this study. As mentioned above case studies depend on data on how the reduction of pollutants generates benefits. If these relations can be quantified more precisely, reliability of the results will improve. Particularly the transmission of health risks needs to receive some further research.

Chapter 6
Conclusions

The general objective of this thesis is to study how economic incentives of stakeholders determine welfare along the water chain of use, treatment and reuse and how these incentives can be regulated in order to maximize welfare. In chapters 2 to 5 I identified four characteristic settings in which either asymmetric information or externalities causes welfare losses in the absence of regulation. For each setting I develop a game theoretic model that can be used to design incentive schemes that govern the generation, treatment, and reuse of wastewater in developing countries such that the highest possible welfare is obtained. In this last chapter I summarize the individual results and the conclusions of the main chapters in section 6.1. In section 6.2 I draw some general conclusions from the thesis as a whole, relate them to the state of the art in wastewater treatment and reuse in developing countries and discuss directions for further research.

6.1. Research questions and summary of main findings

Chapter 2 raises the following research question:
Can the allocation of fresh water between a city and fresh water farmers be an instrument to reduce the asymmetric information inefficiency on the local food market?
I find that the allocation of scarce fresh water between a city and irrigation determines quality signalling by price and thereby transparency of the local food market. Allocating a small, medium, and large share of water to the city induces a pooling equilibrium, a separating equilibrium with distorted prices, and a separating equilibrium with efficient prices, respectively. The allocation of fresh water can therefore be an instrument to reduce price distortions on the local food market. In order to determine which equilibrium is welfare optimal we consider three scenarios of consumers' valuation for fresh water irrigated products. We find that the more consumers have a high valuation for fresh water irrigated products, as in prospering developing countries, the more fresh water should be allocated to fresh water irrigation to maximize welfare on the food market.

Chapter 3 raises the following research question:

How much monitoring maximizes welfare in the urban water chain while the costs of the treatment scheme can still be recovered?

The model shows that high marginal benefits from monitoring yield a high optimal monitoring rate. Whether cost can be recovered depends on the monitoring rate. For small monitoring rates monitoring costs and revenues from fines are small which generates only a moderate effect on the budget constraint. For medium monitoring rates revenues from fines are high. This favours budget balancing. For high monitoring rates revenues from fines are low while monitoring costs keep increasing, which renders budget balancing difficult. Because the optimal monitoring rate cannot be determined explicitly without further specifications of the model we employ a numerical example where we specify the relevant functions and parameters. The numerical example illustrates three findings. First, net benefits for low optimal monitoring rates can be negative because for a low optimal monitoring rate benefits are too low to cover costs of pre-treatment and treatment. Hence, the treatment scheme is worse than having no-treatment. One way to avoid this result is to apply a treatment technology that is more robust against deviations of pollution concentrations from target concentrations. Such a technology would, hence, be less dependent on the monitoring rate. Second, the numerical analysis shows that the results are sensitive to the number of firms. An increase in the number of firms reduces the optimal monitoring rate which facilitates cost recovery. The third result is most intriguing. For medium optimal monitoring rates fines alone can recover the costs of the treatment scheme and even generate a surplus. This result is driven by the fact that revenues from fines reach their maximum for medium optimal monitoring rates.

Chapter 4 raises the following research question:

Can voluntary cooperation in wastewater treatment among water users improve the welfare in the river basin?

I find that all coalitions of a certain size are stable for symmetric players and interior solutions. This is the same result as in the standard public goods game (cf. Barrett, 1994a) where location does not matter. Hence, location has, surprisingly, no impact on coalition stability in the river basin. Location does, however, affect overall welfare. The more upstream the members of the coalition are the higher is the overall welfare because downstream singletons benefit from upstream coalition abatement. The welfare maximizing stable coalition is therefore obtained when the coalition consists of the most upstream players. In the standard public goods game with identical players (cf. Barrett, 1994a), on the other hand, only the number of players determines welfare. I conclude that authorities should facilitate the formation of upstream coalitions in river basins with identical players because this maximizes total welfare.

