SHARING TRANSBOUNDARY RIVERS

by

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Thesis submitted to the University of Nottingham
for the degree of Doctor of Philosophy.

August 2005

Abstract

This thesis is a collection of three essays on the economics of transboundary river management (contained in chapters 2-4) the contents of which is outlined below:

Chapter 2 examines the equity-efficiency trade-off on a transboundary river where an upstream and a downstream riparian withdraw irrigation water. Equity is defined as 'equal sharing of waters' - a notion consistent with *egalitarianism* and *equality of opportunity*. Property rights are undefined, *a priori*, but riparians can enter an equal quota cooperative agreement (with side payments and restricted trade in water quotas). We find that the equity-efficiency trade-off is relatively insignificant, in prevalence as well as magnitude, and limited to special cases where the upstream riparian has a substantial relative cost advantage and/or water is very scarce.

Chapter 3 examines a transboundary river conflict arising when upstream hydropower water releases do not coincide with the seasonal irrigation needs of a downstream riparian. We consider and rank the qualitative impact of a range of infrastructure investments, potentially initiated and co-financed by multilateral development banks (MDBs). Basinwide social efficiency and regional stability can, under certain conditions, be improved through Pareto-improving investments, including enhancement of upstream hydropower efficiency and expansion of downstream reservoir capacity. The findings are used to analyse proposed infrastructure projects in the Syr Darya Basin shared by Kyrgyzstan, Uzbekistan and Kazakhstan.

Chapter 4 examines riparian cooperative behaviour on the Syr Darya river. To resolve their conflict of interest, riparian states have resorted to annual cooperative agreements. This arrangement, however, has largely failed due to lack of trust between the parties. Striving for self-sufficiency in irrigation water, Uzbekistan has initiated new reservoir construction. The chapter examines their economic impact. We report a laboratory experiment modelling the Syr Darya river scenario as a multi-round three-player trust game with non-binding contracts. Payoff schemes are estimated using real-life data. While basinwide efficiency maximisation requires regional cooperation, our results demonstrate that cooperation in the laboratory is hard to achieve. Uzbek reservoirs improve the likelihood of cooperation only weakly and their positive economic impact is limited to low-water years.

Acknowledgements

I wish to express my sincere thanks to my supervisors Professor Oliver Morrissey and Professor Richard Cornes. Their support, encouragement and guidance throughout the preparation of this thesis is greatly appreciated.

Other academic staff at the University also deserves mention: Dr Klaus Abbink showed an early interest in my work and contributed through discussion, comments and co-authorship. Moreover, I got to know him as a great travel companion as we traversed Central Asia together. I wish to thank Professor Sarah O'Hara (School of Geography) for drawing my attention to the water conflicts in the Central Asian region, co-authorship and for her support in arranging our field trip. Thanks to Dr Bouwe Dijkstra for his thorough comments and suggestions on chapter 2 of the thesis. Gratitude is also extended towards the support staff in the School of Economics who have at one point or the other offered their assistance. I am indebted to the many government officials and donor representatives in Central Asia who agreed to participate in our interviews (see appendix D for a full list of names). Special thanks go to my former and future colleague, Mr Simon Kenny from the World Bank office in Almaty, for keeping me abreast with the latest developments in the region throughout the period of thesis writing.

My postgraduate research was financed jointly by *School of Economics* and *Centre for Research in Economic Development and International Trade* (CREDIT) both of the University of Nottingham. In addition, I received financial support from *Dansk Tennis Fond* and *Anglo-Danish Society.* The field trip to the Kyrgyz Republic and Kazakhstan in December 2004 was funded by the *University of Nottingham Asia Fund.* I benefited from funding to conduct laboratory experiments (awarded to Lecturer Klaus Abbink) from the *Water Initiative Fund* of the Faculty of Law and Social Sciences.

Finally, and most importantly, I wish to thank my wife, Karla, for her outstanding personal and moral support through the last three years. This thesis is dedicated to her.

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Chapter 1: Introduction

This thesis is a collection of three essays on the economics of transboundary river management. The essays address different aspects of what is essentially the same problem: how to share water which originates within the geographical boundaries of an upstream country and flows into the territory of at least one other downstream country.

Transboundary river sharing raises several interesting issues and we shall focus on three broad themes in this thesis. The first relates to a classical topic in economic analysis, namely that of *equity and efficiency*. We consider whether it is possible to share transboundary rivers in an economically efficient manner which also reflects reasonable notions of equity. The second theme is *conflict and cooperation*. We examine potential sources of conflict and identify determinants of cooperative behaviour. A third theme relates to the role of third-party agencies in promoting transboundary river management. More specifically, the thesis aims to answer the following questions:

- What is the relationship between equity and efficiency when an upstream and a downstream riparian withdraw irrigation water from a transboundary river?
- How can multilateral development banks help reduce the regional tension that may arise from upstream hydropower use and downstream irrigation use?

- Can economic analysis contribute to understanding the incentives for cooperation on transboundary rivers? Specifically, how will the construction of re-regulating reservoirs in Uzbekistan affect cooperative behaviour on the Syr Darya river in Central Asia?

Each of these questions will be dealt with separately in Chapters 2, 3 and 4, respectively. Our approach is motivated by the *global public goods* literature which extends the public goods concept to the regional and international level using the concept of *spill-over range* across national borders (see section 3.1 in this chapter). To address the above questions, we draw primarily upon microeconomic theory on unidirectional externalities combined with insights from game theory and bargaining theory. Additionally, we conduct a behavioural investigation in Chapter 4 which makes use of laboratory experiments. These experiments were informed by primary data collected on a field visit to Kyrgyzstan and Kazakhstan in December 2004 (see Appendix E for details).

The remainder of this introductory chapter is organised as follows: Section 1 highlights the relevance of transboundary river management and motivates the choice of case study. Section 2 presents some basic characteristics about transboundary rivers and the international treaties that govern them. Section 3 examines the relevance of existing analytical frameworks to the analysis of transboundary rivers. Finally, section 4 outlines the contents of the thesis.

1. Motivation

1.1 The relevance of transboundary river management

Transboundary river management encompasses a wide range of mechanisms and instruments. Examples include: data and information exchange between riparians, river flow modelling for improved planning, reservoir construction and maintenance, provision of third-party process financing, and the development and management of river basin commissions.

There are two main reasons why transboundary river management is important. The first relates to the fact that freshwater is a scarce natural resource, upon which all life depends. Thus, to ensure preservation, national as well as transboundary water resources must be carefully managed. The second reason is political. While transboundary rivers can elicit cooperation it is particularly disruptive in cases where water is the source of conflict between nations. Not only do the people who (want to) use the water suffer, but water conflicts can also gravely affect other important issues (such as trade and investment relations) to the detriment of the regional population as a whole.

Although there is a tendency to believe that resource scarcity is a principal source of conflict (the neo-Malthusian hypothesis[1]) it may be more appropriate to consider water scarcity and river conflict as two distinct challenges, as elaborated further below.

[1] According to Neomalthusians, resource depletion and scarcity (caused by population pressures and high consumption) lead to resource competition and, ultimately, armed conflict (see for instance Gleditsch (2002)).

1.1.1 Water as a scarce resource[2]

Water plays an essential role for human survival and well being. In addition to its use for drinking and sanitation, water is an important economic input, especially in the agricultural sector. Around 40 percent of global food crops are produced using irrigated agriculture. Irrigation alone accounts for 70 percent of global water withdrawals while industrial and municipal use 20 percent and 10 percent respectively. There are non-consumption economic benefits of water use too. The most important example is hydropower production which generates almost 20 percent of world electricity output. Many of the world's rivers and lakes are also used for navigation and tourism.

Today, around 3,800 billion cubic metres (BCM) of fresh water is withdrawn annually from the world's lakes, rivers and aquifers. This is twice the volume extracted 50 years ago. Population growth and economic development are the main driving forces. Between 1950 and 2000, world population more than doubled and world GDP more than quadrupled. The unprecedented increase in water consumption has brought major gains. The introduction of high-yielding varieties (HYVs) during the *Green Revolution*, for instance, neccessitated a huge expansion in irrigated area and improved water management practices. The resultant abundance in food production cut food-grain prices by half to great benefit for consumers worldwide, especially the poor. Substantial improvements have also been registered in terms of water and sanitation. Over the past 20 years, more than 2.4 billion people have gained access to water supply and 600 million people to sanitation.

[2]This section is based on the following sources: Merrett (2003), Moller *et al.* (2005), *Nationmaster.com.*, World Bank (2003, 2004c, 2004e), World Commission on Dams (2000) and World Water Commission (2000).

Despite these achievements, there is growing recognition that the world is starting to experience a more chronic and systemic water crises. There are a number of unsolved problems: 1.2 billion people continue to lack access to clean water and 3.4 billion people still do not have access to adequate sanitation facilities. There is also evidence of a slowdown in both the growth of irrigated land and the productivity of that land. On top of this, there are 'new problems' of environmental degradation: some rivers no longer reach the sea; 50 percent of the world's wetlands have disappeared in the past century; 20 percent of freshwater fish are endangered or extinct; and many of the most important groundwater aquifers are being mined. At the very extreme, human activity has caused environmental disaster, such as in the case of the Aral Sea in Central Asia which has shrunk to a fraction of its original size due to excessive water diversions for agricultural irrigation.

It is useful to examine the aggregate balances of supply and demand, with due recognition of the fact that the issues of water are specific to time and place. In doing so, some observers, such as the World Water Commission (2000), conclude that the arithmetic simply does not add up: By 2025, the world population will increase by about one-third to 8 billion while there is no prospect of any increase in the global effective rainfall that feeds its lakes, rivers and aquifers. Global water use is projected to increase by a further 50 percent over the same period. An estimated 4 billion people will live under conditions of severe water stress in 2025, with conditions particularly severe in Africa, the Middle East and South Asia. As is often the case, it is the poorest countries and poorest people who are most directly affected. Addressing this challenge requires political will and implies changes from current practices. A wide range of interventions at the national level are relevant in this respect, including improvements in water use efficiency, full-cost pricing of water, construction of dams and technical innovation. Management of transboundary rivers will equally require attention. Consider the Syr Darya river in Central Asia - the case study of this thesis - where annual water losses are estimated at 14 to 17 BCM (billion cubic metres), or approximately 70 percent of the water diverted. The water scarcity experienced in this region can be characterised primarily as a management and incentive problem.

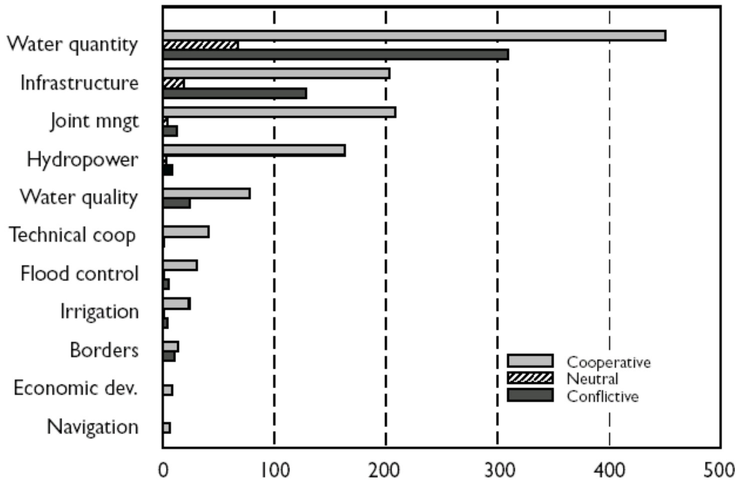
1.1.2 Water as a source of conflict (and catalyst for cooperation)

Early post-cold war research on water conflicts exaggeratedly predicted 'water wars' - a term coined by Starr (1991) - and subsequent research in the field of environmental security endorsed the notion that water scarcity leads to international conflict (Ravnborg, 2004). This claim, however, seems to have been based on highly selective evidence of the 'hottest basins' such as the Jordan, Tigris, Euphrates, Indus and Nile. A comprehensive study of 1,831 recorded international water related events between 1948 and 1999 by Wolf *et al.* (2003) reveals a more balanced reality: Two-thirds of all water-related events on international rivers were cooperative; 28 percent were conflictive and 5 percent were neutral/non-significant.[3] Moreover, no war has ever been fought over water. Figure 1.1 illustrates the frequency of the issue

[3] Water events were assessed according to a political intensity scale consisting of 15 steps ranging from *formal declaration of war* (-7) to *neutral* (0) through to *voluntary unification into one nation* (+7). A conflictive event represents a serious deterioration in the international relations between the riparians such as negative verbal expressions, hostile and even military actions. In comparison, the term *noncooperation* - a term frequently used in the economic literature - signifies the absence of cooperation.

associated with a water related event. While cooperative events involve a wide variety of issues, conflict events tend to be dominated by water quantity (sharing of water) and infrastructure - accounting for 86 percent of the total. Water sharing, associated with most cooperative water related events, will be explored further in Chapter 2. In Chapters 3 and 4 we consider the impact of infrastructure investments (i.e. reservoirs or hydropower plants) on noncooperative outcomes and cooperative behaviour.

Figure 1.1 Cooperative, neutral and conflictive water events by issue.



Source: Yoffe *et al.* (2001) reprinted from Ravnborg (2004).

The study by Wolf *et al.* (2003) found no support for the neo-Malthusian hypothesis. The data analysed contained no statistically significant correlation between water scarcity and conflict. Instead, the authors hypothesise that 'the likelihood of conflict is determined by increases in the magnitude and amount of physical or institutional change relative to the capacity to absorb such changes' (ibid. p. 51). The most radical of such changes is the internationalisation of a basin, i.e. division of basins whose management was developed institutionally under one single jurisdiction into two or more nations. The collapse of the Soviet Union, for instance, has caused conflicts between the now independent Central Asia republics in the Syr Darya and Amu Darya basins.

1.2 The relevance of Syr Darya as a case study

In addition to illustrating the importance of transboundary river management in addressing the twin challenges of scarcity and conflict, the Syr Darya river has a number of interesting characteristics which makes it an ideal candidate for a case study. First, as already mentioned, it is one of several 'hot basins' in the world where riparian relations are fundamentally conflictive and water a source of regional tension. Policy recommendations aimed at 'dehydrating the conflict' thus have the potential of improving the well being of millions of people across the region. Secondly, the type of conflict currently experienced on the Syr Darya is likely to become more widespread across the globe in the future as upstream riparians move to exploit their substantial, but yet unused hydropower potential. Thirdly, the Syr Darya conflict has attracted substantial interest within the international community and several donors have been actively engaged in promoting regional cooperation. The case study thus fits squarely with one of the themes of the thesis: the role and relevance of third party agencies in promoting transboundary river management. Fourthly, despite considerable interest in identifying cooperative solutions on the Syr Darya, economic analysis of the conflict has been surprisingly limited. The contributions in Chapters 3 and 4 of this thesis aim at filling this gap. Finally, although incomplete, cooperative efforts on the Syr Darya have been based on the sound economic principle of side payments. This in itself is interesting since side payments across international borders are quite rare in practice. Moreover, it underscores the relevance of applying game theoretical concepts in analysing the conflict as we do in Chapter 4.

2. Transboundary rivers: some basic characteristics

2.1 Defining shared rivers: transboundary or international?

This thesis deals with the management of rivers that cross the border of two or more riparian states. Some scholars refer to these as 'international rivers' while others call them 'transboundary rivers'. Neither concept is without its flaws (see Sadoff and Grey (2002) for a discussion). To some, the use of the word 'international' is incorrect as it implies that the waters (as in seas) do not belong to any state, whereas in reality only the basin states have rights to the water. Others may be confused about 'transboundary rivers' as many river channels form international borders without crossing them. 'Transboundary' may also refer to rivers that cross intra-national (e.g. state) borders - not only international borders.

To complicate matters, these terms also have political connotations implying that some countries may prefer the use of one over the other if it serves their interests. Turkey, for instance, which is an upstream riparian in the Euphrates/Tigris river basin distinguishes a border river from a transboundary river that crosses the border. This distinction serves a purpose by allowing Turkey to claim sovereignty over the Euphrates/Tigris watercourse within its borders. Iraq, which is a downstream riparian in this basin, is against the use of the term 'transboundary river' and calls for the removal of this term from the legal text wherever it occurs. Syria, the midstream riparian of both Euphrates/Tigris and the Orontes river, argues that the former are international rivers while the latter is not (although the Orontes touches Lebanon and Turkey as well). The Syrian non-recognition of Turkish sovereignty over Alexandria, where the Orontes water reach the Mediterranean Sea, explains this equivocal attitude (Yetim, 2002).

The fact that both concepts are politically contentious and widely used in the literature makes it difficult to use one at the exclusion of the other. Nevertheless, for practical reasons we shall primarily use the term 'transboundary rivers' albeit we occasionally make reference to 'international river basins', particularly when referring to statistics about rivers and the treaties that govern them. Although this choice of terms has inevitable political implications these are entirely unintentional.

2.2 International river basins in the world

The best source of statistics about international river basins is Wolf *et al.* (1999) which contains an update of the 1978 UN Register of International Rivers. They define a *river basin* as 'the area which contributes hydrologically (including both surface- and groundwater) to a first order stream, which, in turn, is defined by its outlet to the ocean or to a terminal (closed) lake or inland sea.' Such a basin is *international* if 'any perennial tributary crosses the political boundaries of two or more nations.' By this definition, there are 261 international river basins in the world covering 45.3 percent of the land-surface of the earth (excluding Antarctica). Table 1.1 breaks this data down by continent and Appendix A presents maps of these river basins.

Table 1.1 International river basins by continent

	Africa	Asia	Europe	N. America	S. America	World
River basins	60	53	71	39	38	261
Percentage	23.0	20.3	27.2	14.9	14.6	100.0

Source: Wolf *et al.* (1999).

Around two-thirds of all international river basins are shared by only two countries. River basins shared by a large number of countries such as the Danube (17), the Congo (11), the Niger (11), the Nile (10), the Rhine (9), the Zambezi (9), the Amazon (8) and Lake Chad (8) are therefore exceptional (Table 1.2 refers and Appendix B provides a complete list).

Table 1.2 Number of countries that share a river basin

Number of countries in basin	2	3	4	5+
River basins (number)	176	49	17	19
Percentage	67.4	18.8	6.5	7.3

Source: Wolf *et al.* (1999).

It should be noted that an international river basin can contain several transboundary rivers. This is best illustrated with an example. The Aral Sea basin is shared by the following six countries: The Kyrgyz Republic, Tajikistan, Afghanistan, Uzbekistan, Turkmenistan, Kazakhstan. This basin consists of two major transboundary rivers, both of which feed the Aral Sea: The Amu Darya (shared by Afghanistan, Tajikistan, Uzbekistan and Turkmenistan) and the Syr Darya (The Kyrgyz Republic, Tajikistan, Uzbekistan and Kazakhstan). In addition, there are a number of smaller transboundary rivers in the Aral Sea basin, such as the Chui and Talas rivers shared by the Kyrgyz Republic and Kazakhstan. It follows that the number of transboundary rivers in the world is greater than the number of international river basins.

2.3 International river basin treaties

There are 145 treaties (dating from 1870 onwards) which deal with non-navigational issues of water management such as flood control, hydropower projects, or allocations for consumptive or non-consumptive uses in international river basins. Eighty-six percent of these treaties are bilateral (Hamner and Wolf, 1998). This is partly because two-thirds of all international river basins are shared by only two nations, but partly because multilateral agreements are more difficult to reach. To illustrate, some riparian countries (such as India) have a deliberate policy to enter only bilateral agreements over transboundary rivers so as to maximise their political influence.

Table 1.3 provides a summary of relevant treaty characteristics. Most treaties deal with hydropower and water supplies. It is fair to say that the 145 treaties covering the world's 261 international river basins, and the international law on which they are based, are in their respective infancies. Less than half of these treaties include no monitoring provisions, two-thirds do not delineate specific allocations and four-fifths have no enforcement mechanisms. This state of affairs, combined with the fact that almost half of all international river basins are not currently covered by a treaty, offers potential breeding ground for conflict over shared water resources.

Table 1.3 Characteristics of the 145 international river basin treaties

Signatories:		**Monitoring:**		**Water allocations:**	
Bilateral	86%	Provided	54%	Equal portions	10%
Multilateral	14%	Not provided, N/A	46%	Complex but clear	27%
				Unclear	10%
Principal		**Conflict**		None or N/A	53%
focus:		**resolution:**			
Hydropower	39%	Council	30%		
Water supply	37%	Other govt. unit	6%	**Unequal power**	
Flood control	9%	UN	10%	**relationship:**	
Industrial uses	6%	None or N/A	54%	Yes	36%
Navigation	4%			No	64%
Pollution	4%	**Enforcement:**			
Fishing	<1%	Council	18%	**Nonwater linkages:**	
None or N/A	<1%	Force	1%	Money	30%
Information:		Economic	<1%	Land	4%
Sharing		None or N/A	80%	Political concessions	1%
Yes	64%			Other	7%
No or N/A	36%			None or N/A	56%

Source: Hamner and Wolf (1998).

3. The relevance of existing analytical frameworks

In this thesis we analyse problems that may arise when at least two countries share a river. Economists tend to classify rivers as either public goods, common-pool resources or externalities. This section briefly reviews existing analytical frameworks and assesses their relevance for analysing the river sharing problem. It begins by recalling some definitions.

It is sometimes useful to distinguish an economic good by whether its benefits are non-rival and/or non-excludable. Non-rivalry implies that an economic agent can consume the good without affecting the consumption possibilities of other agents. Non-excludability means that it is difficult to exclude other agents from enjoying the benefits. Table 1.4 classifies goods according to these two properties.