Chapter 5 raises the following research questions:
Is there scope for stable coalition(s) in wastewater treatment in the Upper Citarum River Basin? What are general characteristics of the structure of the stable coalitions in transboundary river pollution games with asymmetric players?
For a benchmark calibration I find that no coalition with positive coalition abatement is stable because abatement benefits are too small compared to abatement costs to motivate any coalition to abate emissions. As the calculation of abatement benefits contains considerable uncertainty we also conduct a sensitivity analysis in order to check which coalitions turn stable for higher abatement benefits. In the sensitivity analysis I find that coalitions with 4 or 5 members are stable where only the most upstream members abate emissions. Regarding the membership of particular regions we find two results. First, the most upstream region is a member in all cases but one. Second, the region with the highest abatement benefits is a member in all cases but one which indicates that the region with the highest abatement benefits is the key region in the river basin. Lastly, we find that total welfare is the highest for the coalition consisting of the regions that have the highest marginal abatement benefits. This might not hold in general, however, because of the following trade off. If the most upstream region is a member but a downstream singleton has higher marginal benefits abatement is lower but all regions benefit from it. If on the other hand the two regions swap membership coalition abatement becomes higher but fewer regions benefit from it because it is done by a more downstream region. Hence, location does matter when marginal benefits of the regions are similar.

6.2. General conclusion and future research options

In this thesis I analyzed the incentives of stakeholders in the water chain in developing countries in four distinct settings. While the contributions to the literature of the individual settings are presented in section 1.3 and their main findings with conclusions in 6.1, I will reflect on the impact of this thesis as a whole in this section. First, I will present the general findings and conclusions of this thesis. Second, I will relate these conclusions to the state of the art of research on incentives in wastewater treatment and its reuse in developing countries. Third, I will suggest future research possibilities that help to meet the persisting challenges.

A general finding of this thesis is that strategic interaction due to asymmetric information and externalities can have considerable negative welfare effects in the water chain. Asymmetric information causes inefficiencies on the local food market and hampers the effectiveness of a wastewater treatment scheme as presented in the second and third chapter, respectively. Externalities prevent the first best solution in providing wastewater treatment along a river in the fourth and fifth chapter. One must therefore conclude that creating strong institutions which assure the functioning of markets should be a key strategy for improving the welfare outcome in the water chain. Concerning the different settings in this thesis this includes creating institutions that implement market transparency on local food markets, creating institutions that install a system which monitors compliance of industrial polluters and creating institutions that issue and implement wastewater discharge standards along rivers.

The second conclusion is related to individual preferences of people which crucially drive the results. In the second chapter consumers' preferences for either fresh or wastewater irrigated food determines the efficient allocation of water between fresh water irrigation and a city. In the third chapter the optimal monitoring level is determined by benefits from wastewater treatment. These benefits are ultimately determined by consumers and farmers preferences for safe reuse of treated wastewater. The same applies to chapters four and five where benefits from water pollution abatement determine cooperation in wastewater treatment along a river. The importance of preferences becomes particularly apparent in the case study in chapter five. For the benchmark calibration I find that no coalition with positive abatement is stable because abatement benefits are too low compared to abatement costs. Only in the sensitivity analysis with higher abatement benefits stable coalitions which provide positive abatement emerge. I therefore conclude that all studies which deal with wastewater treatment and reuse must have a microeconomic foundation that focuses on the preferences of the individual stakeholders. If these preferences are ignored they might generate incentives that trigger strategic interaction causing well-designed technical facilities or policies to fail. This also counts for applying general guidelines to reduce public health risks. A better way to reduce these risks is to develop a general methodology based on the preferences of stakeholders that can be applied to different cases producing individual solutions. This is the approach taken in this thesis.

The following relates the contribution of this thesis to the state of wastewater treatment and reuse in developing countries. Hamilton et al. (2007) find that the prime driver for the use of wastewater in irrigation in developing countries is livelihood dependence and food security. Several studies describe and quantify the underlying incentives of stakeholders. Bradford, Brook and Hunshal (2003) study farmers who use wastewater for irrigation in Hubli-Dharwad, India, and find that wastewater irrigation is particularly lucrative during the dry season when wholesale market prices rise between two- and six-fold. Ensink, Simmons and van der Hoek (2004) find that wastewater irrigating farmers in Haroonabad and Faisalabad in Pakistan earned approximately 300