Table 1.4 A general classification of goods

	Rival	**Non-rival**
Excludable	Private Goods	Club Goods
Non-excludable	Common-Pool Resources	(Pure) Public Goods

Public goods are goods whose benefits have characteristics of being non-rival and non-excludable. A *common-pool resource* is an impure public good which is rival, but non-excludable. Conversely, club goods are non-rival but excludable. More generally, it can be argued that public goods 'can be thought of as a special case of externalities' (Cornes and Sandler, 1996: 6). *Externalities*, in turn, arise when an economic agent does not bear all the costs or benefits of his/her actions.

3.1 Global Public Goods

Interest in public goods can be traced back to the classical economists, notably David Hume and Adam Smith. Modern economic theory of public goods starts with Paul Samuelson's seminal work (1954, 1955) and has evolved considerably since then as illustrated in the textbook by Cornes and Sandler (1996). Public goods have traditionally been analysed in a local or national context, although in recent years considerable attention has been given to the fact that many global challenges can be framed as regional, international and global public goods (Sandler, 1997, Kaul *et al.*, 1999, Kanbur and Sandler, 1999). This includes problems as diverse as reducing the spread of HIV/AIDS, controlling climate change, containing financial crises and combating drug trafficking.

In addition to their characteristics on the demand side, i.e. non-rivalry and non-excludability of consumption, public goods can also be differentiated in terms of their supply characteristics. Samuelson defined public good supply as the simple sum of individual private contributions. Hirshleifer (1983, 1985) expanded this definition by including *weakest-link* and *best-shot* supply technologies. For a weakest-link public good the supply equals the smallest of the individual contributions while in the case of best-shot only the largest individual contribution matters. Finally, Cornes (1993) introduced a general class of public goods by suggesting a CES-type public good supply function which also included intermediate cases such as *weaker-link*, *better-shot* and *average* technologies. Public goods can also be sorted according to their place in the production chain, i.e. whether they are a *final* (i.e. an outcome or an end) or *intermediate* (i.e. an output or means) towards the provision of final public goods (Kaul *et al.*, 1999).

Transboundary rivers as regional public goods

Having briefly introduced the public goods concept we now turn to the question of the extent to which it can be applied to analyse transboundary rivers. Starting with the demand side characteristics, we observe that consumptive river sharing is nonexcludable, but rival in consumption. (Transboundary) rivers therefore belong to the particular class of (regional) impure public goods known as common-pool resources. The non-excludability property derives from the fact that all the riparian countries, by definition, have access to the transboundary river and cannot be excluded from making use of the water which runs through their sovereign territory.[4] As the name

[4]We ignore here the case where a regional hegemon prevents water use by co-riparians

suggests, rivers are also rival in their use.[5] Water withdrawals by an upstream riparian clearly reduces the consumption possibilities of any riparian further downstream. A similar case can be made for transboundary water pollution by interpreting this as 'consumption of water quality'. Consider also the case where an upstream riparian decides to operate its hydropower plant such that it affects downstream water availability in any given season. By interpreting the upstream action of storing water in its reservoir as consumption, water use at time t is rival. We now demonstrate how the public good concept can be applied to analyse the management and infrastructure of a transboundary river.

Transboundary river management as a regional public good

Transboundary river management may be classified as a regional public good. This public good can be provided by transboundary river management institutions (ranging from treaties to river basin commissions) as well as by a third party (i.e. international development agencies). If all riparians on the river take part in the institutional arrangement then the services provided by this institution, such as data and information exchange, have a pure public good nature. However, if at least one of the riparians is excluded or choose to opt-out then the institution becomes a club good. Irrespective of this, the public good provision is provided by the weighted sum of individual contributions. Furthermore, transboundary water institutions

through the use of political power and threat of military force. Until recently, Egypt successfully pursued such a strategy on the Nile, effectively preventing upstream riparians such as Tanzania and Kenya from withdrawing water from that river. In recent years, however, these countries have openly challenged Egypt's 'right' to the water.

[5] The word rival has the same root as river, derived from the riparian concept of dwellers on opposite riverbanks (Sadoff and Grey, 2002).

may also be classified as a 'means' type public good to the extent that its output produces other public goods such as regional peace and security (ODI, 2001). While such classifications demonstrate the application of the concept of global public goods and may yield insights which are relevant for other types of analysis, their usefulness for our research is relatively limited.

Transboundary river infrastructure as a regional public good[6]

Infrastructure, such as dams or pumping stations, located on transboundary rivers may also be classified as regional public goods. This is the case if the benefits of dam operation and maintenance accrue to the host riparian as well as the downstream riparian(s) and the latter cannot be excluded from these benefits. Dams play many useful roles, intra-seasonal as well as inter-seasonal, through their ability to regulate the natural river flow. Some examples of the water storage services provided by dams include: timely release of irrigation water; storage during wet years and release during dry years, and absorption of excess water inflow to reduce flood risk. Dams operated exclusively to produce upstream hydropower, on the other hand, may have a negative downstream impact, as analysed in detail in Chapters 3 and 4. In this case, an upstream dam can be considered a *regional public bad* from the perspective of the downstream riparian(s). Another example of a potential negative impact is the issue of dam safety. The collapse of a dam would instantly release enormous water masses and the resulting shock wave can have a tremendously damaging downstream impact for humans, animals and infrastructure. In this case the proper maintenance of dam structures and the development and maintenance of early warning systems

[6] This section is based on Moller *et al.* (2005).

are a regional public good. As expected, it is often quite difficult to make downstream riparians contribute towards the maintenance of upstream infrastructure from which they benefit, because of the free-riding property of public goods. This leads to under-investment in these facilities because the host riparian will only contribute up to the point where its marginal costs equal its marginal benefits. Optimal provision, in contrast, requires that the marginal costs of all riparians equal the sum of their marginal benefits (the Samuelson condition). As emphasised in the global public goods literature, this incentive structure can be used as a rationale for development assistance. In Central Asia, for instance, international donors have played an important role in contributing towards the maintenance of river infrastructure to ensure dam safety.

The pure public goods model and river conflicts

As demonstrated above, the consumptive water use, the institutions and the infrastructure of a transboundary river can indeed be considered regional public goods. This raises the question of whether the basic model of pure public goods provision would be suitable to address the questions pursued in this thesis.[7] Recall that this model produces a best-response or replacement function of player i whose payoff depends partly on that player's own contribution as well as the contribution of other players. While some degree of heterogeneity can be introduced in the public goods model, such as the initial resource endowment of player j, the structure of the model is essentially symmetrical. Since each player must choose an optimal response without

[7] A formal description of this model would be unnecessary for our purposes, but see Cornes and Sandler (1996).

knowing the decisions of the other players, there is some degree of strategic interaction between the players, i.e. it is a game.

Consider next the basic set-up on a transboundary river involving an upstream and a downstream riparian. The actions of the upstream riparian may affect the welfare of the downstream riparian while the reverse is not the case. The optimal upstream choice is strategically independent of the optimal downstream choice unless the downstream riparian is equipped with an additional strategic variable, such as military action or a monetary transfer. This asymmetry in water use, or unidirectional rivalry, distinguishes this situation from other pure public goods problems. The pure public goods model would therefore be inadequate in describing the transboundary river problem. There is, however, also a class of models for common-pool resources and the relevance of this framework is considered next.

3.2 Common-Pool Resources

Common-Pool Resources (CPRs) are commonly thought to lead to situations of overexploitation. There are at least three formal arguments in support of this hypothesis. First, there is the so-called *Tragedy of the Commons* - a phrase often associated with Hardin (1968). Analysis of this type of problem, however, dates back at least to the work of David Hume in 1739. The tragedy is often illustrated by referring to a situation in which n farmers share an open grassland where they graze their animals. Over-exploitation occurs because each farmer considers only the marginal benefits and costs of adding yet another grazing animal to the field, but ignores the negative externality one extra grazing animal imposes on other farmers. A second argument in support of the over-exploitation hypothesis is contained in the seminal work by Olson (1965) on *The Logic of Collective Action.* Olson's central thesis was that self-interested and rational individuals would not necessarily choose a socially optimal outcome. Although none of the propositions put forward by Olson are true in general, most are valid in many cases that correspond to important real-world scenarios (Sandler 1992). Amongst others, Olson highlighted the free-riding problem, caused by the non-excludability property, as one of the toughest dilemmas in providing public goods and preserving the commons.[8] Third, and finally, there is the *Prisoner's Dilemma Game* which suggests it is impossible for rational individuals to cooperate, since defection is the best strategy in which individuals are always better-off no matter what others choose. To be precise, the Nash equilibrium is Pareto inferior in one-shot games with complete information.

The overexploitation hypothesis has been criticised by the neo-institutionalist school (Ostrom, 1990; Ostrom, Gardner and Walker, 1994). While acknowledging the relevance of the insights outlined above, Ostrom (1990) argues that these arguments cannot explain all CPR situations. For instance, by changing the assumptions of the Prisoner's Dilemma and allowing communication between players or by repeating the game, Pareto optimal outcomes can indeed be attained. More generally, it is argued that 'by devising their own rules-in-use, individuals using such CPRs have overcome the *Tragedy of the Commons'* (Ostrom *et al.*, 1994: 5). This conjecture is supported by a wide range of case studies in which the institutions governing

[8]Although his analysis can be applied to natural resources management, Olson (1965) himself does not discuss this subject.

CPRs are shown to have been effective in avoiding the tragedies associated with open access. From these case studies follows a list of design principles which characterise long-enduring CPR institutions, including:

1. Clearly defined boundaries: the individuals or households who have the right to withdraw resource units from the CPR must be clearly defined, as must the boundaries of the CPR itself.

2. Congruence between appropriation and provision rules and local conditions: appropriation rules restricting time, place, technology, and/or quantity of resource units relate to local conditions and to provision rules requiring labour, material, and/or money.

3. Collective-choice arrangements: most individuals affected by the operational rules can participate in modifying the operational rules.

4. Monitoring: monitors who actively audit CPR conditions and appropriator behaviour are accountable to the appropriators or are the appropriators.

5. Graduated sanctions: appropriators who violate operational rules are likely to be assessed graduated sanctions (depending on the seriousness and context of their offence) by other appropriators, by officials accountable to these appropriators, or by both.

6. Conflict-resolution mechanisms: appropriators and their officials have rapid access to low-cost local arenas to resolve conflicts among appropriators, or between appropriators and officials.

7. Minimal recognition of rights to organise: the rights of appropriators to devise their own institutions are not challenged by external governmental authorities.

8. Nested enterprises for CPRs that are part of larger systems: appropriation, provision, monitoring enforcement, conflict resolution, and governance activities are organised in multiple layers of nested enterprise (this last principle is for CPRs that are parts of a larger system) (Ostrom, 1990).

Transboundary rivers as international common-pool resources

To what extent can the insights provided by the neo-institutionalist school be applied to the management of transboundary rivers? Some scholars, such as Yetim (2002), argue that the CPR approach yields useful insights and can help identify important aspects of the commons problem which must be addressed to effectively manage transboundary rivers. In his case study of the international water courses of the Middle East, Yetim highlights the need for determination of property rights and enforcement mechanisms in international common pool disputes - a need exacerbated by high levels of complexity, transaction costs, lack of predictability and information, and trust among riparians. Other scholars, such as Williams (2003) are more sceptical about the explanatory power of the CPR framework. Williams addresses the more fundamental question of whether transboundary rivers can be classified as common-pool resources in the first place. The prototypical commons problem, he argues, implies a relative symmetry of harmful consequences related to a unique combination of structural attributes: total supply of benefits is subtractable, thereby generating rivalry, but it is costly (but not impossible) to exclude the potential beneficiaries from obtaining benefits to its use. In other words, the users of the commons harm each other reciprocally through over-consumption. Williams highlights that Ostrom's (1990) seminal work explicitly omitted cases in which some users can control the supply or unreciprocally pass the negative externality costs of their over-consumption along to others. Clearly, this would exclude transboundary rivers formed along an upstream-downstream axis because they create an asymmetrical rivalry. According to Williams, this seems to call into question the non-exclusivity criterion because, to some extent, the upstream riparian has the ability to exclude the downstream riparian(s) from using the water. Moreover, it patently strains the CPR concept to reconcile the notion that water is a common resource with the assumption that individual states have a sovereign right to control territorial resources. Williams sums up his point by arguing that it is this asymmetrical physical interdependence that forms one of the largest barrier to constructing the sense of 'common fate' necessary to resolve the collective-action dilemma.

The common pool-model and river conflicts

Is the standard common-pool model suitable to address the questions pursued in this thesis? In this model each individual ultimately cares about the total availability of the resource (because this determines private consumption) and the costs of accessing the resource. As noted by Cornes and Sandler (1996: 65), this model has precisely the same structure as the standard pure public good model. This, again, implies that the common pool model is equally inadequate in describing the asymmetric nature of a river conflict.

In conclusion, the upstream-downstream transboundary river problem is characterised by a unidirectional rivalry which cannot be adequately described if a public goods or common-pools model is applied. Therefore, to characterise this problem we must model the unidirectional externality explicitly.

3.3 Unidirectional externalities

As previously argued, the *public good* and *open access* problems can be thought of as special cases of externalities. The underprovision of a public good, for instance, occurs because contributors fail to internalise the positive externality that their public good supply confers on others. In these special cases, each individual is simultaneously a sender as well as a receiver of a reciprocal externality. In contrast, a *unidirectional externality* occurs when the spill-over effect arising from the action of one economic agent affects at least one other agent, while the reverse is not the case.

Modern literature on externalities flows from Pigou's (1946) classical contribution. Pigou's approach consists of a system of taxes and subsidies designed to distort individual choices towards an optimal outcome. His solution recognises the distortions introduced by externalities and attempts to nullify them imposing precisely equal and opposite tax distortions, thereby effectively internalising the externality. The Pigouvian approach has been clarified, extended and criticised by countless others. James Meade (1973), for instance, introduced a much broader, and hence controversial, definition of the externality concept including situations where no inefficiency or market failure are present. The most powerful critique of Pigou's analysis was presented in a well-known paper by Coase (1960). He argued that an externality would not persist - but would be internalised - if the sender and the recipient of an externality could bargain costlessly. In other words, there would be an amount which the recipient would be willing to pay as compensation in return for a reduction of a negative externality (and vice versa). An important policy implication of this argument is that the mere existence of an externality is not a sufficient reason for government intervention (Cornes and Sandler, 1996: 6).

Transboundary rivers as unidirectional externalities

There are at least two papers in the economics literature which classify transboundary rivers as *unidirectional externalities.* In his essay on international environmental problems, Mäler (1990) uses a taxonomy in which he *inter alia* distinguishes between unidirectional and reciprocal externalities. To model unidirectional externalities he examines the case of an upstream polluting country and a downstream suffering country. While Mäler's treatment gives the impression that river externalities are typically negative, Rogers' (1997) analysis highlights that they be positive as well and he gives a range of examples (see Table 1.5).

Table 1.5 Downstream effects of upstream water use

	Downstream effect	
Water use	Positive	Negative
Direct Hydropower -base load -peak load	 Helps regulate river 	 Creates additional peaks
Irrigation diversions		Removes water from the system
Flood storage	Provides downstream flood protection	
Municipal and industrial diversions		Removes water from the system
Wastewater treatment		Adds pollution to the river
Navigation	Keeps water in river	
Recreation storage		Keeps water out of the system
Ecological maintenance	Keeps flow low in river	
Groundwater development		Reduces groundwater availability and stream flows
Indirect Agriculture		 Adds sediment and chemicals
Forestry		Adds sediment and chemicals and increases run-off
Animal husbandry		Adds sediments and nutrients
Filling wetlands		Reduces ecological carrying capacity and increases floods
Urban development		Induces flooding; adds pollutants
Mineral deposits		Adds chemicals to surface and ground water

Source: Rogers (1997).

Unidirectional externalities - a basic model

A model of a unidirectional externality may take the following form (Cornes and Sandler, 1996: 70). Consider a two-person model with two marketed commodities where y_j^i denotes individual i's consumption of commodity j. Each consumer has a given money income, I^i, and can trade with the rest of the world at fixed prices p_1 and p_2. The externality is modelled by including the quantity of commodity 2 chosen by individual A in the utility function of individual B. The problems of individuals A and B are, respectively:

$$\underset{\{y_1^A, y_2^A\}}{Max} \left\{U^A(y_1^A, y_2^A) | p_1 y_1^A + p_2 y_2^A = I^A\right\} \tag{1}$$
$$\underset{\{y_1^B, y_2^B\}}{Max} \left\{U^B(y_1^B, y_2^B, e^B) | p_1 y_1^B + p_2 y_2^B = I^B, e^B = y_2^A\right\}$$

The equilibrium allocation is characterised in the usual way by the equalities:

$$\frac{\partial U^A / \partial y_1^A}{\partial U^A / \partial y_2^A} = \frac{\partial U^B / \partial y_1^B}{\partial U^B / \partial y_2^B} = \frac{p_1}{p_2} \tag{2}$$

It can be shown that the competitive equilibrium in (2) is not Pareto-efficient due to the presence of the externality e^B.[9] To attain Pareto-efficiency, economists have traditionally proposed one of three alternative policy remedies: (a) a quantity constraint; (b) a Pigouvian tax/subsidy and (c) Coasian externality trading. The relative merits and de-merits of these alternative approaches shall not be discussed further here. Instead we engage in an informal illustration of the qualitative properties of the Pigouvian approach and draw parallels to results presented later in the core chapters, notably in Chapter 3.

[9] We shall not attempt a formal demonstration of this result here. Interested readers are referred to Cornes and Sandler (1996).

Suppose in the above model, that individual A's consumption of commodity 2 has a negative impact on individual B's utility, i.e. $\frac{\partial U^B}{\partial e^B} < 0$. A Pigouvian taxation scheme aimed at attaining Pareto-efficiency would therefore involve taxation of individual A's consumption of commodity 2. This intervention is income-neutral because A receives a positive lump-sum transfer L so that his or her new budget constraint is given as:

$$p_1 y_1^A + (p_2 + t_2^A) y_2^A = I^A + L \tag{3}$$

while that of individual B remains unchanged. This implies that there are no net transfers between the two individuals. As illustrated in Figure 1.2 (on page 41), the effect of the tax is to change the relative prices facing individual A. This correction of relative prices makes A worse-off in the 'Pigouvian' equilibrium P compared to the initial equilibrium O. If the Pigouvian tax is indeed sufficient to attain Pareto-efficiency, then by implication individual B must be better-off ex-post because the externality has been reduced. The effect of a Pigouvian tax can also be illustrated using a diagram of the utility possibility frontier (see Figure 1.3). The Pigouvian tax implies a move from the inefficient point O to the Pareto-efficient point P on the frontier and A will be worse-off while B is better-off.

Pareto-efficiency vs. Pareto improvement

The question of how economic agents can sustain a Pareto-efficient allocation has received a great deal of attention in the economic literature. An important drawback of the Pareto-efficiency criterion, however, is that it ignores distributional issues. While in a Pareto optimum the winners of a policy could potentially compensate the losers such compensation will typically require access to some means of making net transfers between individuals. To illustrate, the Pigouvian tax discussed above addresses the objective of Pareto-efficiency, but lacks a transfer policy to improve the utility of individual A. To incorporate this, consider the modified budget constraints of the two individuals:

$$p_1 y_1^A + (p_2 + t_2^A) y_2^A = I^A + L + T \tag{4}$$

$$p_1 y_1^B + p_2 y_2^B = I^B - T \tag{5}$$

where T is a lump-sum net transfer from individual B to individual A.[10] Thus, the attainment of what is, in effect, two policy objectives, namely the improvement of the utility of individual A *and* individual B, requires two policy instruments (t_2^A and T).

One way to overcome the distributional problem is to focus attention on Pareto-improving policies in which at least one individual is made better off without making any other individual worse-off. This approach is taken by Cornes and Sandler (2000) in the context of public goods provision. In Chapter 3 of this thesis we adopt a similar approach. More specifically, we analyse a situation in which the actions of an upstream riparian state generate a negative unidirectional externality affecting a downstream riparian state. In the absence of a supra-national tax-collecting agency, the use of a Pigouvian taxation scheme is generally not feasible. On the other hand, a

[10] The treatment of T as genuinely lumpsum may be justified if we assume that the economy consists of large number of A and B types. Then a small change of behaviour by one of the A types will hardly affect the share of transfer that he expects to pay or receive.

subsidy paid by a third-party agency to either of the riparians may well be feasible. Indeed, we investigate a number of ways in which multilateral development banks can finance externality-reducing infrastructure projects, such as hydropower plants or dams, in the riparian states. Without pre-empting the analysis, we derive an interesting and nontrivial result: A subsidy provided from a third-party agency to the upstream riparian may, under certain circumstances, lead to a Pareto-improvement.

While this type of intervention has the flavour of a Pigouvian subsidy there are a number of noticeable differences which are worth pointing out at this stage. First, the transfer from the third-party agency is a net transfer, i.e. the subsidy is not financed through a lump-sum tax of the externality sender (but possibly through taxation in donor countries). Secondly, as opposed to a pure monetary transfer the subsidy is used to improve the technical efficiency of the externality sender. Thirdly, the intervention achieves two policy objectives (improves upstream *and* downstream welfare) with only one policy instrument (the subsidy). Finally, while the intervention may produce a Pareto-improvement it will generally not be sufficient to guarantee the attainment of Pareto-efficiency. We use Figure 1.3 to illustrate this conceptual point, although this figure cannot immediately be derived from the analysis in Chapter 3. The the ex-post equilibrium E is located north-east of the ex-ante equilibrium O, but the Pareto frontier expands simultaneously due to the increase in upstream technical efficiency.