US$/annum more than farmers using freshwater. Besides these benefits both studies acknowledge the health risks for farmers and consumers. Keraita, Drechsel and Konradsen (2008) study farmers' perceptions on health risks and risk reduction measures in Ghana and find that farmers were willing to adopt risk reduction measures to avoid further pressure from the media, authorities and the general public. Weldesilassie (2008) studies health risk reduction in Addis Ababa, Ethiopia, and finds that a large welfare gain to society can be achieved from policies for safe use of wastewater for irrigation. While these studies describe and quantify stakeholders' incentives they do not analyze how these incentives determine strategic interaction between stakeholders. Feinerman, Plessner and DiSegni Eshel (2001), Axelrad and Feinerman (2009) and Axelrad and Feinerman (2010) analyze such incentives and interaction for the allocation of costs and benefits of wastewater reuse. Chapter four and five of this thesis contribute to this literature.

Besides in the allocation of costs and benefits of wastewater reuse stakeholders interact in a variety of markets including the food market and the labour market. As the volume of wastewater steadily grows and therefore also the number of people who depend on it for their livelihoods (Quadir at al. 2008) interaction on markets related to wastewater reuse will also increase. Even though this development is apparent the special features of these interactions have not received much attention in the literature. Chapter two of this thesis analyzes strategic pricing on the food market when wastewater and freshwater irrigated food is sold. Understanding such interaction is a key to manage the water chain properly. By analyzing four characteristic setting this thesis contributes to this immense challenge.

I will close my thesis with some suggestions for further research. For four settings I studied how economic incentives of stakeholders determine welfare along the water chain of use, treatment and reuse and how these incentives can be regulated in order to maximize welfare. Each setting is analyzed with a game theoretic model that captures the relevant strategic interaction among the set of involved stakeholders as players. Extending these models with further stakeholders as players is a step towards a more complete model of the entire water chain in a river basin. This might raise further interesting research questions and produce further insights. In the second chapter, for example, the water polluting city is not modelled as a player because wastewater treatment is not addressed in this chapter. If it were addressed, however, the city must be included in the set of players. In the third chapter, farmers who reuse wastewater in irrigation are neither modelled as player. In the fourth and fifth chapter, players are regions in the river basin. Many different types of people who differ in e.g. wealth, education or age live in these regions. Breaking down these regions into groups of heterogeneous stakeholders might be worthwhile to enhance insights.

Besides extending the models for further analytical insights, the models are ready-to-use tools for applications. On the one hand such applications will produce quantitative insights about the effects of strategic interaction in the analyzed settings. On the other hand, they might give an intuition on how to extend the models of this thesis to gain further qualitative insights. For the application of the models one needs a thorough understanding of how pollution reduction translates into monetary benefits. It is particularly difficult to assess how pollution reduction generates benefits by reducing health hazards. Although considerable effort was directed to quantify these relations, it is still difficult to calibrate models to assess economic benefits. Further research is needed to reduce the uncertainty of the health and monetary benefits of a in quantifying the relation between the reduction of pollutant concentrations in wastewater and its monetary benefits.

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Summary

The proper management of wastewater and its reuse is crucial in order to reduce hazards and maintain a variety of benefits. The merits of improvements in wastewater management are particularly high in many developing countries where effective wastewater treatment is not in place and completely untreated wastewater is reused. In order to achieve the welfare optimum, the reuse of wastewater has to be organized in a way which trades off its benefits and costs efficiently. This comprises two tasks. First, technical facilities which provide the appropriate wastewater treatment level need to be designed. Technical facilities cannot operate successfully, however, when the incentives of stakeholders do not support their viable operation. Hence, the second task is to design an institutional setting in which the technical facilities can be operated effectively. This requires a complementary incentive scheme that brings the incentives of stakeholders in line with effective wastewater management. To achieve this it is necessary to understand the complex behavioural pattern which emerges from strategic interaction between a large variety of stakeholders along the water chain of use, treatment and reuse. Asymmetric information and externalities make this interaction even more complex.

The general objective of this thesis is to study how economic incentives of stakeholders determine welfare along the water chain of use, treatment and reuse and whether these incentives can be regulated in order to maximize welfare. This thesis identifies four characteristic settings in which either asymmetric information or externalities initiate strategic interaction which causes welfare losses in the absence of regulation. For each setting this thesis develops a game theoretic model that can be used to design incentive schemes that govern the generation, treatment, and reuse of wastewater in developing countries such that the highest possible welfare is obtained.