In sum, the unidirectional externality framework turns out to be the most useful analytical framework to study the type of upstream-downstream transboundary river sharing problems considered in this thesis. Since externalities are sources of inefficiency there is a scope for identifying policy interventions aimed at enhancing economic efficiency as we do in Chapter 3. Further, in Chapters 2 and 4 we propose the use of efficiency-enhancing cooperative agreements (with side payments). To some extent, these two contributions are reminiscent of a Coasian analysis in which the downstream receiver of the unidirectional externality 'bribes' the upstream sender to reduce the externality. In Chapter 2 the unidirectional externality arises over the consumptive rivalry of the river water. A quota allocation is proposed in which the two riparians share the water equally. Full-scale Coasian water trading across international borders is assumed infeasible, however, such that riparians are only allowed to trade unutilised water units. In Chapter 4 we explore the possibility that the downstream riparians on the Syr Darya pay a 'bribe' to the upstream riparian to reduce the negative externality caused by its regulation of the natural river flow. We show how lack of trust between the riparians can be an obstacle for the attainment of Pareto efficiency.[11] The subsequent section presents a more detailed outline of the thesis.

4. Thesis outline

This thesis seeks to fill some gaps in the economics literature on transboundary river management. More specifically, it examines two different types of conflict over shared water resources. In the first type of conflict, explored in Chapter 2, there is rivalry over the total amount of water resources

[11] To a certain degree, therefore, it can be argued that all three 'classical' instruments of environmental policy making are considered at various stages of the thesis: a) quota (chapter 2); b) taxation/subsidy (chapter 3) and c) quota trading (chapters 2 and 4).

available. In the second type of conflict, explored in Chapters 3 and 4, water use at time t is rival. The difference between the two types of conflict is explained in more detail below as the contents of each of the thesis chapters is outlined.

At the heart of many transboundary river disputes is the lack of internationally accepted criteria for sharing water resources between riparians (Wolf, 1999). The identification of equity criteria is essentially a political question, but economists have an important role to play in terms of highlighting the efficiency implications of the proposed criteria. Is there a trade-off between the policy objectives of equity and efficiency? To address this question, Chapter 2 develops a theoretical model of an upstream and a downstream riparian both of which use water for agricultural irrigation. Equity, of course, is a contestable term. We define it as 'equal sharing of waters' - a notion consistent with several theories of justice, such as *egalitarianism* and *equality of opportunity*. Property rights are undefined in the model, *a priori*, but riparians can enter an equal quota cooperative agreement with side payments and restricted water trade. To model riparian heterogeneity we allow for differences in the economic value of alternative uses of water. After detailing the relationship between equity and efficiency, the chapter concludes by presenting an algorithm that can guide policy makers in deciding how to share transboundary rivers fairly and efficiently. The main contribution of the chapter is the development of an analytical framework within which the efficiency implications of any exogenously defined sharing rule, or equity criteria, can be examined.

In Chapter 3 we present a theoretical model of a transboundary river conflict involving upstream hydropower use and downstream irrigation use. The conflict arises because upstream water release may not coincide with seasonal irrigation needs of the downstream riparian. From the perspective of the downstream riparian, the result is that in any given season either 'too little' or 'too much' water is available relative to its optimum. Conflict-reducing policy interventions by multilateral development banks (MDBs) are of particular interest because these agencies have a comparative advantage in transboundary river management. There are essentially two different approaches to reducing the conflict: A cooperative approach where the downstream riparian issues a side payment to persuade the upstream riparian to introduce a more favourable water release vector. This approach is explored further in Chapter 4. The noncooperative approach, examined in Chapter 3, on the other hand, considers the conflict-reducing role of infrastructure investments, such as construction of hydropower plants and dams, potentially initiated and co-financed by a MDB. The chapter addresses two different policy questions: First, is it possible to identify policy interventions that simultaneously promote regional stability and enhance social efficiency? Secondly, could a downstream client be more effectively assisted through indirect intervention in an upstream state, as opposed to direct investments within the client's own territory? These questions are addressed within a theoretical model. We discuss the relevance of some of the findings in a case study of the Syr Darya river. The contribution of the chapter is twofold: It adds to the sparse literature on international hydropower-irrigation conflicts by providing an analytical framework within which real-life cases can be analysed. Secondly, it contributes to the general literature on transboundary rivers by explicitly considering a potential role for third-party intervention.

In Chapter 4 we explore the cooperative approach in the conflict over hydropower and irrigation use on the Syr Darya river. With the disintegration of the USSR a conflict arose between Kyrgyzstan, Uzbekistan and Kazakhstan. Upstream Kyrgyzstan operates the Toktogul reservoir which generates hydropower demanded mainly in winter for heating. Downstream Uzbekistan and Kazakhstan need irrigation water in summer, primarily to grow cotton. Regional agreements obliging Kyrgyzstan to high summer discharges in exchange for fossil fuel transfers in winter have generally been unsuccessful, notably due to lack of trust between the parties. Striving for self-sufficiency in irrigation water, Uzbekistan has therefore initiated new reservoir construction. This chapter examines their potential impact on riparian cooperative behaviour. To address this question we conducted a laboratory experiment modelling the Syr Darya river scenario as a multi-round three-player trust game with non-binding contracts. Payoff schemes were estimated using real-life data. The chapter contributes to the literature on transboundary river conflicts by introducing a novel methodology to investigate riparian cooperative behaviour.

The concluding Chapter 5 summarises the main findings of the chapters. This includes the main contributions of the thesis, the drawbacks of the techniques used, and some lines of suggestion for future work.

Figure 1.2 The effect of a Pigouvian tax on A's optimal choice

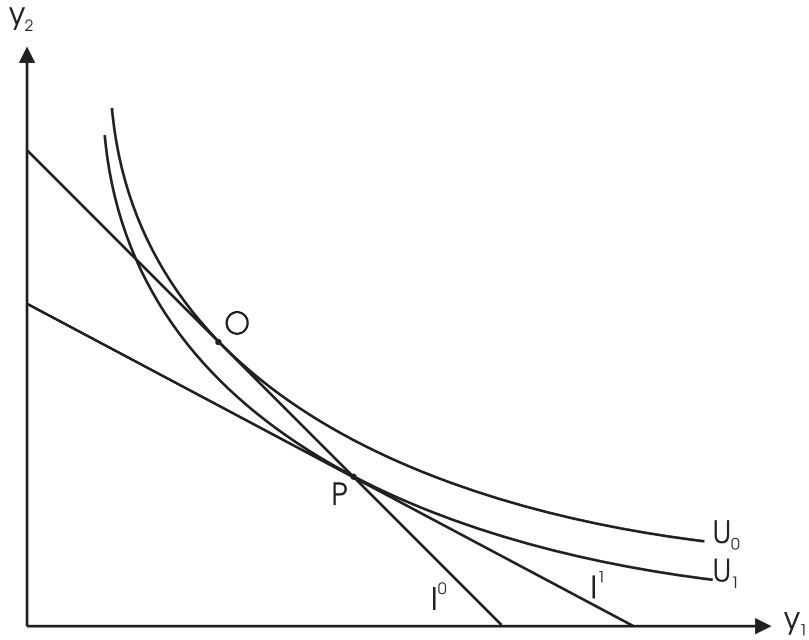
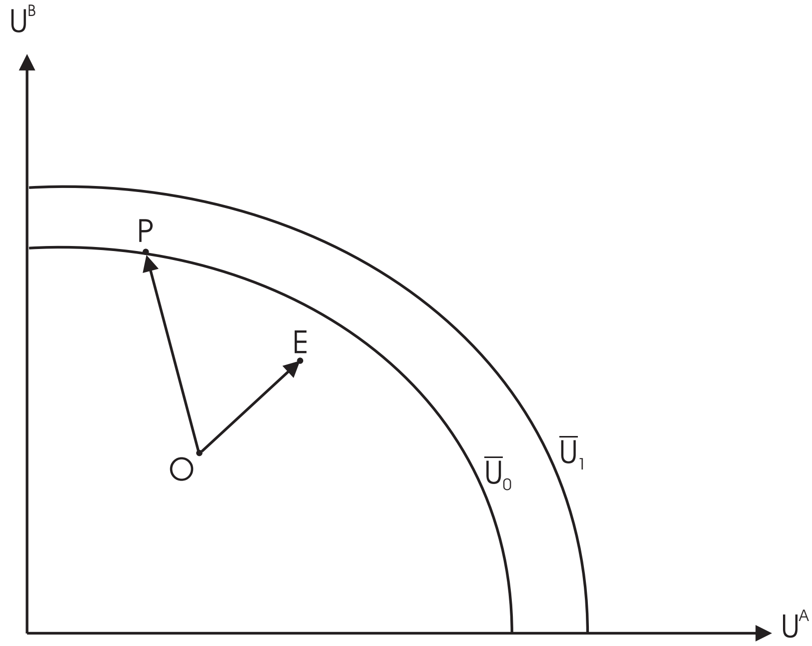


Figure 1.3 Pareto-efficiency vs. Pareto-improvements



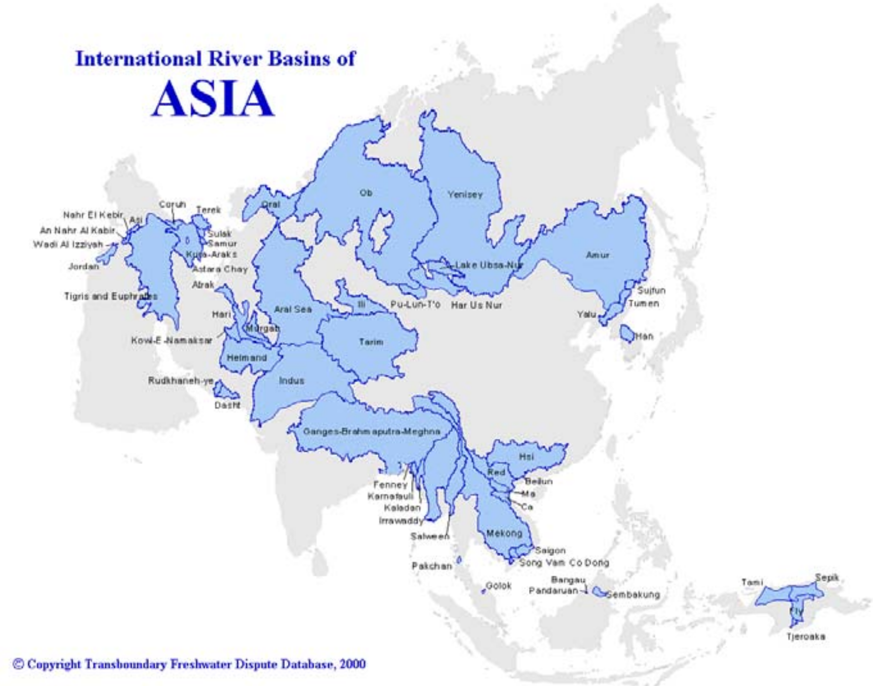
Appendix A. Maps of international river basins

Map A.1 International river basins of Africa

Source: Product of the Transboundary Freshwater Dispute Database (TFDD), Department of Geosciences, Oregon State University. Additional information about the TFDD can be found at: http://www.transboundarywaters.orst.edu (Printed with the permission of the copyright holder.)

Appendix A. Maps of international river basins

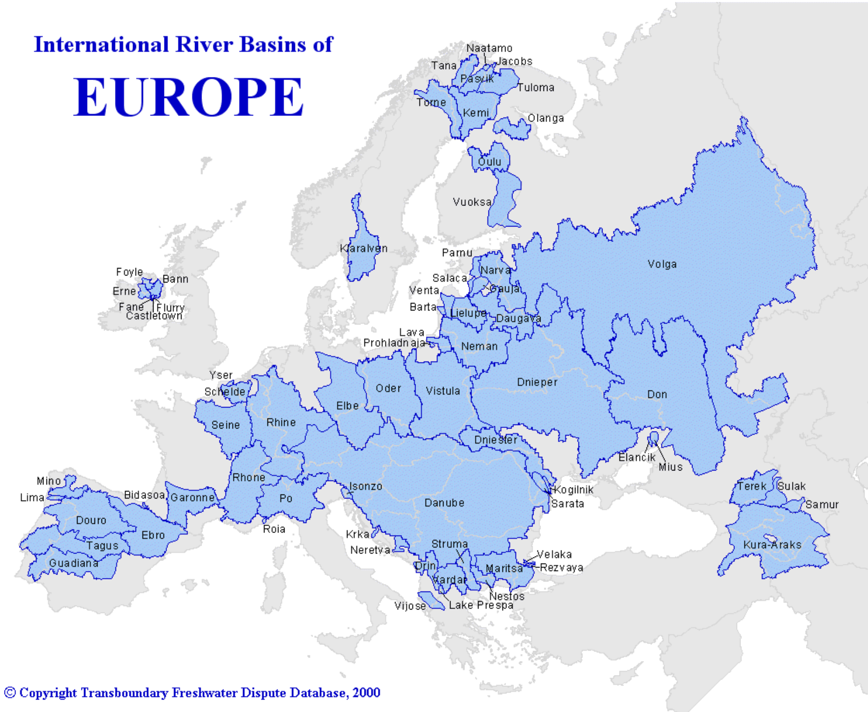
Map A.2 International river basins of Asia



Source: Product of the Transboundary Freshwater Dispute Database (TFDD), Department of Geosciences, Oregon State University. Additional information about the TFDD can be found at: http://www.transboundarywaters.orst.edu (Printed with the permission of the copyright holder.)

Appendix A. Maps of international river basins

Map A.3 International river basins of Europe



Source: Product of the Transboundary Freshwater Dispute Database (TFDD), Department of Geosciences, Oregon State University. Additional information about the TFDD can be found at: http://www.transboundarywaters.orst.edu (Printed with the permission of the copyright holder.)

Appendix A. Maps of international river basins

Map A.4 International river basins of North America

Source: Product of the Transboundary Freshwater Dispute Database (TFDD), Department of Geosciences, Oregon State University. Additional information about the TFDD can be found at: http://www.transboundarywaters.orst.edu (Printed with the permission of the copyright holder.)

Appendix A. Maps of international river basins

Map A.5 International river basins of North America

Source: Product of the Transboundary Freshwater Dispute Database (TFDD), Department of Geosciences, Oregon State University. Additional information about the TFDD can be found at: http://www.transboundarywaters.orst.edu (Printed with the permission of the copyright holder.)

Appendix B. Names of international river basins

Countries	Basins	International basins
17	1	Danube.
11	2	Congo and Niger.
10	1	Nile.
9	2	Rhine and Zambezi.
8	2	Amazon and Lake Chad.
6	8	Aral Sea, Ganges-Brahmaputra-Meghna, Jordan, Kura-Araks, Mekong, Tarim, Tigris and Euphrates, and Volta.
5	3	La Plata, Neman, and Vistula.
4	17	Amur, Daugava, Elbe, Indus, Komoe, Lake Turkana, Limpopo, Lotagipi Swamp, Narva, Oder, Ogooue, Okavango, Orange, Po, Pu-Lun-T'o, Senegal, and Struma.
3	49	Asi, Awash, Cavally, Cestos, Chiloango, Dnieper, Dniester, Drin, Ebro, Essequibo, Gambia, Garonne, Gash, Geba, Har Us Nur, Hari, Helmand, Hondo, Ili, Incomati, Irrawaddy, Juba-Shibeli, Kemi, Lake Prespa, Lake Titicaca-Poopo System, Lempa, Maputo, Maritsa, Maroni, Moa, Neretva, Ntem, Ob, Oueme, Pasvik, Red, Rhone, Ruvuma, Salween, Schelde, Seine, St. John, Sulak, Torne, Tumen, Umbeluzi, Vardar, Volga, and Zapaleri.
2	176	Akpa, Alesek, Amacuro, An Nahr Al Kabirm, Artibonite, Astara Chay, Atrak, Atui, Aviles, Aysen, Baker, Bangau, Bann, Baraka, Barima, Barta, Beilun, Belize, Benito, Bia, Bidasoa, Buzi, Ca, Cancoso Candelaria, Castletown, Catatumbo, Changuinola, Chico, Chilkat, Chira, Chiriqui, Choluteca, Chuy, Coatan Achute, Coco, Colorado, Columbia, Comau, Corubal, Coruh, Courantyne, Cross, Cullen, Daoura, Dasht, Don, Douro, Dra, Elancik, Erne, Etosha/Cuvelai, Fane, Fenney, Firth, Flurry, Fly, Foyle, Fraser, Gallegos-Chico, Gauja, Goascoran, Golok, Great Scarcies, Grijalva, Guadiana, Guir, Han, His, Isonzo, Jacobs, Jurado, Kaladan, Karnafauli, Klaralven, Kogilnik, Kowl-E-Namaksar, Krka, Kunene, Lagoon Mirim, Lake Fagnano, Lake Natron, Lake Ubsa-Nur, Lava, Lielupe, Lima, Little Scarcies, Loffa, Ma, Mana-Morro, Massacre, Mataje, Mbe, Medjerda, Mino, Mira, Mississippi, Mius, Mono, Motaqua, Murgab, Naatamo, Nahr El Kebir, Negro, Nelson-Saskatchewan, Nestos, Nyanga, Olanga, Oral, Orinoco, Oued Bon Naima, Oulu, Oyupock, Pakchan, Palena, Pandaruan, Parnu, Pascua, Patia, Paz, Pedernales, Prohladnaja, Puelo, Rezvaya, Rio Grande (N. America), Rio Grande (S. America), Roia, Rudkhaneh-ye, Sabi, Saigon, Salaca, Samur, San Juan, San Martin, Sarata, Sarstun, Sassandra, Sembakung, Seno Union, Sepik, Sixaola, Song Vam Co Dong, St. Croix, St. John, St. Lawrence, St. Paul, Stikine, Suchiate, Sujfun, Tafna, Tagus, Taku, Tami, Tana, Tano, Terek, Tijuana, Tjeroeka/Wanggoe, Tuloma, Tumbes-Poyango, Umba, Utamboni, Valdivia, Velaka, Venta, Vijose, Vuoksa, Wadi Al Izziyah, Whiting, Yalu, Yaqui, Yelcho, Yenisey, Yser, Yukon, and Zarumilla.

Chapter 2:
Sharing Transboundary Rivers Fairly and Efficiently[1]

1. Introduction

Transboundary rivers can elicit either cooperation or conflict depending on the perceptions of their relative benefits (Sadoff and Grey, 2002). Encouragingly, the study by Wolf *et al.* (2003) cited in the introductory chapter suggests that cooperation is relatively more common than conflict. Nevertheless, water has indeed been a cause of political tensions between the Arabs and Israelis; Indians and Bangladeshis; Americans and Mexicans; and several of the ten riparian states of the Nile River. At the heart of many regional water disputes is the lack of internationally accepted criteria for sharing water resources between riparians (Wolf, 1999). The identification of suitable equity criteria is essentially a political question, but economists can inform decision making by highlighting the efficiency implications of the various criteria under consideration. Indeed, if economic analysis is to make an important contribution to policy formulation in transboundary water cooperation it must give due attention to distributive issues in addition to its traditional focus on efficiency (Just *et al.*, 1998). The purpose of this chapter is therefore to provide an analytical framework within which the equity-efficiency relationship on transboundary rivers can be explored.

Several authors emphasise the intrinsic and instrumental importance of 'reasonable and equitable use' of transboundary rivers (Barrett (1994), Sadoff *et al.* (2002), Wolf (1996, 1999), Wolf and Dinar (1994)). These papers

[1] A version of this chapter also exists as a working paper (Moller, 2004).

take a discursive approach to equity by presenting and contrasting the vague, numerous and sometimes contradictory principles of international law. The principle of *absolute territorial sovereignty*, for instance, gives a country the right to manage the waters within its territory, but is potentially in conflict with the principle of *unlimited territorial integrity* which gives a country the right of uninterrupted water flow upstream of its territory. The most comprehensive analysis is undertaken by Wolf (1999) who compares international practice with legal principles in 149 existing treaties on international freshwater resources. Wolf observes a general shift in negotiations over time away from rights-based towards needs-based criteria (e.g. for agricultural irrigation).

There are relatively few contributions in the economics literature on efficient water sharing agreements among countries sharing a transboundary river. Efficiency is typically approached either via *market solutions* (Kilgour and Dinar (1995, 2001), Dinar and Wolf (1994)), or via cooperation in the form of *joint development projects* (Rogers (1997), Barrett (1994), Ambec and Sprumont (2002)). Acknowledging that annual river flows vary considerably, Kilgour and Dinar identify Pareto-optimal allocations for every possible flow volume, but they do not directly address questions of equity. Dinar and Wolf (1994) find that a welfare-enhancing market scheme for the Middle East is theoretically feasible under certain conditions, but acknowledge that political obstacles are likely to occur.

The joint development approach lends itself directly to equity analysis because a cooperative agreement between the riparians must be reached on which projects to pursue and how to distribute the benefits and costs. Some authors take the view that the objectives of equity and efficiency are inseparable and potentially at odds with each other. The best example is Rogers (1997) who demonstrates how the simultaneous pursuance of both objectives can lead to situations where one riparian might prefer a Pareto-inferior project solution to one which is Pareto optimal, even though this would give it (and other riparians) a lower net benefit. The potential problem with some Pareto-optimal allocations, according to Rogers, is that they might induce envy between the parties, for instance regarding the geographical location of infrastructure investments. The implication of this is a second-best solution where efficient development of the river basin is planned under the restriction of non-envy. A related point is found in Sadoff *et al.* (2002) who criticise the conventional economic argument that, first, aggregate benefits to society should be maximised, and thereafter issues of distribution can be addressed. Redistribution of economic gains, especially over international borders, is extremely complex in reality and the authors argue that there are few successful precedents anywhere in the world. The absence of side payments implies a recommendation of second-best policies which do not necessarily maximise social welfare, but lead to equitable agreements, acceptable to all parties.

Finally, a few authors apply cooperative game theory to identify fair and efficient water allocations in river sharing problems. Barrett (1994) analyses how two different rights-based doctrines (territorial sovereignty vs. territorial integrity) affect the set of core allocations in situations with three riparians. The Shapley value is also invoked, although primarily as a means to select a unique, stable and efficient allocation rather than as a means to achieve equity. Ambec and Sprumont (2002) analyse a model of n identical riparians who have quasi-linear preferences over water and money (thus allowing for side payments). They identify exactly one welfare distribution in the core, and this fair and efficient outcome represents a compromise between the two conflicting doctrines analysed by Barrett.

In sum, the literature on transboundary rivers presents several different views on how the objectives of equity and efficiency interrelate. The market approach interprets water as a private good with clearly defined property rights. Guided by the second welfare theorem and the Coase theorem, this approach implies *separability* and the corresponding policy implication of 'efficiency first - equity afterwards'. In comparison, the joint development approach interprets water as an open access resource with undefined property rights which, in addition to possible restrictions on side payments, implies *inseparability.* Trade-offs may occur if equity is defined as 'non-envy' or 'agreement acceptability', but objective compatibility is also a possibility if an appropriate measure of equity can be identified within the core.

The common approach in the economics literature is to initiate the analysis by identifying efficient allocations and address distributional issues subsequently, if at all. This chapter turns issues around by examining the efficiency implications of an 'equity-first' policy. Equity, of course, is a contestable term. We define it as 'equal sharing of waters' - a notion consistent with several theories of justice, such as *egalitarianism* and *equality of opportunity.* Property rights are undefined in the model, *a priori*, but riparians can enter an equal quota cooperative agreement with side payments and restricted water trade. We find that an 'equity-first' policy does not necessarily imply an efficiency trade-off and that it may, under certain conditions, introduce efficiency gains. The remainder of the chapter is organised as follows: Section 2 introduces the model. Section 3 presents the main results. Section 4 discusses agreement stability. Section 5 draws policy implications. Section 6 concludes.

2. The model

An upstream and a downstream riparian share a transboundary river with a (perfectly forecasted) average annual flow of $\overline{Q} > 0$ units of water originating entirely within the former. Sharing takes place when the upstream riparian (u) does not use the entire volume, instead passing some of it on to the downstream neighbour (d). Any unused water can be costlessly discharged into the sea. Each riparian withdraws irrigation water $q_i \geq 0$ ($i = u, d$) to produce an agricultural output $y_i \geq 0$ which may be thought of as rice or cotton. The agricultural output is sold at competitive world markets that both riparians are too small to influence, thus $p_i^w(y_u, y_d) = p^w = 1$. Riparians are described in terms of an agricultural production function exhibiting diminishing returns to scale $y_i = y(q_i)$ where $y(0) = 0$, $\frac{dy(q)}{dq} > 0$ and $\frac{d^2y(q)}{dq^2} < 0$.[2] Each riparian incurs a constant unit cost c_i of using water, thus $C_i(q_i) = c_i q_i$, which can be thought of as the fuel cost associated with pumping irrigation water to the fields. Differences in unit costs are introduced as a means to model differences in the economic value of alternative uses of water.

[2]In the market approach, riparians are represented by water demand functions (see Kilgour and Dinar, 1995).

2.1 Non-cooperative equilibrium

Riparian i chooses an optimal level of water input q_i^* to maximise profit π_i subject to a water availability constraint $\overline{q}_i$, where $\overline{q}_u = \overline{Q}$ and $\overline{q}_d = \overline{Q} - q_u^*$. The upstream riparian chooses q_u^* first thereby affecting the constraint of the downstream riparian.[3] The optimisation problem of riparian i is:

$$\max_{q_i} \{\pi_i = y(q_i) - c_i q_i \mid q_i \leq \overline{q}_i\} \tag{1}$$

which yields the necessary and sufficient Kuhn-Tucker first-order conditions:

$$\frac{dy(q_i^*)}{dq_i} - c_i \geq 0,\ q_i^* \leq \overline{q}_i,\ \left(\frac{dy(q_i^*)}{dq_i} - c_i\right)(\overline{q}_i - q_i^*) = 0 \tag{2}$$

At an interior solution for optimal water input we get $q_i^* = \left(\frac{dy(q_i)}{dq_i}\right)^{-1} \equiv g(c_i)$ where $g\left(c\right) > 0$ and $\frac{dg(c)}{dc} < 0$. Since we are particularly interested in relative unit costs, we normalise the cost differential by assuming $c_u = 1$ and $c_d = c > 0$. Thus, for $c > 1$ the upstream riparian has the relative cost advantage, while the opposite is the case for $c < 1$. Table 2.1 presents the noncooperative equilibria for the three possible cases N_H, N_M and N_L where N stands for Noncooperation and the subscript refers to the water level (High, Medium or Low). In N_H water is abundant and the riparians coexist peacefully without any need for cooperation. To some extent, this reflects the historical situation in many river basins decades ago. In N_M and N_L water is scarce relative to demand and this introduces a conflict of interest with which most riparians are familiar today. In the model, the upstream riparian imposes a negative unidirectional externality upon

[3] The first-mover advantage is determined entirely on the basis of geography here, but could equally well be a consequence of political power. An alternative specification of a relatively powerful downstream riparian with a credible punishment strategy would yield the same qualitative results.

the downstream riparian by preventing the latter from attaining an unconstrained profit maximising water input level. In N_M the upstream riparian has sufficient water to attain a profit maxium, while the downstream riparian experiences water scarcity. In N_L water is so scarce that the upstream riparian leaves a volume insufficient for the downstream riparian to engage in any commercially viable agricultural production with irrigation water as an input. The three noncooperative cases can be defined more precisely as sets in $(c, \overline{Q})$-space: $N_H = \left\{g(1) + g(c) \leq \overline{Q}\right\}$, $N_M = \left\{g(1) < \overline{Q} < g(1) + g(c)\right\}$ and $N_L = \left\{0 < \overline{Q} \leq g(1)\right\}$.

Table 2.1 Noncooperative equilibria

	N_H	N_M	N_L
q_u^*	$g(1)$	$g(1)$	$\overline{Q}$
q_d^*	$g(c)$	$\overline{Q} - g(1)$	0
π_u^*	$y(g(1)) - g(1)$	$y(g(1)) - g(1)$	$y\left(\overline{Q}\right) - \overline{Q}$
π_d^*	$y(g(c)) - cg(c)$	$y\left(\overline{Q} - g(1)\right) - c\left(\overline{Q} - g(1)\right)$	0

2.2 Basinwide social efficiency

A feasible water allocation is *socially efficient* if it maximises basinwide profit. The socially efficient allocation is thus the solution to the social planner's problem:

$$\max_{q_u, q_d}\{\Pi = \pi_u + \pi_d = y(q_u) - q_u + y(q_d) - cq_d \mid q_u + q_d \leq \overline{Q}\} \tag{3}$$

The necessary and sufficient Kuhn-Tucker first-order conditions yield:

$$\frac{dy(q_u)}{dq_u} - 1 \geq 0,\ \frac{dy(q_d)}{dq_d} - c \geq 0, \frac{dy(q_u)}{dq_u} - 1 = \frac{dy(q_d)}{dq_d} - c \tag{4}$$

$$\left(\frac{dy(q_u)}{dq_u} - 1\right)\left(\frac{dy(q_d)}{dq_d} - c\right)\left(\overline{Q} - q_u - q_d\right) = 0,\ \overline{Q} - q_u - q_d \geq 0 \tag{5}$$

Thus in an efficient allocation the marginal profits of both riparians must be equalised. If this is not the case then a water redistribution from the riparian with lowest marginal profit to that with highest marginal profit will increase regional profit. We have the following result:

Proposition 1 *Suppose that riparians are identical* ($c = 1$)*. The equal quota allocation* ($q_u = q_d = \frac{\overline{Q}}{2}$) *is at least as efficient as the noncooperative equilibrium.*

Proof. First, the equal quota allocation is always efficient because conditions (4)-(5) are satisfied. Secondly, consider the efficiency properties of the noncooperative equilibrium. If water is abundant then $\overline{Q} - q_u - q_d > 0$ and $\frac{d\pi_u(q_u)}{dq_u} = \frac{d\pi_d(q_d)}{dq_d} = 0$ thus satisfying the efficiency conditions (4)-(5). However, if water is scarce then $\overline{Q} - q_u - q_d = 0$. Since upstream chooses first then $q_u > q_d \Rightarrow \frac{d\pi_u(q_u)}{dq_u} < \frac{d\pi_d(q_d)}{dq_d}$ because of concavity and noncooperation is socially inefficient. ■

2.3 Equity and equal quota

The noncooperative equilibrium emerges as an undesirable solution to the water conflict if water is scarce (N_M and N_L) for two reasons. First, it is socially inefficient, i.e. it does not maximise basinwide profit, as demonstrated for identical riparians in Proposition 1 and generalised later in the chapter. Secondly, recall the tendency observed by Wolf (1999) that international water negotiations are increasingly focusing on needs-based allocations. Apart from differences in location and cost structure, our model assumes that both riparians are identical, i.e. they have the same GDP per capita, population size, geographical area etc. They therefore also have the same absolute and relative need for water for agricultural irrigation. This begs the question why one riparian should be entitled to a larger share of the water than the other. In light of the undesirable properties of the noncooperative solution we aim to identify an alternative distribution rule which can enhance basinwide economic efficiency and satisfy reasonable notions of equity.

As demonstrated later in the chapter, the *equal quota distribution rule* emerges, on efficiency grounds, as a superior alternative to noncooperation. We define equal quota as an equal share of the available flow to each of the two riparians. Is the equal quota allocation *equitable*? We shall not attempt a definitive answer to this difficult philosophical question here. Rather, we are interested in making explicit the value judgements that are embodied in an affirmative answer.

Approaching equity

In deciding how to share water equitably between riparians one must specify a distribution rule. There are at least four different (but not mutually exclusive) conceptual approaches to identifying such a rule. First, by using a 'reference base', such as population size, proportion of land area within the river basin or relative contribution to the water course. This is a pragmatic approach commonly used in political debates when riparians argue over water sharing. Secondly, through the use of 'differentiation rules' which focus on principles which are likely to be acceptable or coalition forming in international agreements. Examples include, but are not limited to, principles derived from cooperative game theory such as 'individual rationality' and 'the core'. Thirdly, distribution rules can be derived on the basis of stand-alone equity criteria which can be traced back to either moral philosophy, economic or political theory. These principles, which are based on a normative approach to distribution issues, have been widely applied in other circumstances, for instance in domestic tax systems (e.g. vertical equity) or in international affairs (e.g. sovereignty). The fourth approach is to use a distribution rule which can be derived from a *theory of distributive justice.* Theories of distributive justice specifically address the question of how a society or group should allocate its scarce resources or product among individuals with competing needs or claims (see Roemer (1996) or Shaw (1999) for an introduction). This type of philosophical inquiry goes back at least two millennia to great thinkers such as Aristotle, Plato and the Talmud.[4]

Theories of Distributive Justice[5]

Alternative theories of distributive justice can be distinguished by whether they subscribe to the *egalitarian* principle of *equal treatment of equals.* Since equal water sharing is quintessentially an egalitarian distribution rule[6], this immediately rules out two prominent theories of justice, namely utilitarianism and Nozick's Entitlement Theory. Utilitarianism, originally proposed by Bentham (1789), aims at maximising the sum of utilities across all indi-

[4]The difference between the third and the fourth approach is often discussed in the literature as: 'micro' vs. 'macro' justice. Micro justice aims at identifying the most appropriate distributive rule given the practical problem in question (see Young (1994)). In contrast, macro justice aims at identifying a single principle of justice which should be used in all different aspects of society (see Roemer, 1996).

[5]The summary discussion in this sub-section draws upon Roemer (1996) and World Bank (2005).

[6]There is some empirical support for choosing an egalitarian standard in water disputes. A household survey undertaken in the urban areas of Western Australia where groundwater allocation was an ongoing salient issue found relatively strong support for this principle (Syme *et al.*, 1999). The universality of this finding to other types of water disputes and locations remains to be tested.

viduals, but is not concerned with its distribution.[7] Nozick's (1974) theory is distinctively anti-egalitarian. He argued that justice should concern itself not with the patterns of outcome, but with the procedures by which agents interact economically. According to the Entitlement Theory, a person is entitled to his/her possessions if these have been obtained without infringing the rights of others. The policy implication is that any redistribution is unwarranted and unjust (Heywood, 1994).

Since the early 1970s, a number of influential thinkers, including John Rawls, Amartya Sen, Ronald Dworkin and John Roemer, have made separate and important contributions to a range of egalitarian theories of distributive justice. Although distinct, these theories have several elements in common: First, they reject the use of final welfare (or utility) as the equalisandum or equity metric to judge the fairness of a given allocation or system. Secondly, they acknowledge the importance of individual responsibility in moving from resources to final outcomes, including welfare. Thirdly, all prefer to see some combination of the set of liberties and resources available to individuals as the right space to form a social judgment. Finally, they appeal, at some stage, to the 'veil of ignorance' argument (Harsanyi, 1955), that a fair allocation of resources should be one that all 'prospective members of society' would agree on, before they knew which position they would occupy (also known as 'the original position').

One important source of disagreement in these theories of distributive

[7] Utilitarianism may nevertheless have egalitarian implications under certain restrictive assumptions: (1) the existence of a utility function; (2) cardinality; (3) inter-personal comparability; (4) decreasing marginal utility of income, and; (5) all individuals have identical utility functions.

justice is the choice of equalisandum. In his seminal work, *A Theory of Justice*, Rawls (1971) argues that social justice requires that two basic principles of justice should hold. The first demands the most extensive liberty for each, consistent with similar liberty for others. The second requires that opportunities - which he related to the concept of 'primary goods' - should be open to all members of society. Under 'the Difference Principle', he proposes that the chosen allocation should be one that maximizes the opportunities of the least privileged group.

Amartya Sen (1985) suggested in his *Theory of Well-Being* that different people might have different 'conversion factors' from resources to actions and welfare. He argued that all goods, including Rawls' 'primary goods' are inputs to a person's 'functionings' - the set of actions a person performs and of states the person values or enjoys. For Sen, the concept to be equalized across people is the set of possible functionings from which a person might be able to choose. This he called the 'capability set' - or 'midfare' as Cohen (1993) termed it, i.e. something which is midway between goods and welfare.

In 1981, Ronald Dworkin published a pair of articles in which he discussed the most appropriate equalisandum for an egalitarian theory of justice (Dworkin, 1981ab). He argued that the right alternative to equalizing welfare is to equalize the bundles of resources available to persons. To him, justice required that individuals should be compensated for aspects of their circumstances over which they had no control, or for which they could not be held responsible. He argued for a distribution of resources that compensates people for innate differences that they could not have helped, including differences in talent.

Finally, according to Roemer (1998), equity demands an 'equal opportunities policy' (which he discusses in the context of access to education and jobs). He acknowledges that individuals bear some responsibility for their own welfare, but also that circumstances over which they have no control affect both how much they invest and the level of welfare they eventually attain. He argued that public action should therefore aim to equalize 'advantages' among people from groups with different circumstances at every point along the distribution of efforts within the group.

Equal quota as equality of opportunity

The application of the equal quota rule to the sharing of transboundary waters follows largely the same principles as the egalitarian theories of justice discussed briefly above.[8] Water input is used as the equalisandum as opposed to the benefits of water (agricultural profit). Each riparian is responsible for arriving at these benefits, for instance by investing in cost-effective irrigation technologies. Finally, the rule aims at reducing, although not eliminating, the geographical disadvantage of the downstream riparian by offering access to an equal share of the resource - an appealing proposition, arguably, when judged from 'the original position'.

Which of these alternative theories, then, can be most appropriately be invoked in support equal water sharing? Since all invoke a notion of equality

[8] The conceptual problem of applying theories of justice - originally designed to address distributive issues between *individuals* within societies rather than between *societies* - cannot immediately be overcome, unless we assume the existence of a 'representative individual' for each riparian state.

of opportunity the key difference lies in the choice of equalisandum. Equal water sharing would satisfy neither a Rawlsian nor a Senian theory of justice. Rawls' index of primary goods - which includes basic rights, liberties, opportunities, income and wealth - would clearly not be equalised since incomes may differ even if water access is equalised due to assumed differences in cost-effectiveness. Similarly, Sen would be concerned about equalising the functionings that individuals attain, i.e. what the representative individual is capable of doing or being as a consequence of selling the irrigation-fed crop on the world market. Equal water sharing is comparatively more in line with the resource egalitarian view of Dworkin (1981b) and, to some extent, with Roemer's idea of an 'equality of opportunities policy'. On the basis of Dworkin we can argue that the downstream riparian should be compensated because its geographical position on the river is beyond its control. However, we must assume that both riparians are equally talented, otherwise Dworkin would also ask us to equalize those talents. Equality of opportunity, according to Roemer, leads to a policy which aims at equalizing advantages, which in our case translates into a policy aimed at equalizing advantage to access water. Again, other advantages would not be equalized in our case. To sum up the discussion, by interpreting equal water quota as an equitable allocation, we subscribe to the ethical principle of egalitarianism, and, to some extent, to Dworkin and Roemer's notion of equality of opportunity.

In conclusion, it is worth noting that discussions over choice of equalisandum is not merely a matter of philosophical inquiry. In practice, international negotiators have had to decide between sharing the water or sharing the benefits of the water (Wolf, 1999). Although water measurement is not trivial it is generally much more easily measured than benefits. Equal water sharing (9 out of 149 treaties) is also more common in international agreements than equal benefit sharing (2 out of 149 treaties), possibly for this reason. Equal sharing of water, even between very unequal neighbours, is therefore not an uncommon arrangement. To give an example from the Central Asian region, the water in the Chui and Thalas rivers is shared equally between the Kyrgyz Republic and Kazakhstan.

2.4 The equal quota allocation

In the remainder of this chapter we focus our attention on the efficiency properties of equal quota vis-a-vis noncooperation, particularly when unit costs are allowed to differ. It should be emphasised, though, that the model presented here is sufficiently flexible to deal with a wide range of exogenously defined sharing rules. Under equal quota each riparian chooses an optimal level of water input q_i^* to maximise profit π_i subject to the constraint $\overline{q}_i \leq \frac{\overline{Q}}{2}$. The optimisation problem of riparian i is otherwise similar to (1). We note that the equal quota entitlement has neutralised the strategic first-mover advantage of the upstream riparian due to the assignment of property rights.

Since we are not only interested in interior solutions for identical riparians, but also in corner solutions where unit costs can differ between riparians we must examine a number of special cases. Nine possible cases for the equal quota allocation can be identified and we label them as follows: H, M and L stand for High, Medium and Low water flow. In addition, subscript U refers to a situation when the Upstream riparian has the relative cost advantage; D when Downstream has the lowest cost and; I when the riparians have identical unit cost. Cases E_{HU}, E_{HD} and E_{HI} therefore refer to Equal quota allocations where there is sufficient water for both riparians to maximise profits unconstrained thus the allocations are identical to N_H. Cases E_{MU} and E_{MD}, where one of the two riparians is constrained, differ from each other because of cost differences. The riparian with the cost advantage will choose higher scales of production and will thus be the first to become constrained under an equal quota allocation. Finally, both riparians are constrained in E_{LU}, E_{LD}, E_{LI} and E_{MI} (identical riparians become constrained simultaneously). Table 2.2 gives an overview of the equal quota allocation and Table 2.3 summarises the nine definitions.