In chapter 2 I consider a setting where fresh water and wastewater irrigated products are supplied to the local food market where consumers prefer fresh water irrigated products, but cannot distinguish the two types of food. Hence, they face a situation of asymmetric information which might cause inefficiencies in the market. I assume that both fresh water and wastewater production is constrained because fresh water supply is limited. I develop a price signaling game where farmers use price to signal whether they sell fresh water or wastewater irrigated food to consumers. This chapter contributes to the literature of signalling games by integrating a public agency which sets production constraints by allocating a scarce resource. Besides inefficient pooling equilibria and separating equilibria

with distorted prices I surprisingly find efficient equilibria with undistorted prices. Efficient equilibria evolve if the water allocation to wastewater irrigated agriculture is large. I conclude that the allocation of fresh water can be an instrument to reduce price distortions on the local food market.

In chapter 3 I analyze a typical urban setting in a developing country where households and industrial firms are not separated into distinct zones and urban wastewater consists of domestic and industrial wastewater. A treatment scheme is suggested which requires firms to pre-treat their industrial wastewater before discharging it into urban wastewater. The success of such a scheme depends on whether firms pre-treat which is private information to them. I develop a compliance game where a regulator has incomplete information about the pre-treatment compliance of firms that produce industrial wastewater. This chapter contributes to the literature by providing a formal model to analyze economic incentives in the entire urban water chain consisting of water pollution, wastewater treatment and its reuse in a developing country context. I find that cost recovery is most favourable for medium optimal monitoring rates because then fines charged to not complying firms are high. Furthermore, I find that net benefits of wastewater treatment can be negative for low optimal monitoring rates. I conclude that cheaper and more robust treatment technologies need to be developed.

In chapter 4 I analyze cooperation in wastewater treatment among cities along a river where a regulating authority is absent. Without regulation downstream cities suffer damages and rely on cooperation in form of a self enforcing coalition in which members take abatement benefits of downstream coalition members into account. Coalition members distribute the coalition payoff in order to stabilize the coalition. Free riding is an obstacle, however, to such cooperation because downstream water users cannot be excluded from upstream cooperation treatment. To analyze this setting I develop a coalition formation game which contributes to the literature in two domains. First, we add to the literature on transboundary river pollution games by analyzing coalition stability in a multi-player setting. Second, we contribute to the literature on international environmental agreements by analyzing a case of unidirectional pollution flow where abatement is a public good for downstream players only and the emission stock varies between players unless all upstream players choose full abatement. A player's location matters therefore in our game. I find for interior solutions that location has, surprisingly, no impact on coalition stability. Location does, however, affect overall welfare. The more upstream the members of the coalition are, the higher is the overall welfare because downstream singletons benefit from upstream coalition abatement. I conclude that authorities should facilitate the formation of upstream coalitions because this maximizes the welfare in the river basin.

Chapter 5 continues the analysis of transboundary river pollution in a multi-agent setting started in chapter 4 by conducting a case study in the Upper Citarum River Basin. I calibrate a coalition formation game with asymmetric players and compute its equilibria. This contributes to the literature in three ways. First, it is a case study which provides insights into the scope and structure of voluntary cooperation in wastewater treatment in the Upper Citarum River Basin. Second, it illustrates the applicability of the approach developed in Chapter 4. Third, its findings contribute to the theoretical literature on coalition formation games for transboundary river pollution. As analytical results of the asymmetric player game can only be obtained under very restrictive assumptions the findings of this chapter give an intuition on which assumptions should be made and how to proceed in the analytical analysis of these games. I find that in the original calibration no coalition with positive coalition abatement is stable because abatement benefits are too small compared to abatement costs to motivate any coalition to abate emissions. As the calculation of abatement benefits contains considerable uncertainty we also conduct a sensitivity analysis in order to check which coalitions turn stable for higher abatement benefits. In the sensitivity analysis I find that coalitions with 4 or 5 members are stable where only the most upstream members abate emissions. Regarding membership of particular regions we find two results. First, the most upstream region is a member in all cases but one. Second, the region with the highest abatement benefits is a member in all cases but one which indicates that the region with the highest abatement benefits is the key region in the river basin. Lastly, we find that total welfare is the highest for the coalition consisting of the regions that have the highest marginal abatement benefits.