Table 2.2 The equal quota allocation

	E_{HU}, E_{HD}, E_{HI}	E_{MU}	E_{MD}	$E_{LU}, E_{LD}, E_{LI}, E_{MI}$
q_u^*	$g(1)$	$\frac{\overline{Q}}{2}$	$g(1)$	$\frac{\overline{Q}}{2}$
q_d^*	$g(c)$	$g(c)$	$\frac{\overline{Q}}{2}$	$\frac{\overline{Q}}{2}$
π_u^*	$y(g(1)) - g(1)$	$y\left(\frac{\overline{Q}}{2}\right) - \frac{\overline{Q}}{2}$	$y(g(1)) - g(1)$	$y\left(\frac{\overline{Q}}{2}\right) - \frac{\overline{Q}}{2}$
π_d^*	$y(g(c)) - cg(c)$	$y(g(c)) - cg(c)$	$y\left(\frac{\overline{Q}}{2}\right) - c\frac{\overline{Q}}{2}$	$y\left(\frac{\overline{Q}}{2}\right) - c\frac{\overline{Q}}{2}$

Table 2.3 Equal quota definitions

$E_{HU} = \left\{c > 1 \mid 2g(1) \leq \overline{Q}\right\}$	$E_{MU} = \left\{c > 1 \mid 2g(c) < \overline{Q} < 2g(1)\right\}$
$E_{LU} = \left\{c > 1 \mid 0 < \overline{Q} \leq 2g(c)\right\}$	$E_{HD} = \left\{c < 1 \mid 2g(c) \leq \overline{Q}\right\}$
$E_{MD} = \left\{c < 1 \mid 2g(1) < \overline{Q} < 2g(c)\right\}$	$E_{LD} = \left\{c < 1 \mid 0 < \overline{Q} \leq 2g(1)\right\}$
$E_{HI} = \left\{c = 1 \mid 2g(1) < \overline{Q}\right\}$	$E_{MI} = \left\{c = 1 \mid \overline{Q} = 2g(1)\right\}$
$E_{LI} = \left\{c = 1 \mid 0 < \overline{Q} < 2g(1)\right\}$	

2.5 Restricted water trading

With property rights well-defined under the cooperative equal quota agreement we must also specify the conditions under which riparians are allowed to trade water. At one extreme, one could allow for full-scale trading as in the market approach literature. At the other extreme, trading could be assumed infeasible. The stylised facts suggest that both extremes are unrealistic. No two countries are currently involved in anything resembling full-scale water trading across international borders. One explanation is that riparians may lack the necessary information to estimate the marginal value of water in alternative uses. Another reason is that existing water users (e.g. farmer's groups) are likely to oppose sale of water, especially if they do not expect to be adequately compensated. There are, nevertheless, empirical examples of inter-country water trade of relatively small quantities, also known as *water loans*. The 1959 Nile River Waters Treaty, for instance, allocated 55.5 billion cubic meter (BCM) per year for Egypt and 18.5 BCM per year for Sudan. Since Sudan could not absorb that much water at the time, the Treaty provided for a Sudanese water loan to Egypt of up to 1.5 BCM per year through 1977 (Wolf, 1996). Allowing for this possibility in the model we shall henceforth assume that if one riparian has unutilised water which is in demand by the other riparian then the former will sell these units to the latter. Arguably, the practical obstacles to this type of trading are limited. The economic value-in-use of unutilised water to the seller is zero while the buyer has some information about its alternative value from the noncooperative situation. It is reasonable to expect that a transaction would occur between the two parties due to the mutual benefits of trade. Political objections are also less likely to occur since there are no existing water users in the territory of the selling riparian. Finally, such trade only requires a minor adjustment of the existing equal quota arrangement. In contrast, trading in water which is already in use is not allowed in the model because of the combination of informational constraints and political objections. In sum, our water market institution amounts to a tradeable quota scheme with upper bounds on transferable quantities. We define it formally as follows:

Definition 1 *Let* $\frac{\overline{Q}}{2}$ *be the water entitlement of riparians* j *and* k, $(j \neq k)$. *If* $\widehat{q}_j$ *denotes the unconstrained optimal water use of riparian* j *then* $\delta = \max\{\widehat{q}_j - \frac{\overline{Q}}{2}, 0\}$ *expresses riparian* j*'s water deficit. The water surplus of riparian* k *is given by* $\sigma = \max\{\frac{\overline{Q}}{2} - q_k^*, 0\}$. *A restricted water trade is a transfer of* $\Delta = \min\{\delta, \sigma\}$ *units of water from riparian* k *to riparian* j *in exchange for a transfer payment* $p \geq 0$.

The size of the transfer payment depends critically upon geography. In the case of an upstream seller we may expect that $p = 0$. If upstream has no alternative but to release the water to the downstream riparian why should the latter pay for it? In the case of a downstream seller we assume that upstream can withdraw an additional Δ units from the perfectly forecasted flow volume, $\overline{Q}$, before releasing it downstream. Here we would expect $p > 0$ because downstream could legitimately claim its entitlement and release it in the ocean. Irrespective of our expectations, the transfer payment would be the result of a negotiated agreement between the two riparians. More importantly, this outcome does not affect the central results of this analysis.

To take restricted water trading into account we must modify some of the results presented in Table 3.2. We note that trading only occurs in scenarios E_{MU} and E_{MD} where one of the two riparians is constrained while the other does not use its full quota. Before presenting the post-trade allocation, however, we must complete the taxonomy. Consider all the possible combinations of noncooperative and equal quota cases by recalling the definition of the respective sets. The combination of two cases (sets) yield a number of scenarios (joint sets), such as $E_{MD} \cap N_H = \{0 < c < 1, g(1) + g(c) < \overline{Q} \leq 2g(c)\}$ which reads as follows: The exogenously determined values of c and $\overline{Q}$ are such that the two riparians would be in case N_H in a noncooperative situation but in case E_{MD} under equal quota. One can identify fourteen joint sets: ($E_{HD} \cap N_H$, $E_{MD} \cap N_H$, $E_{MD} \cap N_M$, $E_{LD} \cap N_M$, $E_{LD} \cap N_L$) when the downstream riparian is most cost-effective, ($E_{HI} \cap N_H$, $E_{MI} \cap N_M$ and $E_{LI} \cap N_L$) for identical riparians and ($E_{HU} \cap N_H$, $E_{MU} \cap N_H$, $E_{LU} \cap N_M$, $E_{MU} \cap N_M$, $E_{LU} \cap N_L$, $E_{MU} \cap N_L$) when the upstream riparian is most cost-effective (see Appendix C for a definition).

Restricted trading takes place in five of the fourteen scenarios. To illustrate, consider $E_{MD} \cap N_H$ again. At the unconstrained optima $q_u = g(1) < \frac{\overline{Q}}{2}$ and $q_d = g(c) > \frac{\overline{Q}}{2}$. Downstream therefore has a water deficit of $\delta = g(c) - \frac{\overline{Q}}{2}$ while upstream has a surplus of $\sigma = \frac{\overline{Q}}{2} - g(1)$. From the definition of $E_{MD} \cap N_H$ we have $g(1) + g(c) \leq \overline{Q} \Rightarrow g(c) - \frac{\overline{Q}}{2} \leq \frac{\overline{Q}}{2} - g(1)$ implying that there is excess water on the market (unless the expression holds with equality). $\Delta = \delta = g(c) - \frac{\overline{Q}}{2}$ units of water are transacted from upstream to downstream at the negotiated transfer payment p. The post-trade water allocations are $q_u = g(1)$ and $q_d = \frac{\overline{Q}}{2} + \Delta = g(c)$. The remaining four scenarios are calculated in a similar manner. Table 2.4 gives an overview of the results where we have omitted the transfer payments in the profit expressions since these do not affect regional profit.

Table 2.4 The equal quota allocation after trade of unused water units.

	$E_{MD} \cap N_H$		$E_{MU} \cap N_M$
	$E_{MU} \cap N_H$	$E_{MD} \cap N_M$	$E_{MU} \cap N_L$
q_u^*	$g(1)$	$g(1)$	$\overline{Q} - g(c)$
q_d^*	$g(c)$	$\overline{Q} - g(1)$	$g(c)$
π_u^*	$y(g(1)) - g(1)$	$y(g(1)) - g(1)$	$y\left(\overline{Q} - g(c)\right) - \overline{Q} + g(c)$
π_d^*	$y(g(c)) - cg(c)$	$y\left(\overline{Q} - g(1)\right) - c\left(\overline{Q} - g(1)\right)$	$y(g(c)) - cg(c)$

Finally, we note that restricted trade does not occur on the remaning nine joint sets: ($E_{HD} \cap N_H$ $E_{LD} \cap N_M$, $E_{LD} \cap N_L$,$E_{HI} \cap N_H$, $E_{MI} \cap N_M$, $E_{HU} \cap N_H$, , $E_{LU} \cap N_M$, , $E_{LU} \cap N_L$,) The equal quota allocation for these joint sets is presented in table 2.2.

3. Main Results

Proposition 1 established that the equal quota allocation is at least as efficient as noncooperation when riparians are identical. Indeed, in situations of water scarcity the introduction of an equal quota will generate an efficiency gain (i.e. a cooperative surplus). To what extent does this result hold when relative cost differences are introduced? If the downstream riparian has the relative cost advantage then the result is qualitatively similar, although the cooperative surplus exceeds that attained for identical riparians. When the upstream riparian has the lowest unit cost the results are less straightforward and will ultimately depend on the functional form of the production function. We demonstrate and explain these results below.

3.1 Downstream has a cost advantage

Proposition 2 *Suppose the downstream riparian has the relative cost advantage ($c < 1$). The equal quota allocation is at least as efficient as the noncooperative allocation.*

Proof. Let Π^E and Π^Ndenote the regional profit in the equal quota allocation (net of trade) and under noncooperation, respectively. We must show that $\Pi^E \geq \Pi^N$ $\forall(c, \overline{Q})$ on the relevant domain for each of the five joint sets identified in section 2.4. Since the noncooperative equilibria and equal quota allocations differ on each of these sets (see tables 2.1, 2.2 and 2.4) we have to check five different (weak) inequalities:

On $E_{HD} \cap N_H, E_{MD} \cap N_H, E_{MD} \cap N_M$ we get $\Pi^E = \Pi^N$ because the equal quota (net of trade) and noncooperative allocations are identical in each of these three cases.

On $E_{LD} \cap N_M$ we get $\Pi^E > \Pi^N$ since the full profit expression yields:
$y\left(\frac{\overline{Q}}{2}\right) - \frac{\overline{Q}}{2} + y\left(\frac{\overline{Q}}{2}\right) - c\frac{\overline{Q}}{2} > y\left(g(1)\right) - g(1) + y\left(\overline{Q} - g(1)\right) - c\overline{Q} + cg(1) \Leftrightarrow$
$2y\left(\frac{\overline{Q}}{2}\right) - (1-c)\frac{\overline{Q}}{2} > y\left(g(1)\right) + y\left(\overline{Q} - g(1)\right) - (1-c)g(1).$
which is true since $2y\left(\frac{\overline{Q}}{2}\right) > y\left(g(1)\right) + y\left(\overline{Q} - g(1)\right)$ because of concavity and because $E_{LD} \cap N_M = \{g(1) < \overline{Q} \leq 2g(1)\}$ so we have $\frac{\overline{Q}}{2} \leq g(1) \Rightarrow$ $(1-c)\frac{\overline{Q}}{2} \leq (1-c)g(1)$.

On $E_{LD} \cap N_L$ we get $\Pi^E > \Pi^N$ since the full profit expression yields:
$y\left(\frac{\overline{Q}}{2}\right) - \frac{\overline{Q}}{2} + y\left(\frac{\overline{Q}}{2}\right) - c\frac{\overline{Q}}{2} > y\left(\overline{Q}\right) - \overline{Q} \Leftrightarrow 2y\left(\frac{\overline{Q}}{2}\right) + (1-c)\left(\frac{\overline{Q}}{2}\right) > y\left(\overline{Q}\right)$
which is true since $2y\left(\frac{\overline{Q}}{2}\right) > y\left(\overline{Q}\right)$ (concavity) and $(1-c)\left(\frac{\overline{Q}}{2}\right) > 0$. ■

The intuition behind Proposition 2 is straightforward. Equal quota implies a redistribution of water from the upstream to the downstream riparian. When the downstream riparian has the relative cost advantage then its productivity (marginal profit) is at least as high as that of the downstream riparian. This is the case in the noncooperative allocation as well as in the equal quota allocation. It follows that basinwide profit cannot fall when riparians move from noncooperation to equal quota.

A more careful analysis of each of the five possible scenarios reads as follows: If water is sufficiently abundant then the riparians would be unconstrained by equal quota, i.e. the noncooperative and equal quota basinwide profits are identical ($E_{HD} \cap N_H$). The second scenario is that where there is sufficient water in the noncooperative case, but where the downstream riparian is constrained by the equal quota ($E_{MD} \cap N_H$). Here the downstream riparian buys unused water from its upstream neighbour to attain exactly the same profit level as under noncooperation and basinwide profits again become identical. The third scenario ($E_{MD} \cap N_M$) where the downstream riparian is constrained in the noncooperative as well as the equal quota allocation yields the same qualitative result. Fourthly, if water is so scarce that the downstream riparian is constrained under noncooperation and both riparians are constrained in equal quota ($E_{LD} \cap N_M$) then the two parties generate a cooperative surplus. In the fifth and final case, both riparians are constrained under noncooperation as well as equal quota ($E_{LD} \cap N_L$). The marginal product of the downstream riparian is very high under noncooperation because it is producing zero output. By sharing the water equally in this situation the riparians can attain substantial cooperative benefits.

Corollary 1 *If the downstream riparian has the relative cost advantage and water is sufficiently scarce,* $\overline{Q} \leq 2g(1)$, *then the equal quota allocation is more efficient than noncooperation thus generating a cooperative surplus.*

Proof. Follows from the proof of Proposition 2 given the definition of E_{LD}. ■

3.2 Upstream has a cost advantage

The efficiency implications of introducing equal quota when the upstream riparian has the relative cost advantage are ambiguous. In the noncooperative equilibrium the productivity (marginal profit) of the downstream riparian is at least as high as that of the upstream riparian. In the equal quota allocation, however, the opposite is the case: the productivity of the upstream riparian is at least as high as that of the downstream riparian. Consequently, the cooperative surplus can take positive as well as negative values. To reduce this ambiguity we need to introduce more structure to the model by making additional assumptions about the production function. An exact specification of the functional form of the production function would be sufficient to draw inferences about the efficiency implications of equal quota for any given values of the exogenous variables $(c, \overline{Q})$. More generally, it emerges that the sign of the third derivative of the production function, $\frac{d^3y(q)}{dq^3}$, is an important determinant of the sign of the cooperative surplus.[9] Assumptions about the third derivative are sufficient to fully determine the efficiency implications of introducing equal quota in 13 out of 18 special cases.

Proposition 3 *Suppose the upstream riparian has the relative cost advantage* $(c > 1)$*. The equal quota allocation is at least as efficient as the noncooperative allocation, except for the following four special cases: (1)* $E_{MU} \cap N_M$ *for* $\frac{d^3y(q)}{dq^3} < 0$*; (2)* $E_{LU} \cap N_M$ *for* $\frac{d^3y(q)}{dq^3} < 0$*; (3)* $E_{LU} \cap N_L$ *for* $\frac{d^3y(q)}{dq^3} \gtreqless 0$*, and; (4)*$E_{MU} \cap N_L$ *for* $\frac{d^3y(q)}{dq^3} \gtreqless 0$*. Table 2.5 summarises the results:*

[9] I thank Bouwe Dijkstra for bringing this to my attention.

Table 2.5 Sign of the cooperative surplus for $c > 1$.

	$\frac{d^3y(q)}{dq^3} = 0$	$\frac{d^3y(q)}{dq^3} > 0$	$\frac{d^3y(q)}{dq^3} < 0$
$E_{HU} \cap N_H$	$= 0$	$= 0$	$= 0$
$E_{MU} \cap N_H$	$= 0$	$= 0$	$= 0$
$E_{MU} \cap N_M$	$= 0$	> 0	< 0
$E_{LU} \cap N_M$	> 0	> 0	$\gtreqless 0$
$E_{LU} \cap N_L$	$\gtreqless 0$	$\gtreqless 0$	$\gtreqless 0$
$E_{MU} \cap N_L$	< 0	$\gtreqless 0$	< 0

Proof. See appendix D. ■

The general conclusion that emerges from Table 2.5 is that equal quota is at least as efficient as noncooperation unless water is too scarce and the cost differential too substantial. If $\frac{d^3y(q)}{dq^3} = 0$ then the combination of water scarcity and cost differential is problematic on $E_{MU} \cap N_L$ and parts of $E_{LU} \cap N_L$. For $\frac{d^3y(q)}{dq^3} > 0$ these problems may occur on the same two joint sets, while they are much more pervasive when $\frac{d^3y(q)}{dq^3} < 0$.

To improve the understanding of these results we provide a graphical illustration of the case where $\frac{d^3y(q)}{dq^3} = 0$. If the third derivative is zero then the production function is quadratic and of the form $y = aq_i - bq_i^2$ where a, b are positive parameters. The profit function can be written $\pi_i = (a - c_i)q_i - bq_i^2$ where $a > c_i$. At an interior solution $q_i^* = \frac{a-c_i}{2b}$. Supposing for simplicity that $a - c_u = 1$ for the upstream riparian and $b = \frac{1}{2}$ we get $q_u^* = 1$ and $q_d^* = a - c_d > 0$. If the upstream riparian has the cost advantage then $0 < a - c_d < 1$. Figure 2.1 illustrates the marginal profit curves of the two riparians. The width of the diagram is determined by the availability of water $\overline{Q}$. Water use by the upstream riparian q_u is measured from left to right and that of the downstream riparian q_d in the opposite direction.

In what follows we compare the two allocations (noncooperative and equal quota) as water becomes increasingly scarce.

If water is abundant, $E_{HU} \cap N_H$, the riparians choose the unconstrained optimal water input under noncooperation as well as equal quota where marginal profit equals zero (points A and B in the diagram). In both allocations, upstream and downstream profit are given by $|OPA|$ and $|RSB|$, respectively. On $E_{MU} \cap N_H$ the noncooperative allocation is in A for the upstream riparian and in B for the downstream riparian. Upstream is constrained by equal quota (point D) while downstream has surplus water. Trade in unused water units (moving from D to A) increases upstream profit by $|ACD|$ which implies that regional profit $|OPA| + |RSB|$ is identical in both allocations. At lower levels of $\overline{Q}$ the introduction of equal quota has distributional implications. On $E_{MU} \cap N_M$ the noncooperative allocation is in A. By moving to the post-trade equal quota allocation, in B, upstream loses $|ABD|$ but downstream gains an equivalent amount $|ABE|$. On $E_{LU} \cap N_M$ the noncooperative allocation is in A and the post-trade equal quota allocation in F. Downstream gain $|AEDF|$ is larger than upstream loss $|ACF|$ so equal quota generates a cooperative surplus. On $E_{MU} \cap N_L$, noncooperation is in R and equal quota (net of trade) in B. Equal quota causes a loss of $-|DERB| + |RSB|$ due to the low values of $(a - c, \overline{Q})$. Finally, on $E_{LU} \cap N_L$ the noncooperative allocation is in point R and the equal quota allocation in H. In this scenario equal quota can lead to trade-offs as well as the opposite depending on the values of $(a - c, \overline{Q})$. Upstream loses $|CFRH|$ and downstream gains $|RSDH|$. In Figure 2.1.e the two areas are identical, and higher values of $(a - c)$ would lead to a regional gain, while lower values to a regional loss. More generally, it can be shown that equal quota is at least as efficient as noncooperation if $\overline{Q} \geq 2 - 2(a - c)$.

Figure 2.2 gives an overview of the fourteen different scenarios in $((a - c), \overline{Q})$-space when $\frac{d^3y(q)}{dq^3} = 0$ (where for simplicity the three scenarios for identical riparians are omitted). The figure is drawn using the definitions of the joint sets presented in Apppendix C. The trade-off between equity and efficiency is limited to the dark shaded area close to the origin where water is very scarce and the cost differential too substantial. Figure 2.3 illustrates the magnitude of the cooperative surplus for different values of $(a - c, \overline{Q})$ (note that the horizontal axis is inverted). We make the following observations. First, the cooperative surplus is an increasing function of the relative cost advantage of the downstream riparian, $(a - c)$. Secondly, it is maximised when $Q = 1$, i.e. on the $N_M - N_L$ border. Thirdly, cooperative surpluses are generally of a higher order of magnitude than cooperative deficits.

Diagrams similar to those produced in Figure 2.1 can also be drawn for the two cases $\frac{d^3y(q)}{dq^3} > 0$ and $\frac{d^3y(q)}{dq^3} < 0$. If the third derivative of the production function is positive (negative) then the marginal profit function is downward sloping and convex (concave) in q. To ascertain the sign of the cooperative surplus, one merely has to compare the two areas under the marginal profit curves associated with the gain (loss) of the downstream (upstream) riparian. Figure 2.4 illustrates scenario $E_{MU} \cap N_M$ under alternative assumptions of the third derivative of the production function where upstream loss is given by $|ABD|$ and downstream gain by $|ABE|$. A positive (negative) third derivative implies a cooperative surplus (deficit) under equal quota.

4. Agreement stability

The principal analytical concern thus far has been whether equal quota represents a superior alternative to noncooperation in terms of its efficiency and equity properties. As previously highlighted equal quota can only be attained by means of a cooperative agreement between the two riparians. In the absence of a supranational body to enforce the agreement, neither of the signatories must find it in their own interest to deviate and act unilaterally. Since equal quota implies a redistribution of water, and hence profit, from upstream to downstream the key question is whether the upstream riparian would find it individually rational to enter the agreement. Clearly, were the downstream riparian to keep all its additional profits under an equal quota agreement then the upstream riparian would never sign. The analysis therefore presupposes the possibility of lump-sum side payments payable from the winner of cooperation to the loser. This is why the size of the cooperative surplus matters. If the surplus is non-positive then it would be undesirable from an efficiency point of view for any of the riparians to enter the agreement although this could be justified on equity grounds provided the trade-off is politically acceptable.

Suppose in the following example that there are benefits from cooperation. The subsequent analysis gives an illustration of how a stable agreement can be reached. We assume identical Cobb Douglas production functions, $y_i = q_i^{\alpha}$, where $\alpha = \frac{1}{2}$, $c = 2$ (upstream riparian has the cost advantage) and $Q = \frac{1}{5}$ which implies that the riparians are in $E_{MU} \cap N_L$. For simplicity we set the transfer payments p of the water trade equal to zero. Table 2.6 gives an overview:

Table 2.6 Example of a stable equal quota agreement

	q_u^*	π_u^*	q_d^*	π_d^*	Π
1. Noncooperation	0.20	0.247	0.00	0.000	0.247
2. Equal quota (net of trade)	0.14	0.233	0.06	0.125	0.358
3. Stable agreement	0.14	0.247	0.06	0.111	0.358
4. Splitting the surplus	0.14	0.302	0.06	0.056	0.358

Given the noncooperative payoffs, the individual rationality constraint of the upstream riparian is $\pi_u^E \geq \pi_u^N = 0.247$, and, $\pi_d^E \geq \pi_d^N = 0$ for the downstream riparian. The downstream riparian gains substantially under equal quota (after selling 0.04 units) while upstream incurs a minor loss. Although equal quota is more efficient than noncooperation ($\Pi^E = 0.358 > \Pi^N = 0.247$) it is not individually rational for the upstream riparian to cooperate. To make the upstream riparian sign the agreement, the downstream riparian must issue a side payment of at least $\pi_u^N - \pi_u^E = 0.247 - 0.233 = 0.014$. This side payment is sufficient to guarantee a stable agreement (see line 3 in Table 2.6). Ultimately, the size of the side payment will be a matter of negotiation between the two riparians. The Nash bargaining solution provides a theoretical solution to this problem. Supposing both riparians are risk neutral we must solve the following problem $\max_{\pi_u+\pi_d \leq 0.358} \{(\pi_u - 0.247)^\beta (\pi_d - 0)^{1-\beta}\}$. The result embodies the popular notion of splitting the cooperative surplus for riparians with identical bargaining power ($\beta = \frac{1}{2}$).