Samenvatting (summary in Dutch)

Het juiste beheer van afvalwater en het hergebruik daarvan zijn belangrijk om schade te verminderen en verschillende voordelen te behouden. In veel ontwikkelingslanden, waar effectieve afvalwaterbehandeling nauwelijks plaatsvindt en onbehandeld afvalwater hergebruikt wordt, valt veel winst te behalen in het afvalwaterbeheer. Om het welvaartsoptimum te bereiken moet het hergebruik van afvalwater op een zodanige manier worden georganiseerd dat kosten en baten efficiënt worden afgewogen. Deze afweging behelst twee taken. Ten eerste moeten technische faciliteiten worden ontworpen met een voldoende capaciteit voor een geschikt niveau van afvalwaterbehandeling. Technische faciliteiten alleen zijn echter niet afdoende wanneer belanghebbenden deze niet aannemen, ondersteunen of gebruiken. Daarom bestaat de tweede taak uit het ontwerpen van een juiste institutionele omgeving waarbinnen de technische faciliteiten effectief werken. Een dergelijke omgeving biedt zodanige economische prikkels aan belanghebbenden dat hun gedrag op één lijn wordt gebracht met effectieve afvalwaterbehandeling. Hiervoor is het noodzakelijk het complexe gedragspatroon te begrijpen, dat bestaat uit de strategische interactie tussen een grote variatie aan belanghebbenden uit verschillende sectoren van de waterketen (gebruik, behandeling en hergebruik). Asymmetrische informatie en externe effecten maken deze interactie nog complexer.

Het hoofddoel van deze scriptie is het onderzoeken hoe economische prikkels van belanghebbenden de welvaart in de waterketen (gebruik, behandeling en hergebruik) beïnvloeden en om te onderzoeken of deze prikkels zodanig gereguleerd kunnen worden dat deze welvaart wordt gemaximaliseerd. In deze scriptie beschrijf ik vier situaties waarin óf asymmetrische informatie, óf externe effecten de veroorzaker zijn van strategische interactie, waardoor bij gebrek aan regulatie welvaartsverlies optreedt. Voor elk van deze situaties ontwikkel ik een speltheoretisch model dat kan worden gebruikt om een schema van economische prikkels te ontwerpen die het ontstaan, de behandeling en het hergebruik van afvalwater in ontwikkelingslanden op een zodanige manier reguleren dat de hoogst mogelijke welvaart wordt behaald.

In hoofdstuk 2 beschouw ik een scenario waarin producten die met schoon water en met afvalwater geïrrigeerd zijn, aan een lokale voedselmarkt worden geleverd. Consumenten geven de voorkeur aan producten die met schoon water geïrrigeerd zijn, maar kunnen niet onderscheiden welk voedsel met de ene soort en welke met de andere soort zijn geïrrigeerd. De consumenten bevinden zich dus in een situatie met asymmetrische informatie die marktinefficiëntie zou kunnen veroorzaken. Ik veronderstel dat zowel schoon waterproductie als afvalwaterproductie beperkt is omdat de bron van schoon water beperkt is. Ik ontwikkel een spel waarin boeren hun prijs gebruiken als een signaal of zij voedsel verkopen dat met schoon water of afvalwater geïrrigeerd is. Dit hoofdstuk draagt bij aan de literatuur over dit type signaal-spellen door de introductie van een publieke instelling die productiebeperkingen oplegt door schaarse grondstoffen te verdelen. Naast inefficiënte "pooling" evenwichten en scheidende evenwichten met verstoorde prijzen, vind ik verassend genoeg efficiënte evenwichten met onverstoorde prijzen. Efficiënte evenwichten ontstaan bij een hoge allocatie van water voor landbouw dat met afvalwater geïrrigeerd wordt. Ik concludeer dat de allocatie van schoon water een instrument kan zijn om prijsverstoringen op de lokale voedselmarkt te verminderen.

In hoofdstuk 3 analyseer ik een typische stedelijke situatie in een ontwikkelingsland waarbij de waterhuishouding van huishoudens en industrie niet zijn gescheiden en waarbij het stedelijke afvalwater bestaat uit zowel huishoudelijk en industrieel afvalwater. Ik introduceer een zuiveringsschema dat bedrijven verplicht stelt een eerste zuivering van afvalwater uit te voeren voordat het wordt geloosd in het stedelijke afvalwater. Het succes van een dergelijk schema is afhankelijk van de daadwerkelijke uitvoering van deze voorbehandeling door het bedrijf, informatie die niet openbaar is. Ik ontwerp een "compliance" spel waarbij de overheid over incomplete informatie beschikt wat betreft de mate waarin de bedrijven die afvalwater produceren voldoen aan het systeem van voorbehandeling. Dit hoofdstuk draagt bij aan de literatuur door een model aan te dragen voor economische stimuli in de gehele stedelijke waterketen bestaande uit watervervuiling, afvalwaterbehandeling en het hergebruik in de context van een ontwikkelingsland. Hierbij ontdek ik dat het terugverdienen van kosten het meest waarschijnlijk is bij een gemiddeld toezichtniveau omdat dit gepaard gaat met hogere boetes voor bedrijven die in overtreding zijn. Verder ontdek ik dat de netto baten van afvalwaterzuivering negatief kunnen zijn bij een laag toezichtniveau. Ik concludeer dat goedkopere en meer robuuste zuiveringstechnologieën moeten worden ontwikkeld.

In hoofdstuk 4 analyseer ik samenwerking in afvalwaterzuivering tussen steden langs een rivier wanneer er geen regelgevende autoriteit is. Zonder regelgeving ondervinden stroomafwaartse steden schade en moeten ze hun toevlucht zoeken tot samenwerking in de vorm van een samenwerkingsverband. In een dergelijk verband houdt iedere stad rekening met de voordelen van afvalwaterzuivering voor de leden stroomafwaarts. De leden van het samenwerkingsverband verdelen de opbrengsten van de samenwerking onder elkaar om de samenwerking stabiel te maken en te houden. Een obstakel is de aanwezigheid van profiteurs die niet bijdragen aan het verband maar ook niet kunnen worden uitgesloten van de baten van stroomopwaartse waterzuivering. Om deze situatie te analyseren ontwikkel ik een samenwerkingsformatiespel dat op twee vlakken bijdraagt aan de literatuur. Ten eerste dragen we bij aan de literatuur op het gebied van grensoverschrijdende riviervervuilingsspelen door de stabiliteit van samenwerking in een verband met meerdere spelers te analyseren. Ten tweede dragen we bij aan de literatuur over internationale afspraken op milieugebied door een casus te analyseren met een eenzijdige vervuilingsbron, waarbij een afvalwaterzuivering alleen een publiek goed is voor stroomafwaarts steden en de emissie varieert tussen de steden, tenzij alle stroomopwaartse steden voor volledige zuivering kiezen. De locatie van de leden van het verband is daarom van belang. Ik heb ontdekt dat, verrassend genoeg, voor interne oplossingen de locatie van geen invloed is op samenwerking. De locatie heeft echter wel effect op de algemene welvaart. Des te verder stroomopwaarts de leden van het samenwerkingsverband zich bevinden, des te hoger is de algemene welvaart, omdat profiteurs stroomafwaarts profiteren van afvalwaterzuivering stroomopwaarts. Ik concludeer dat autoriteiten samenwerking stroomopwaarts zouden moeten stimuleren, omdat dit de welvaart in het stroomgebied maximaliseert.