To what extent can the final outcome (in terms of water shares and profit) in the Nash bargaining solution be said to be equitable? It is important here to re-emphasise that our notion of equity is the *egalitarian standard of equal shares of water to equals,* or alternatively, *equality of opportunity (water access).* The cooperative agreement does indeed reflect these principles:

Both countries are given an equal share of the water. The reason why the downstream riparian only uses 30 percent of the water is due to a lack of innate capability of making productive use of its entitlement. The inequality of profit is a consequence of the fact that the noncooperative outcome is very unequal (upstream gets all the profits). The cooperative surplus, however, is split evently. Irrespective of this, since our equity metric is water - not final outcomes such as profits - we should refrain from making any evaluative judgement of the fairness of the basinwide profit distribution.

Before concluding the analysis of stability it is worth pointing out that riparians do sometimes sign (and respect) international agreements even though they are unstable in a narrow economic sense. As pointed out in the international relations literature such behaviour can be entirely rational if one also considers the broader political benefits from signing such an agreement (LeMarquand, 1977). First, the signatories to an agreement may want to project a positive international image of themselves as in the case of the decision by the US Government to build a desalting plant on the Lower Colorado River in the 1970s. Secondly, river sharing agreements are only one of many ways in which countries interact, thus one country might accept a 'bad deal' if a linkage has been made to another bilateral agreement on which it stands to gain more substantially (see Bennett *et al.*, 1998). Finally, a reluctant upstream riparian may be downstream to the same or other countries on other rivers and this produces a more flexible stance (Sadoff *et al.*, 2002). On the other hand, there are also examples of economically rational, but politically infeasible agreements, as exemplified by Dinar and Wolf's (1994) analysis of water markets for the Middle East.

5. Policy implications

Suppose the model presented in this chapter gives a sufficiently reasonable description of reality. How could it be used for practical purposes to guide the negotiation of a water sharing agreement between two riparians? What are the informational requirements? What are the policy implications? The answers to these questions are best addressed by proposing an algorithm that negotiators can adopt. Inevitability, this proposal represents a simplification of what in most cases is a complex negotiation scenario. Nevertheless, it constitutes a basic prescription of the steps necessary to determine whether an equal quota agreement (or any other exogenously defined share) is worth pursuing vis-à-vis noncooperation when riparians aspire for an efficient and equitable solution.

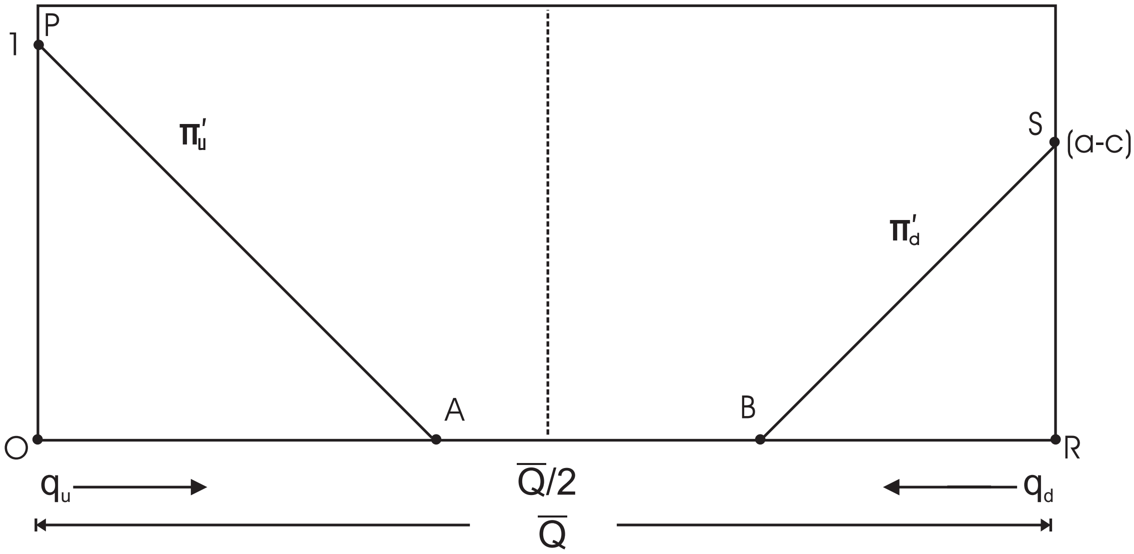
In step 1 the riparians must collect all relevant information. First, this includes an estimate of the production functions (where water is an input) of each riparian. Secondly, riparian cost functions must be estimated. What matters here is the relative difference in unit costs between riparians. Thirdly, a reliable estimate must be made over the range of annual water flow. The annual flow volume is usually stochastic (affected by weather) and fluctuations of 25 percent above or below the mean annual flow are quite common (Kilgour and Dinar, 1995). Flow data is often (but not always) available to negotiators and can be estimated more easily than production or cost functions. Step 2 involves a re-specification of the theoretical model in light of the available data. For instance, riparians may have production or cost functions which are different from those presented in this chapter. On the basis of the data collected in step 1 negotiators must, in step 3, make an overall assessment of which of the many possible scenarios the riparians are most likely to find themselves in. This may not be a unique scenario, such as $E_{LD} \cap N_M$, but rather a range of possible scenarios. The uncertainty derives partly from the statistical uncertainty of the parameter values of the production and cost functions, but most importantly the substantial variation in annual water flow. Step 4 involves an estimation of the expected cooperative surplus of introducing equal quota. This obviously depends on the conclusions of step 3 and riparians must also account for possible transaction costs. In step 5, the riparians must decide whether it is worthwhile to share the water equally (or according to any other exogenous rule). If the cooperative surplus (net of transaction costs) is non-negative then equal quota is a first-best policy. If the cooperative surplus is negative then riparians trade-off efficiency to attain equity. Finally, in step 6 the riparians must embark on negotiations of how to share the cooperative surplus.

6. Conclusion

This chapter has dealt with the question of how, in the context of management of transboundary rivers, the two objectives of social equity and economic efficiency interrelate and whether they conflict with each other. The theoretical results contain a relatively optimistic policy message: Although equity and efficiency are inseparable objectives when water is scarce this does not necessarily imply a trade-off. Under certain circumstance, cooperating riparians can be rewarded with a cooperative surplus. Trade-offs do occur, albeit less frequently and in smaller magnitude relative to cooperative surplus outcomes.

Figure 2.1 Noncooperation and equal quota when the upstream riparian has a relative cost advantage ($y_i=aq_i-1/2q_i^2$, $i=(u,d)$, $c_u=1$, $c_d=c$).

a) $E_{HU} \cap N_H$



b) $E_{MU} \cap N_H$

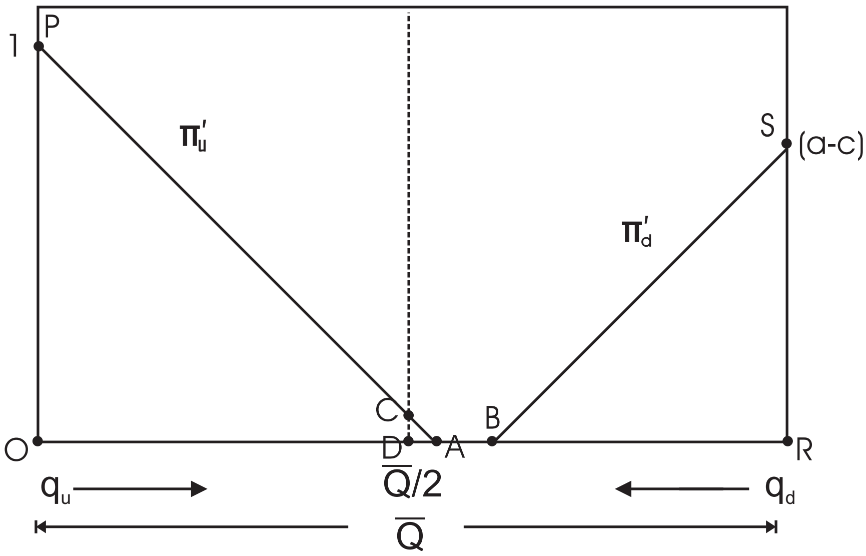
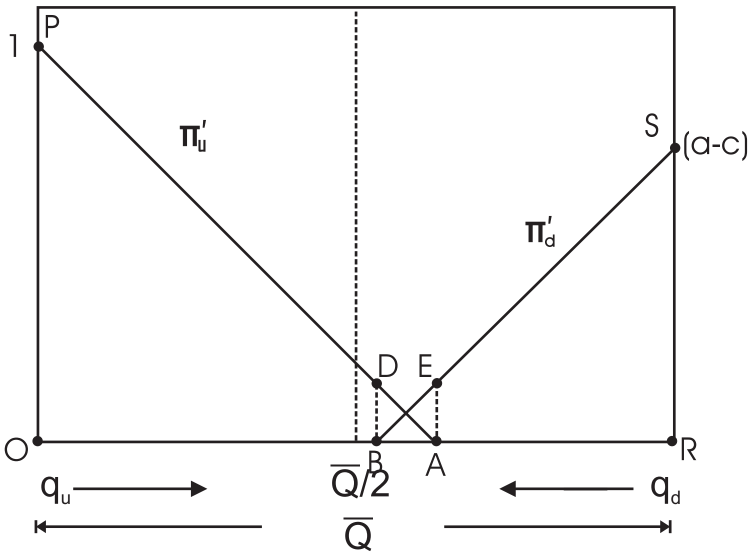


Figure 2.1 Noncooperation and equal quota when the upstream riparian has a relative cost advantage ($y_i=aq_i-1/2q_i^2$, $i=(u,d)$, $c_u=1$, $c_d=c$).

c) $E_{MU} \cap N_M$



d) $E_{LU} \cap N_M$

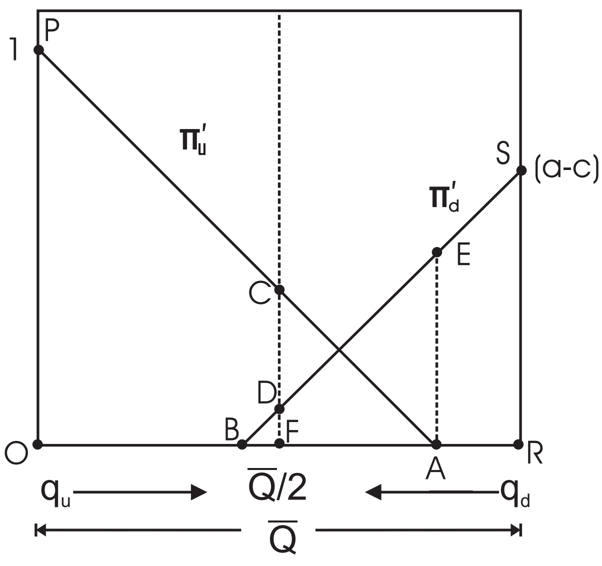
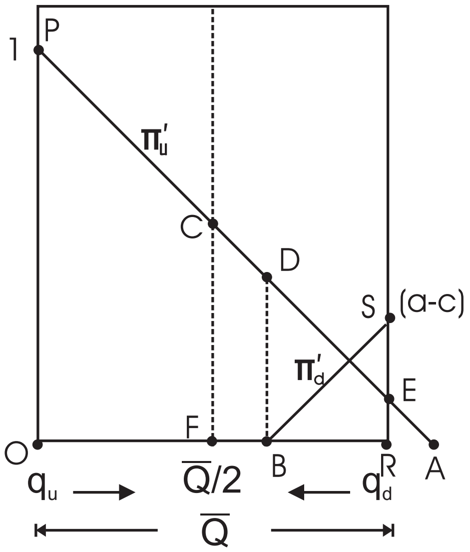


Figure 2.1 Noncooperation and equal quota when the upstream riparian has a relative cost advantage ($y_i = aq_i - 1/2q_i^2$, $i=(u,d)$, $c_u=1$, $c_d=c$).

e) $E_{MU} \cap N_L$



f) $E_{LU} \cap N_L$

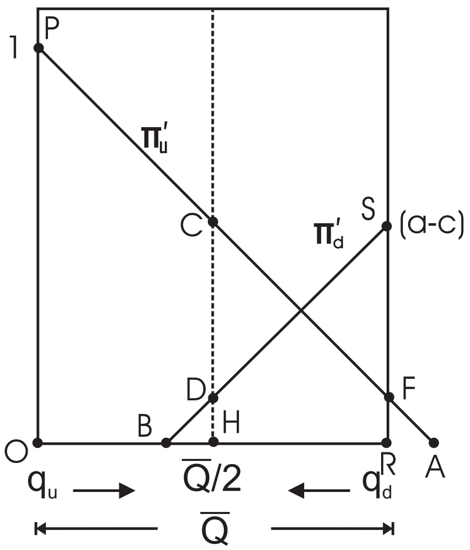


Figure 2.2 The domain of the equal quota and noncooperative sets in (a-c,$\overline{Q}$)-space (y_i=aq_i-1/2q_i^2, i=(u,d), c_u=1, c_d=c).

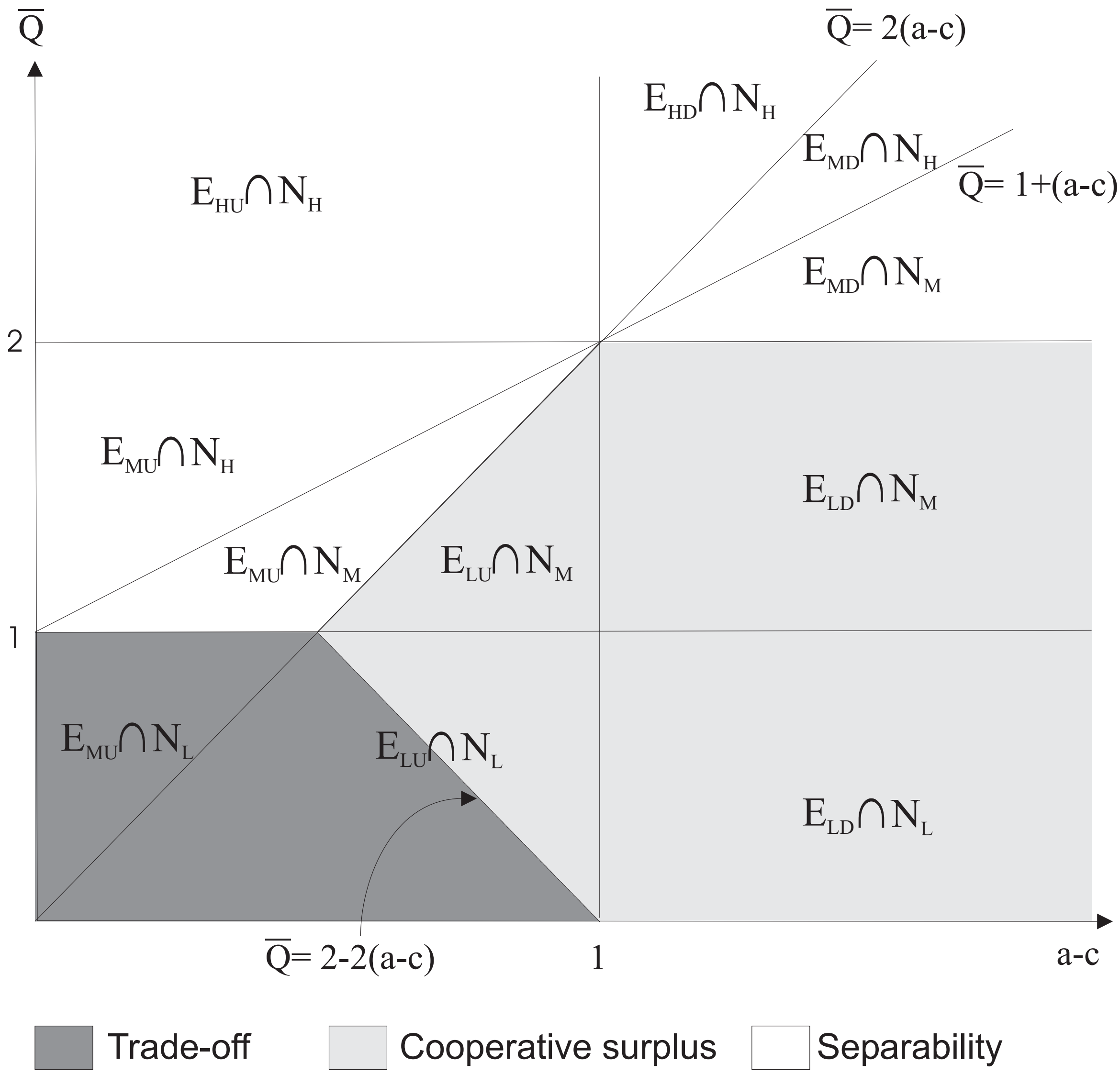


Figure 2.3 Cooperative Surplus (y_i=aq_i-1/2q_i^2, i=(u,d), c_u=1, c_d=c).

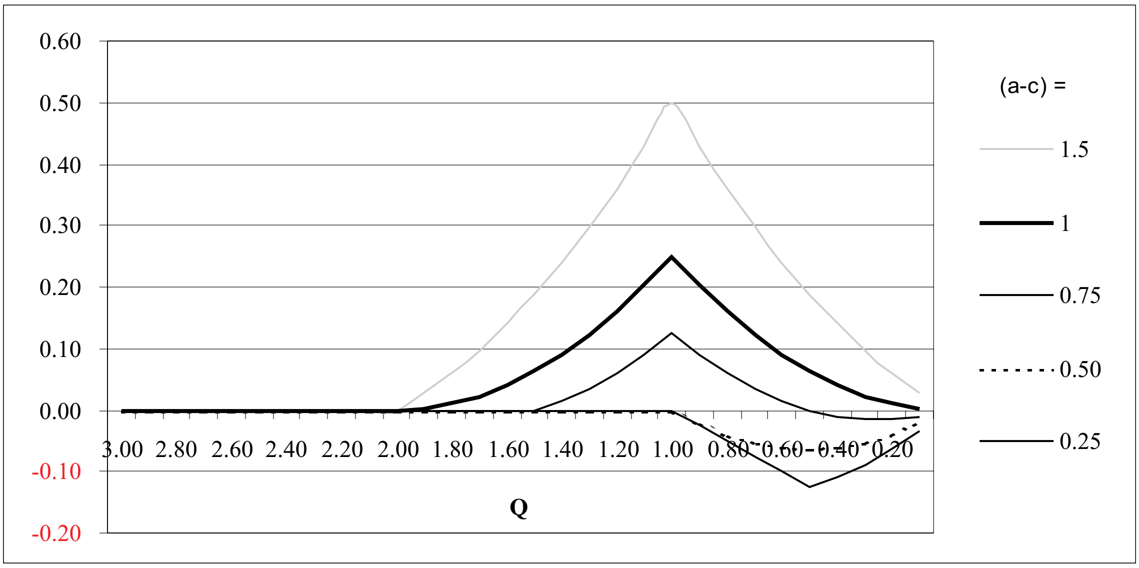
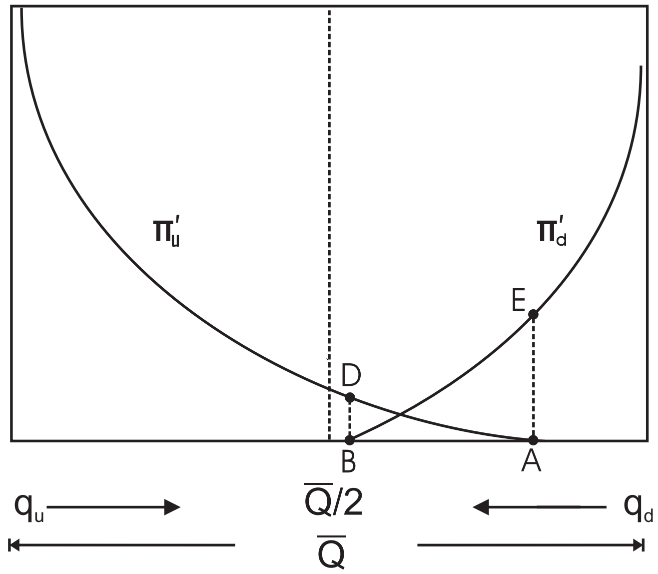
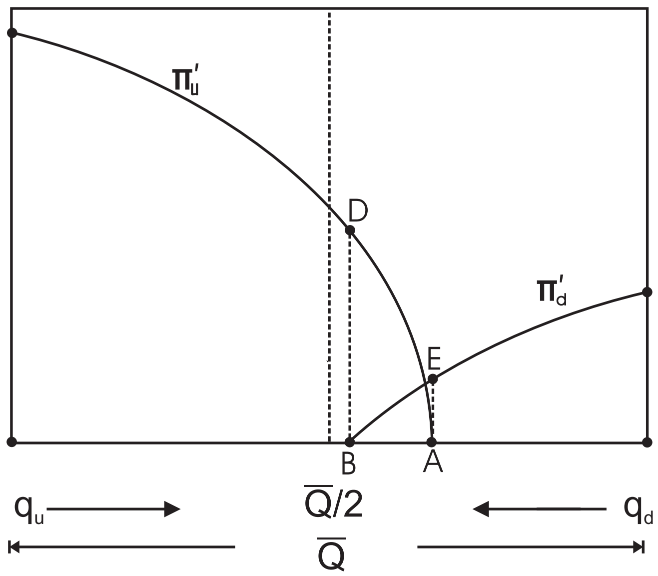


Figure 2.4 Noncooperation and equal quota when downstream riparian has a relative cost advantage.

a) $E_{MU} \cap N_M$ and $\pi''' > 0$



b) $E_{MU} \cap N_M$ and $\pi''' < 0$



Appendix C. Definition of joint sets

This appendix defines the fourteen joint sets identified in section 2.5. Using the definitions of the noncooperative sets (listed above table 2.1) and of the equal quota sets (see table 2.3) we have:

Table C.1 Upstream riparian has a cost advantage

$E_{HU} \cap N_H = \{c > 1 \mid 2g(1) \leq \overline{Q}\}$
$E_{MU} \cap N_H = \{c > 1 \mid g(1) + g(c) \leq \overline{Q} < 2g(1)\}$
$E_{LU} \cap N_M = \{c > 1 \mid g(1) < \overline{Q} \leq 2g(c)\}$
$E_{MU} \cap N_M = \{c > 1 \mid g(1) < \overline{Q} < g(1) + g(c)\}$
$E_{MU} \cap N_L = \{c > 1 \mid 2g(c) < \overline{Q} \leq g(1)\}$
$E_{LU} \cap N_L = \{c > 1 \mid 0 < \overline{Q} \leq 2g(c) \wedge 0 < \overline{Q} \leq g(1)\}$

Table C.2 Downstream riparian has a cost advantage

$E_{HD} \cap N_H = \{c < 1 \mid 2g(c) \leq \overline{Q}\}$
$E_{MD} \cap N_H = \{c < 1 \mid g(1) + g(c) \leq \overline{Q} < 2g(c)\}$
$E_{MD} \cap N_M = \{c < 1 \mid 2g(1) < \overline{Q} < g(1) + g(c)\}$
$E_{LD} \cap N_M = \{c < 1 \mid 0 < \overline{Q} \leq 2g(1)\}$
$E_{LD} \cap N_L = \{c < 1 \mid 0 < \overline{Q} \leq g(1)\}$

Table C.3 Identical riparians

$E_{HI} \cap N_H = \{c = 1 \mid 2g(1) < \overline{Q}\}$
$E_{MI} \cap N_M = \{c = 1 \mid g(1) < \overline{Q} \leq 2g(1)\}$
$E_{LI} \cap N_L = \{c = 1 \mid 0 < \overline{Q} \leq g(1)\}$

Figure 2.2 provides an illustrates of the joint sets for the special case where $\frac{d^3y(q)}{dq^3} = 0$ and production is given by $y = aq_i - bq_i^2, a, b > 0$ and profit by $\pi_i = (a - c_i)q_i - bq_i^2, a > c_i$. Assume further that $b = \frac{1}{2}$ and $a - c_u = 1$. Then the upstream riparian has a cost advantage when $0 < (a - c_d) < 1$ and the downstream riparian has a cost advantage when $(a - c_d) > 1$. To derive the lines in figure 2.2 we use the definitions in table $C.1 - C.3$ where $g(1) \equiv q_u^* = \frac{(a-c_u)}{2b} = 1$ and $g(c) \equiv q_d^* = \frac{(a-c_d)}{2b} = (a - c_d)$.

Appendix D. Proof of results in table 2.5

Let $\tilde{q}_u$ be upstream's water use in the noncooperative outcome and let $\tilde{q}_d$ by downstream's water use in the equal quota arrangement. Define $\gamma \equiv \tilde{q}_u - \tilde{q}_d$ as the quantity of water transferred from upstream to downstream riparian when moving from the noncooperative allocation to the equal quota arrangement. Finally, let $\Delta\pi_u$ be upstream's loss and let $\Delta\pi_d$ be downstream's gain in moving from the noncooperative allocation to the equal quota allocation. Then for $i = (u, d)$:

$$\Delta\pi_i = \int_0^{\gamma} \pi_i'(\tilde{q}_i - \theta)d\theta$$

Note that $\pi_i''(q_i) = y''(q_i) < 0 \; \forall \; q_i, i = (u, d)$.

1. $E_{HU} \cap N_H$ and $E_{MU} \cap N_H$: The noncooperative and equal quota allocations are identical (net of trade), thus $\Delta\pi_d = \Delta\pi_u$ for $y''' \lesseqqgtr 0$.

2. $E_{MU} \cap N_M$:

   In this case, $\pi_i'(\tilde{q}_i) = 0$, $i = (u, d)$, $\tilde{q}_u = g(1), \tilde{q}_d = \overline{Q} - g(c)$ and $\gamma = \tilde{q}_u - \tilde{q}_d = g(1) + g(c) - \overline{Q} > 0$.

   (a) When $y''' = 0$, $\pi_i''(q_i) = y''(q_i) = \rho < 0$. Then $\pi_i'(\tilde{q}_i - \theta) = -\rho\theta \; \forall \; \theta > 0, \; i = u, d$. Thus, $\Delta\pi_d = \Delta\pi_u$.

   (b) When $y''' > 0$, $\pi_i''(\tilde{q}_d) < \pi_i''(\tilde{q}_u)$. Then $\pi_d'(\tilde{q}_d - \theta) > \pi_u'(\tilde{q}_u - \theta) \; \forall \; \theta > 0$. Thus, $\Delta\pi_d > \Delta\pi_u$.

   (c) When $y''' < 0$, $\pi_i''(\tilde{q}_d) > \pi_i''(\tilde{q}_u)$. Then $\pi_d'(\tilde{q}_d - \theta) < \pi_u'(\tilde{q}_u - \theta) \; \forall \; \theta > 0$. Thus, $\Delta\pi_d < \Delta\pi_u$.

3. $E_{LU} \cap N_M$:

   In this case, $\pi'_u(\tilde{q}_u) = 0$ and $\pi'_d(\tilde{q}_d) > 0$, $\tilde{q}_u = g(1)$, $\tilde{q}_d = \frac{\overline{Q}}{2}$ and $\gamma = \tilde{q}_u - \tilde{q}_d = g(1) - \frac{\overline{Q}}{2} > 0$.

   (a) When $y''' = 0$, $\pi''_i(q_i) = y''(q_i) = \rho < 0$. Then $\pi'_d(\tilde{q}_u - \theta) > \pi'_u(\tilde{q}_d - \theta)$. Thus, $\Delta\pi_d > \Delta\pi_u$.

   (b) When $y''' > 0$, $\pi''_i(\tilde{q}_d) < \pi''_i(\tilde{q}_u)$. Then $\pi'_d(\tilde{q}_d - \theta) > \pi'_u(\tilde{q}_u - \theta)$ $\forall$ $\theta > 0$. Thus, $\Delta\pi_d > \Delta\pi_u$.

   (c) When $y''' < 0$, $\pi''_i(\tilde{q}_d) \lesseqqgtr \pi''_i(\tilde{q}_u)$. Then $\pi'_d(\tilde{q}_d - \theta) \lesseqqgtr \pi'_u(\tilde{q}_u - \theta)$ $\forall$ $\theta > 0$. Thus, $\Delta\pi_d \lesseqqgtr \Delta\pi_u$.

4. $E_{MU} \cap N_L$:

   In this case, $\pi'_u(\tilde{q}_u) > 0$ and $\pi'_d(\tilde{q}_d) = 0$, $\tilde{q}_u = \overline{Q}$, $\tilde{q}_d = \overline{Q} - g(c)$ and $\gamma = \tilde{q}_u - \tilde{q}_d = g(c) > 0$.

   (a) When $y''' = 0$, $\pi''_i(q_i) = y''(q_i) = \rho < 0$. Then $\pi'_d(\tilde{q}_u - \theta) < \pi'_u(\tilde{q}_d - \theta)$. Thus, $\Delta\pi_d < \Delta\pi_u$.

   (b) When $y''' > 0$, $\pi''_i(\tilde{q}_d) \lesseqqgtr \pi''_i(\tilde{q}_u)$. Then $\pi'_d(\tilde{q}_d - \theta) \lesseqqgtr \pi'_u(\tilde{q}_u - \theta)$ $\forall$ $\theta > 0$. Thus, $\Delta\pi_d \lesseqqgtr \Delta\pi_u$.

   (c) When $y''' < 0$, $\pi''_i(\tilde{q}_d) > \pi''_i(\tilde{q}_u)$. Then $\pi'_d(\tilde{q}_d - \theta) < \pi'_u(\tilde{q}_u - \theta)$ $\forall$ $\theta > 0$. Thus, $\Delta\pi_d < \Delta\pi_u$.

5. $E_{LU} \cap N_L$:

In this case, $\pi'_u(\tilde{q}_u) > 0$ and $\pi'_d(\tilde{q}_d) > 0$, $\tilde{q}_u = \overline{Q}$, $\tilde{q}_d = \frac{\overline{Q}}{2}$ and $\gamma = \tilde{q}_u - \tilde{q}_d = \frac{\overline{Q}}{2} > 0$.

(a) When $y''' = 0$, $\pi''_i(q_i) = y''(q_i) = \rho < 0$. Then $\pi'_d(\tilde{q}_u - \theta) \lesseqqgtr \pi'_u(\tilde{q}_d - \theta)$. Thus, $\Delta\pi_d \lesseqqgtr \Delta\pi_u$.

(b) When $y''' > 0$, $\pi''_i(\tilde{q}_d) \lesseqqgtr \pi''_i(\tilde{q}_u)$. Then $\pi'_d(\tilde{q}_d - \theta) \lesseqqgtr \pi'_u(\tilde{q}_u - \theta)$ $\forall$ $\theta > 0$. Thus, $\Delta\pi_d \lesseqqgtr \Delta\pi_u$.

(c) When $y''' < 0$, $\pi''_i(\tilde{q}_d) \lesseqqgtr \pi''_i(\tilde{q}_u)$. Then $\pi'_d(\tilde{q}_d - \theta) \lesseqqgtr \pi'_u(\tilde{q}_u - \theta)$ $\forall$ $\theta > 0$. Thus, $\Delta\pi_d \lesseqqgtr \Delta\pi_u$.

Chapter 3. Transboundary Water Conflicts over Hydropower and Irrigation: Can Multilateral Development Banks Help?[1]

1. Introduction

In this chapter we focus on a particular type of conflict which arises when the timing of upstream water discharges does not coincide with the seasonal needs of the downstream riparian. We exemplify the problem by considering the case of an upstream hydropower producer and a downstream agricultural producer. From the perspective of the downstream riparian, the result is that in any given season either 'too little' or 'too much' water is discharged relative to its optimum. The Syr Darya river conflict in Central Asia is an important and interesting case study which we examine in more detail in this chapter. Other relevant case studies also briefly deserve mention. The other great Central Asian river, the Amu Darya, has characteristics that could create a situation similar to that on the Syr Darya, if upstream Tajikistan proceeds with plans to expand its hydropower capacity. On the river Nile there is also potential for conflict if upstream Ethiopia decides to develop its substantial hydropower potential thus disrupting the growing season in Egypt. Namibian plans for the Popa Falls hydropower plant on the Okavango river potentially affect wildlife-oriented tourism in Botswana's national parks in the downstream Okavango delta. These examples share a potential conflict between hydropower in an upstream country and other economic interests in a downstream country. In future it is likely that more such conflicts will emerge since only 10 percent of the world's hydropower potential is currently being exploited (Khagram, 2004).

[1] A version of this chapter also exists as a working paper (Moller, 2005).

Development agencies can play an important role in fostering basinwide cooperation in the developing world, for instance by improving technical and political communication between riparians, acting as honest brokers and providing third-party process support and financing, such as setting up basinwide trust funds (ODI, 2001). Multilateral development banks (MDBs) in particular, i.e. the World Bank and the regional development banks, have a comparative advantage in promoting transboundary river management, especially in the area of infrastructure investments. This is partly because of their extensive lending facilities and partly because the co-riparians are typically also their client countries thus enhancing the scope for basinwide solutions. Furthermore, in the case of the World Bank there is substantial in-house experience in river management in light of its involvement as a financier of large dam construction over the past 30 years. Although regional interventions by MDBs, at times, are impeded by their operational mode of country assistance programs (Cook and Sachs, 1999), there has been a gradual shift in recent years towards a more proactive and conscious support of river basin organisations involving several riparian states. The *Nile Basin Initiative*, supported by the World Bank, is by far the most prominent example of this trend although it does represent the exception rather than the rule. The most progressive regional development bank in the area, the Asian Development Bank, recently included a mandate of promoting regional cooperation in its official Water Policy, but still has relatively few activities on the ground (ADB, 2004). There is thus potential for further involvement by multilateral development banks in transboundary water management.

Almost all of the economic literature addressing the energy versus irrigation trade-off is concerned with inter-state or domestic rivers, especially in the United States. Particularly pertinent are the studies of the Snake-

Columbia river by McCarl and Ross (1985), Houston and Whittlesey (1986), McCarl and Parandvash (1988), and Hamilton *et al.* (1989). The Colorado river has been analysed by Gisser *et al.* (1979) and the irrigation districts in Central California by Chatterjee *et al.* (1998). The study by Owen-Thomsen *et al.* (1982) of Egypt's High Aswan Dam therefore represents an exception to the focus on US-based rivers. These studies use mathematical programming to model agricultural production and to analyse the impacts on the agricultural sector of a water transfer to hydropower production because the latter typically has the highest marginal productivity. They generally conclude that such diversions have the potential to generate welfare gains. Market mechanisms (as studied by Hamilton *et al.* (1989)) could potentially improve resource allocation, although this depends critically upon the establishment of clearer property rights as emphasised by Chatterjee *et al.* (1998). International trade in water is rare, however, partly because the conflicting principles of international law complicate the property rights issue and partly for the reasons discussed in Chapter 2.

To our knowledge, there have been only two economic studies of international hydropower-irrigation conflicts. The World Bank (2004a) examines the conflict between the Kyrgyz Republic, Uzbekistan and Kazakhstan on the Syr Darya. The study finds that basinwide benefits are maximised when the upstream hydropower plant operates to facilitate downstream irrigation. To support a cooperative outcome, downstream riparians should compensate the upstream riparian for its water storage services by issuing side payments. In the other study, Aytemiz (2001) examines the conflict between Turkey and Syria on the Euphrates. In addition to focusing on the optimal allocation of surface water, this study also addresses the question of whether there is sufficient water for both riparians' needs, and comes to a negative conclusion.

There is also a more general economic literature on transboundary rivers as reviewed in Chapter 2. A non-exhaustive list includes contributions by Barrett (1994), Dinar and Wolf (1994), Rogers (1997), Kilgour and Dinar (2001) and Ambec and Sprumont (2002). These authors are typically preoccupied with how and under what circumstances riparians can cooperate on their own, but do not directly address the question of whether third-party intervention may be useful. An important reason for this omission is the common underlying assumption of riparian sovereignty, the consequence of which is to ignore the relevance of supra-national bodies in fostering cooperation. While this may be a realistic assumption in some circumstances, this is not always the case. Many international river basins are located in developing nations (twenty percent are located in Africa, for instance). The ability of poor, indebted and aid-recipient countries to fully control domestic and foreign policy, is sometimes compromised in practice. The proposition that external agencies could play a role in promoting riparian cooperation can therefore not be dismissed *a priori*.

In this chapter we consider a range of policy interventions undertaken by a multilateral development bank in the context of a transboundary hydropower-irrigation water conflict. The chapter considers two policy issues: First, interventions by an MDB can be motivated by at least two objectives: a) maximising basinwide social welfare and b) promoting regional stability. As noted above, existing economic literature has emphasised (a) and paid little attention to (b). This prioritisation can be readily justified in a domestic context where the problem is primarily one of suboptimal resource allocation. In an international context, on the other hand, it is often political priorities which is the major concern and economic objectives are secondary. The distinction is important because interventions may result in a trade-off.

For instance, an intervention which increases upstream welfare more than it reduces downstream welfare enhances basinwide welfare but jeopardises regional stability unless side payments are made. Is it possible to identify policy interventions that simultaneously promote regional stability and enhance social efficiency? Secondly, an interesting policy option emerges for an MDB that intends to assist a downstream client: Could the client be more effectively assisted through *indirect* intervention in an upstream state, as opposed to *direct* interventions within the client's own territory? To illustrate this point in a broader context, annual floods in Bangladesh have been exacerbated in recent years as a consequence of deforestation and overgrazing in upstream India, Nepal and Tibet. Is Bangladesh best protected against floods through upstream measures, e.g. deforestation control, or through in-country interventions, such as flood control defences?[2]

The present chapter contributes to existing literature in two ways. First, it adds to the sparse literature on international hydropower-irrigation conflicts by providing an analytical framework within which case studies, such as those provided by the World Bank (2004a) and Aytemiz (2001), can be examined. Secondly, it contributes to the literature on transboundary rivers by explicitly considering a potential role for third-party intervention. The chapter identifies and ranks a range of policy interventions in terms of their ability to reduce regional tension and enhance basinwide social welfare. In comparison to the existing hydro-irrigation literature, we present an analytical model that is simple enough to capture the essence of the problem. On the other hand, our model is not sufficiently elaborate to allow for accurate

[2]Related policy options arise for a host of other international challenges driven by cross-border spillover effects. Apart from the related area of transboundary pollution, this includes many other 'global public goods' (see Kaul *et al.* 1999).

empirical estimations of individual river basins (see Chatterjee *et al.*, 1998 for an example). It should also be emphasised from the outset that the interventions analysed here are costly infrastructure projects, such as construction of hydropower plants and dams which take several years, sometimes decades, to complete. The theoretical analysis emphasises the qualitative impact of these projects, but is necessarily silent about other important aspects such as the investment cost or the social, environmental or political impact. A final decision to pursue any such projects must obviously also be informed by these factors. The remainder of the chapter is structured as follows: Section 2 presents the model and its noncooperative equilibrium. Section 3 computes the socially efficient allocation. Section 4 contains the policy analysis based on comparative statics. Section 5 ranks and compares policies. Section 6 uses the theoretical findings to illustrate the relevance of the model in the context of the Syr Darya conflict. Section 7 concludes.

2. The Model

Two riparian states share a transboundary river. The upstream riparian (UP) is a hydropower producer and the downstream riparian (DOWN) withdraws water for agricultural irrigation.[3] There are two periods which may be thought of as seasons within a water year (period 1 is the summer season and period 2 is the winter season). Second-period (winter) electricity demand in UP is assumed higher than first-period (summer) demand. In the first period, therefore, UP prefers to store some water in its reservoir in order to increase second-period electricity production. This mode of operation conflicts with the interests of DOWN. It receives insufficient irrigation water in the first period, which is the growing season, and may experience

[3]Note the distinction between consumption and non-consumption water use. Irrigation is an example of the former and hydropower use an example of the latter.

flooding in the second period.

2.1 Upstream hydropower production[4]

Upstream hydropower is generated by a single, state-regulated plant which produces y_t units of electricity in period $t, t = (1, 2)$, by making use of q_t units of water flowing to it. Let $\alpha > 0$ be an efficiency parameter. The hydropower production function

$$y_t = \alpha f(q_t) \tag{1}$$

can exhibit either diminishing or constant returns to scale, thus $\frac{\partial f(q_t)}{\partial q_t} > 0$, $\frac{\partial^2 f(q_t)}{\partial q_t^2} \leq 0$ and $f(0) = 0$.[5] The hydropower plant serves the entire domestic market for electricity which has the inverse demand function in period t, denoted p_t:

$$p_t(y_t) = a_t - by_t \tag{2}$$

for $0 \leq y_t \leq \frac{a_t}{b}$, and $p_t = 0$ for $y_t > \frac{a_t}{b}$ where $a_t > 0$ and $b > 0$ are parameters. Let $0 < \delta < 1$ denote the discount factor between the two periods. The relatively higher second-period electricity demand is reflected in the assumption: $\delta p_2(y_t) > p_1(y_t), \forall y_t$. The natural inflow of water, Q_t, denotes the (perfectly forecast) exogenous volume of water supplied in the reservoir controlled by UP in period t and $\overline{Q} = Q_1 + Q_2$ denotes the annual inflow. It is assumed that water is scarce enough not to be wasted. In other words, over the two periods UP uses all of the water inflows to produce electricity.[6] Water available to UP in period one can be used to produce electricity in the first period or can be stored in UP's reservoir for use in the

[4]The hydropower model presented here is an extension of that developed by Ambec and Doucet (2003).

[5]Ambec and Doucet (2003) assume constant returns to scale while the models developed by Edwards (2003) exhibit diminishing returns.