Hoofdstuk 5 gaat verder met de analyse van grensoverschrijdende riviervervuiling in een situatie met meerdere spelers uit hoofdstuk 4, met de analyse van een casus in het Upper Citarum stroomgebied. Ik kalibreer een samenwerkingsformatiespel met asymmetrische spelers en bereken de mogelijke evenwichten. Dit draagt op drie manieren bij aan de literatuur. Ten eerste is het een casus die inzicht geeft in de mogelijkheid en de structuur van vrijwillige samenwerking in afvalwaterzuivering in het Upper Citarum stroomgebied. Ten tweede illustreert het de toepasbaarheid van de benadering zoals ontwikkeld in hoofdstuk 4. Ten derde dragen de resultaten bij aan de theorie in de literatuur over samenwerkingsformatiespelen voor grensoverschrijdende riviervervuiling. Aangezien de analytische resultaten van het spel met asymmetrische spelers alleen behaald kunnen worden onder zeer strikte voorwaarden, geven de uitkomsten van dit hoofdstuk een richting aan bij de keuze van de aannames en de manier waarop de analyse kan worden aangepakt. Ik ontdek dat in de originele kalibratie geen enkel samenwerkingsverband stabiel is. Omdat de opbrengsten van zuivering te laag zijn in vergelijking met de kosten, is geen enkel samenwerkingsverband te motiveren tot het opzetten van waterzuivering. Aangezien de berekening van de voordelen van de opbrengsten aanzienlijke onzekerheden bevat, hebben we ook een gevoeligheidsanalyse uitgevoerd om uit te vinden welke samenwerkingsverbanden stabiel worden bij hogere opbrengsten. In deze analyse ontdek ik dat samenwerkingsverbanden met 4 tot 5 leden stabiel zijn wanneer deze zich helemaal stroomopwaarts bevinden. Met betrekking tot het lid zijn van specifieke regio’s vinden we twee resultaten. Ten eerste, de meest stroomopwaarts gelegen regio is een lid van het samenwerkingsverband in alle gevallen behalve één. Ten tweede, de regio met de hoogste baten van waterzuivering is lid in alle gevallen behalve één, wat aangeeft dat deze een sleutelrol vervult in het stroomgebied. Tot slot vinden we dat de algemene welvaart het hoogste is voor het samenwerkingsverband dat bestaat uit regio's met de hoogste marginale baten van waterzuivering.

About the author

Michael F. Gengenbach was born on June 6, 1975 in Bad Mergentheim, Germany. He studied Economics at Eberhard Karls University in Tübingen/ Germany and with a scholarship from the German Academic Exchange Service (DAAD) at Universidade Federal Fluminense (UFF) in Niteroi/ Brazil. In 2003 he graduated with an Economics Diploma from Eberhard Karls University. In September 2004 he was appointed PhD candidate at the Environmental Economics and Natural Resource Group at Wageningen University/ The Netherlands. Michael successfully completed the doctoral training programme of the Netherlands Network of Economics (NAKE) and of the Mansholt Graduate School of Social Science (MG3s). For his Ph.D. research he went to Bandung/ Indonesia in 2007 and 2009.

Training and Supervision Plan
Mansholt Graduate School of Social Sciences (MG3S)

Description	Institute / Department	Year	ECTS*
Courses:			
MG3S Introductory Course	MG3S	2005	1
Finalizing the PhD Research Proposal	MG3S	2005	1
Research Methodology	MG3S	2004	3
Techniques for writing and presenting a scientific paper	Wageningen Graduate Schools (WGS)	2005	1.2
Creating your Scientific Network	WGS	2006	1
Microeconomics	NAKE	2009	6
Macroeconomics	NAKE	2007	6
Game Theory	NAKE	2005	6
Environmental Economics	NAKE	2005	3
Development Economics	NAKE	2007	3
Intertemporal Allocation and Natural Resources	MG3S	2009	3
Economic Models	Wageningen University	2006	6
Intervention Methodologies for Irrigation Reform	Wageningen University	2005	6
Presentations at conferences and workshops:			4
WCERE (World Congress of Environmental and Resource Economists), Montreal/ Canada		2010	
NAKE (Netwerk Algemene en Kwantitatieve Economie) Research Day, Utrecht/ The Netherlands		2008	
ISEE (International Society of Ecological Economics), Nairobi/ Kenya		2008	
MG3S Multidisciplinary Seminar (replaced with MG3S PhD Day)		2008	
EAERE (European Association of Environmental and Resource Economists) Conference, Thessaloniki/ Greece		2007	
Asialink-Recreate Conference, Saigon/ Vietnam		2007	
MG3S PhD Day, Wageningen/ The Netherlands		2007	
PhD Workshop Environmental Economics, Zurich/ Switzerland		2007	
Teaching and Supervision Activities			1
Environmental Economics for Environmental Sciences (ENR-21306)		2005-2008	
MSc thesis supervision		2005	
Total (minimum 30 ECTS)			**51.2**

*One ECTS is on average equivalent to 28 hours of course work.