[6]This simplifying assumption reflects the physical limitation that, on average in a long-term equilibrium, hydro plants cannot have net positive or negative accumulation of water.

second period. In the first period, UP relies on water in its reservoir (i.e. no water is available from the previous period). Hence, UP faces the input supply constraint

$$q_1 \leq Q_1 \tag{3}$$

The volume of water stored in UP's reservoir during the first period is used in its entirety to produce electricity in the second period. This volume is bounded by the reservoir capacity denoted $s > 0$. In terms of first-period water release we have:

$$q_1 \geq Q_1 - s \tag{4}$$

We normalise operating costs to zero and write profit in period t as a function of water input, q_t:

$$\pi_t^u(q_t) = p_t y_t = \alpha f(q_t)\left(a_t - b\alpha f\left(q_t\right)\right) \tag{5}$$

By serving the domestic market, the plant generates a consumer surplus in period t of:

$$CS_t(q_t) = \frac{1}{2} y_t(a_t - p_t) = \frac{b\alpha^2}{2}\left[f(q_t)\right]^2 \tag{6}$$

Let social welfare of the upstream riparian in period t be the sum of consumer surplus and profit: $SW_t^u(q_t) = CS_t(q_t) + \pi_t^u(q_t)$. Since second-period water release is determined residually, $q_2 = \overline{Q} - q_1$, we can write down UP's optimisation problem in terms of choosing q_1 optimally:

$$\max_{q_1}\left\{SW_1^u(q_1) + \delta SW_2^u(\overline{Q} - q_1) \mid Q_1 - s \leq q_1 \leq Q_1\right\} \tag{7}$$

The Lagrangian is written:

$$L(q_1, \overline{\lambda}, \underline{\lambda}) = SW_1^u(q_1) + \delta SW_2^u(\overline{Q} - q_1) + \overline{\lambda}(Q_1 - q_1) + \underline{\lambda}(Q_1 + q_1 - s) \tag{8}$$

where $\overline{\lambda}$ and $\underline{\lambda}$ are the Lagrangian multipliers associated with the input supply constraint and the storage constraint, respectively. The first-order conditions yield:

$$\frac{\partial SW_1^u(q_1^*)}{\partial q_1} + \delta \frac{\partial SW_2^u(\overline{Q} - q_1^*)}{\partial q_1} = \overline{\lambda} - \underline{\lambda} \tag{9}$$

$$\overline{\lambda}(Q_1 - q_1^*) = 0 \tag{10}$$

$$\underline{\lambda}(Q_1 + q_1^* - s) = 0 \tag{11}$$

At the interior solution ($\overline{\lambda} = \underline{\lambda} = 0$), the first-order condition reduces to:

$$\frac{\partial f(q_1^*)}{\partial q_1} p_1\left(y_1^*\right) - \delta \frac{\partial f(q_2^*)}{\partial q_2} p_2\left(y_2^*\right) = 0 \tag{12}$$

Upstream social welfare, SW^u, is strictly concave in q_1. The second-order condition yields:

$$\frac{\partial^2 f(q_1^*)}{\partial q_1^2} p_1(y_1^*) - b\alpha \left(\frac{\partial f(q_1^*)}{\partial q_1}\right)^2 + \delta \frac{\partial^2 f(q_2^*)}{\partial q_2^2} p_2(y_2^*) - b\alpha\delta \left(-\frac{\partial f(q_2^*)}{\partial q_2}\right)^2 < 0 \tag{13}$$

The first-order condition (12) captures the upstream planner's choice between first- and second-period water release. To maximise social welfare, UP must equate the discounted marginal social welfare of the two periods. At the interior solution this implies that $q_2^* > q_1^*$ because the assumption $\delta p_2(y_t) > p_1(y_t)$ implies that $\delta p_2\left(y_2^*\right) > p_1(y_1^*)$ so that we must have $\frac{\partial f(q_1^*)}{\partial q_1} > \frac{\partial f(q_2^*)}{\partial q_2}$. The corner solutions are straightforward: When the input supply constraint binds ($\overline{\lambda} > 0$), the optimal production plan requires more water in period one than is available so $q_1^* = Q_1$. This implies that the first-period marginal social welfare is higher than that of the second period (discounted): $\frac{\partial SW_1^u(q_1^*)}{\partial q_1} > -\delta \frac{\partial SW_2^u(q_2^*)}{\partial q_2}$. When the storage constraint binds ($\underline{\lambda} > 0$), the optimal production plan requires more storage capacity in period one than is available thus $q_1^* = Q_1 - s$ and $\frac{\partial SW_1^u(q_1^*)}{\partial q_1} < -\delta \frac{\partial SW_2^u(q_2^*)}{\partial q_2}$. Finally, we note that the assumption of water scarcity implies that the technical efficiency coefficient has a maximum value which is denoted $\overline{\alpha}$. For $\alpha > \overline{\alpha}$

electricity demand is fully satisfied in period 1 and 2 given the total amount of water available in each period, Q_1 and Q_2. By setting $p_1 = p_2 = 0$ and using equations (1) and (2) we get that water scarcity implies $\alpha \leq \frac{a_t}{bf(q_t^*)}$ for $t = 1, 2$. Given the assumption that second-period demand is highest we find that $\overline{\alpha} = \frac{a_2}{bf(q_2^*)}$. It is henceforth assumed that $\alpha < \overline{\alpha}$.

2.2 Downstream agricultural production

In period one, DOWN grows an irrigation-fed agricultural crop x, such as cotton or rice, which it sells on the world market at the exogenous output price $p(x) = p = 1$. Irrigation supply is available from two main sources: upstream water releases, q_1^*, and water available from DOWN's own reservoir, $r > 0$, which is assumed full in the beginning of period one. The agricultural production function, $x(q_1^*+r)$, exhibits diminishing returns to scale, $\frac{\partial x(\cdot)}{\partial q_1} > 0$, $\frac{\partial^2 x(\cdot)}{\partial q_1^2} < 0$ and $x(0) = 0$. The cost function $c(q_1^* + r)$ is convex, $\frac{\partial c_1(\cdot)}{\partial q_1} > 0$ and $\frac{\partial^2 c_1(\cdot)}{\partial q_1^2} \geq 0$. We write DOWN's first-period profit as:

$$\pi_1^d = x(q_1^* + r) - c_1(q_1^* + r) \tag{14}$$

In the second period DOWN is not engaged in any economic activities which use irrigation water from the river as an input. Water may, nevertheless, have economic consequences if flooding occurs. In our model, as in reality, flooding has positive and negative implications. We model the positive effects as a replenishment of DOWN's reservoir, thus we assume $r < \overline{Q} - q_1^*$.[7] The negative effects of flooding, such as damages to physical infrastructure, are described by the convex cost function $c_2(q_2^* - r - \widetilde{q})$ where $\frac{\partial c_2(\cdot)}{\partial q} > 0$ and $\frac{\partial^2 c_2(\cdot)}{\partial q^2} \geq 0$. In words, only second-period water inflow that exceed the sum

[7] Although this is a two-period model, there is an implicit assumption that period two is followed by a third period (which has the characteristics of the first period), a fourth period (similar to the second period) and so on. Thus the reason why the downstream reservoir is assumed full in the first period is that it was fully replenished in period zero.

of the conveyance capacity of the river, $\widetilde{q}$, and the reservoir capacity r has a negative economic impact. Second period profit is given by:

$$\pi_2^d = -c_2(\overline{Q} - q_1^* - r - \widetilde{q}) \tag{15}$$

DOWN's profit is maximised when first-period and second-period marginal profits are equalised:[8]

$$\frac{\partial x(q_1 + r)}{\partial q_1} - \frac{\partial c_1(q_1 + r)}{\partial q_1} = \delta \frac{\partial c_2(\overline{Q} - q_1 - r - \widetilde{q})}{\partial q_2} \tag{16}$$

Note that maximisation of DOWN's profit implies non-positive marginal profits ($\frac{\partial \pi_t(\cdot)}{\partial q_t} \leq 0$). If the sum of the conveyance and reservoir capacity $(\widetilde{q} + r)$ is relatively small, and flooding occurs, then marginal profits are negative. In this case DOWN would prefer to reduce second-period flooding by using more than optimal irrigation input in the first period. If flooding can be avoided ($\widetilde{q} + r$ is relatively substantial) then DOWN would prefer to irrigate until first-period marginal profit equals zero.

2.3 Noncooperative equilibrium

Due to the geographic position of the two riparians the noncooperative equilibrium is determined entirely by the actions of the upstream riparian (at least in the short term).[9] Because of assumed water scarcity in the first period, DOWN does not maximise its profit, thus its first-period marginal profit is positive $\frac{\partial \pi_1^d(q_1^* + r)}{\partial q_1} > 0$.

The noncooperative solution may take any of 3 forms: The interior solution or either of the two corner solutions. Figure 3.1 (at the end of the

[8]The assumptions about the production and cost functions imply that π^d is strictly concave in q_1.

[9]We ignore here the possibility that DOWN issues a side payment to UP in exchange for a release vector more favourable to DOWN. This policy option is discussed further in the Syr Darya case study (section 6) and is treated explicitly in chapter 4.

chapter) illustrates the noncooperative equilibrium at the interior solution. The width of the diagram is determined by the total water inflow over the two periods, $\overline{Q}$. First-period water release, q_1, is measured from left to right and second-period water release, q_2, in the opposite direction. Panel (a) depicts the upstream hydropower producer. Each period is represented by a convex marginal social welfare (MSW) curve. At an interior solution, the noncooperative input vector (q_1^*, q_2^*) is determined at the intersection of the two MSW-curves located between the two vertical lines representing, respectively, the storage constraint $(Q_1 - s)$ and the supply constraint (Q_1). Panel (b) illustrates the downstream riparian. First-period crop production is represented by a convex marginal profit curve. DOWN receives q_1^* water units from UP and by using all the water from its reservoir r it operates at B. First-period profit is maximised at D where marginal profit equals zero. In the second period UP releases q_2^* of which r units are used to replenish DOWN's reservoir. The excess water causes flooding in the territory of the downstream riparian, represented by point C on its concave marginal profit curve. In comparison, total downstream profit is maximised at E where the marginal profit curves intersect. The location of the second-period marginal profit curve is determined by the conveyance capacity $\widetilde{q}$ (a higher $\widetilde{q}$ moves the curve further to the left). If the conveyance capacity $\widetilde{q}$ were sufficiently large then marginal profit curves would not intersect and DOWN's optimum would be at D. Figures 3.2 and 3.3 illustrate the two corner solutions. When the storage constraint binds (Figure 3.2) UP must produce more first-period electricity (and release more water) than it would do if the storage constraint was not binding. In this case the equilibrium is determined by the location of the $(Q_1 - s)$-curve. On the other hand, if the supply constraint binds the equilibria are determined by the location of the Q_1-curve (Figure 3.3).

3. Basinwide social efficiency

The presence of a production externality implies that the noncooperative equilibrium is typically not socially efficient. In this chapter, the socially efficient allocation is defined as the feasible water allocation (q_1^o, q_2^o) which maximises basinwide social welfare, denoted $SW = SW_1^u + \delta SW_2^u + SW_1^d + \delta SW_2^d$. Note that $SW_1^d + \delta SW_2^d = \pi_1^d + \delta\pi_2^d$, i.e. there is no consumer surplus from agricultural production because DOWN's crop is exported to markets outside the basin. The socially efficient allocation is the solution to the problem:

$$\max_{q_1}\{SW_1^u(q_1)+\delta SW_2^u(q_1)+SW_1^d(q_1)+\delta SW_2^d(q_1) \mid \overline{Q}_1-\overline{s} \leq q_1 \leq \overline{Q}_1\} \quad (17)$$

The first-order conditions yield:

$$\frac{\partial f(q_1^o)}{\partial q_1} p_1\left(y_1^o\right) - \delta \frac{\partial f(q_2^o)}{\partial q_2} p_2\left(y_2^o\right) + \frac{\partial x\left(q_1^o + r\right)}{\partial q_1} - \frac{\partial c_1\left(q_1^o + r\right)}{\partial q_1} - \delta \frac{\partial c_2\left(q_2^o - r - \widetilde{q}\right)}{\partial q_2} = \overline{\mu} - \underline{\mu} \quad (18)$$

$$\overline{\mu}(Q_1 - q_1^o) = 0 \quad (19)$$

$$\underline{\mu}(Q_1 + q_1^o - s) = 0 \quad (20)$$

where $\overline{\mu}$ and $\underline{\mu}$ are the Lagrangian multipliers associated with the input supply constraint and the storage constraint, respectively. A basinwide social planner aims to equalise the marginal social welfare of both riparians. In comparison to the noncooperative equilibrium, the externality is internalised because downstream agricultural profits and flooding damage are considered when choosing q_1. First-period water release is generally larger in the socially efficient allocation compared to noncooperation, $q_1^o > q_1^*$, because $\frac{\partial SW_1^d(q_1^*)}{\partial q_1} - \delta\frac{\partial SW_2^u(q_1^*)}{\partial q_2} > 0$. The two allocations may, however, also be identical, $q_1^o = q_1^*$, if there is a binding constraint for the upstream planner as well as for the basinwide planner. Formally, we have:

Proposition 1 *The noncooperative allocation is not socially efficient, except if one of the following conditions is true:*
(a) $\bar{\lambda} > 0$ *then* $\bar{\mu} > 0$ *and* $q_1^o = q_1^* = Q_1$
(b) $\underline{\mu} > 0$ *then* $\underline{\lambda} > 0$ *and* $q_1^o = q_1^* = Q_1 - s$

Proof. This follows from a comparison of the first-order conditions for the upstream planner (9)-(11) with those of the basinwide planner (18)-(20). ∎

4. Policy Analysis

As outlined in the introduction our aim is to identify policy interventions which promote regional stability and enhance social efficiency. Promotion of regional stability requires that an intervention makes at least one riparian better off without making the other riparian worse-off. Such interventions are also known as Pareto improvements. A Pareto improvement, in turn, implies an enhancement of social efficiency (while the reverse is not the case). The root cause of riparian conflict and social inefficiency is the unidirectional, negative externality caused by upstream regulation of the natural river flow. Pareto-improving policies that reduce this externality (or its impact) are therefore particularly attractive because both riparians are made better-off. Although we are primarily interested in interventions co-financed by multilateral development banks, the comparative static results derived in this section are independent of agency and could, in principle, also be undertaken by the riparians themselves or other external agents.

4.1. Increase hydropower efficiency

Consider a policy intervention aimed at increasing the parameter α, i.e. the technical efficiency of hydropower production. A higher α implies that each unit of water released upstream produces more units of electricity than previously. This could, for instance, be achieved through the construction of additional hydropower plants along the river cascade so that each water unit passes through several turbines. The upstream impact is straightforward:

Proposition 2 *An increase in the technical efficiency of hydropower production, α, enhances upstream social welfare.*

Proof. This follows from the fact that $SW^u(q_1^*, \alpha)$ is strictly concave in α and the assumption that $\alpha < \overline{\alpha}$. ■

Upstream welfare increases because water is a scarce input. The downstream impact is less obvious and depends critically upon UP's choice of input vector when it operates with enhanced efficiency. A shift from second- to first-period water release would reduce the negative externality and enhance downstream welfare. We find that UP's input choice depends on several factors, notably: 1) the production technology; 2) whether it operates at an interior solution or a corner solution.

Proposition 3 *At the interior solution, an increase in upstream hydropower efficiency, α, reduces the negative externality and enhances basinwide social welfare if the following condition is satisfied :*

$$\frac{\delta \frac{\partial f(q_2^*)}{\partial q_2}}{\frac{\partial f(q_1^*)}{\partial q_1}} > \frac{f(q_1^*)}{f(q_2^*)} \tag{21}$$

Proof. The externality is reduced if first-period water release, q_1, increases (and q_2 decreases). We totally differentiate the first-order condition (12) and re-arrange for $\frac{dq_1^*}{d\alpha}$ to get:

$\frac{dq_1^*}{d\alpha} = \frac{b}{\Psi}\left(\frac{\partial f(q_1^*)}{\partial q_1} f(q_1^*) + \delta \frac{\partial f(q_2^*)}{\partial q_1} f(q_2^*)\right)$, where

$$\Psi = p_1\left(y_1^*\right)\frac{\partial^2 f(q_1^*)}{\partial q_1^2} - b\alpha\left[\frac{\partial f(q_1^*)}{\partial q_1}\right]^2 + \delta p_2\left(y_2^*\right)\frac{\partial^2 f(q_2^*)}{\partial q_2^2} - b\alpha\delta\left[-\frac{\partial f(q_2^*)}{\partial q_2}\right]^2 < 0 \tag{22}$$

$\Rightarrow \frac{dq_1^*}{d\alpha} > 0 \Leftrightarrow \left(\frac{\partial f(q_1^*)}{\partial q_1} f(q_1^*) + \delta \frac{\partial f(q_2^*)}{\partial q_1} f(q_2^*)\right) < 0$, which after re-arranging yields (21). ■

Condition (21) reflects certain requirements on the production function $f(q_t)$. This is best illustrated with an example:

Example 1 *Let $f(q_t) = \kappa q_t^{\beta}$, $\kappa > 0$. Condition (21) reduces to:*

$$\delta(q_2^*)^{2\beta-1} > (q_1^*)^{2\beta-1} \tag{23}$$

Assume constant returns to scale ($\beta = 1$) and insert the equilibrium value $q_1^* = \frac{\delta Q}{(1+\delta)} + \frac{(a_1-\delta a_2)}{b\alpha(1+\delta)}$ to get $\delta a_2 > a_1$ which is true by assumption. More generally, expression (23) is true for $\beta > \frac{1}{2}$ and $\delta = 1$. Intuitively, expression (21) is satisfied provided that the production function is 'not too curved', which implies that the returns to scale are 'sufficiently high'.

If condition (21) is satisfied then we can fully characterise the effect of enhanced hydropower efficiency at the interior solution: First-period hydropower production increases partly because more water is released and partly because of enhanced efficiency. In period two, higher efficiency more than off-sets the reduction in water release so production increases. Upstream welfare increases in both periods because of water scarcity. The shift towards first-period water release has positive implications downstream. In period one, agricultural production and profit increase due to a higher irrigation input. In period two, the cost of flooding is reduced (provided that it occurs). Figure 3.4 illustrates this scenario where we have assumed constant returns to scale (CRS). An increase in α pivots both MSW-curves downward and changes the noncooperative equilibrium from A to F.

If, on the other hand, condition (21) is not satisfied then upstream welfare increases, while downstream welfare decreases due to lower irrigation input in period one and increased flooding in period two. Graphically, this corresponds to a situation where the ex-post equilibrium F is located to the left of the ex-ante equilibrium A. Under these circumstances, the intervention exacerbates the conflict of interest. The impact on basinwide welfare depends on whether upstream gains outweigh downstream losses. If basinwide welfare improves then there is a trade-off between the two policy objectives of regional stability and social efficiency.

If the hydropower plant is operating at a corner solution (and continues to do so ex-post) then basinwide welfare increases without reducing the externality. This is true, irrespective of whether condition (21) is satisfied. Upstream welfare increases, cf. Proposition 2, but downstream welfare remains unchanged. This is because an increase in hydropower efficiency has no impact on the water release pattern across the two periods. Figure 3.5 illustrates this situation in the case where the supply constraint binds. The downward shift in the MSW curves does not affect the equilibrium which is determined by the resource constraint rather than the intersection of the MSW curves.

Finally, if the hydropower plant is facing a binding constraint, then there is the possibility that an increase in α implies a move to the interior solution ex-post. With a binding supply constraint this must imply a fall in q_1, i.e. the intersection of the MSW curves move to a point to the left of the

Q_1-curve. Conversely, a binding storage constraint ex-ante must imply an increase in q_1 and an intersection to the right of the $(Q_1 - s)$-curve. Table 3.1 summarises the results:

Table 3.1 Comparative static results $(\alpha \uparrow)$

Case	$\frac{\partial SW^u}{\partial \alpha}$	$\frac{\partial SW^d}{\partial \alpha}$	$\frac{\partial SW}{\partial \alpha}$
1. a) IN and (21) or; b) from ST to IN	> 0	> 0	> 0
2. a) IN not (21) or; b) from SU to IN	> 0	< 0	$\lesseqgtr 0$
3. Corner solutions (ex-ante and ex-post)	> 0	$= 0$	> 0

Note: IN = interior solution, ST = storage constraint binds,

SU=supply constraint binds.

4.2 Expand downstream reservoir capacity

DOWN benefits from its own reservoir, r, in two ways: In period one, it increases irrigation input by augmenting to upstream releases, q_1^*. In period two, it enhances the absorptive capacity thus reducing the potentially negative impact of flooding.

Proposition 4 *An expansion in downstream reservoir capacity* r *reduces the impact of the negative externality and enhances basinwide social welfare.*

Proof. From equations (14) and (15) the comparative statics yield: $\frac{\partial \pi_1^d}{\partial r} = \frac{\partial x(\cdot)}{\partial r} - \frac{\partial c_1(\cdot)}{\partial r} > 0$ and $\frac{\partial \pi_2^d}{\partial r} = -\frac{\partial c_2(\cdot)}{\partial r} \geq 0$, thus $\frac{\partial SWF^d}{\partial r} = \frac{\partial \pi_1^d}{\partial r} + \frac{\partial \pi_2^d}{\partial r} > 0$. ■

An expansion in r increases first-period agricultural output. The impact on downstream welfare is positive because water is assumed scarce in the first period. In the second period, the cost of flooding (if it occurs) is reduced. This intervention is illustrated in Figure 3.6.

4.3 Expand upstream reservoir capacity

UP benefits from its own reservoir, s, because it expands the production possibility set. Higher upstream dam capacity changes the production plan if, and only if, the storage constraint is binding.

Proposition 5 *If the storage capacity constraint is binding, an expansion of the upstream reservoir, s, would exacerbate the negative externality.*

Proof. If the storage constraint is binding then $q_1^* = Q_1 - s$, $q_2^* = Q_2 + s$. We get the following comparative static results: $\frac{\partial q_1^*}{\partial s} = -\frac{\partial q_2^*}{\partial s} = -1$.
$\frac{\partial SW_1^u(q_1^*)}{\partial q_1} < -\delta \frac{\partial SW_2^u(q_2^*)}{\partial q_2} \Rightarrow \frac{\partial SW^u}{\partial s} = \frac{\partial SW_1^u(q_1^*)}{\partial q_1}\frac{\partial q_1^*}{\partial s} - \frac{\partial SW_2^u(q_2^*)}{\partial q_2}\frac{\partial q_2^*}{\partial s} > 0$.
$\frac{\partial SW_1^d}{\partial s} = \frac{\partial \pi_1^d}{\partial q_1^*}\frac{\partial q_1^*}{\partial s} < 0$ and $\frac{\partial SW_2^d}{\partial s} = \frac{\partial \pi_2^d}{\partial q_2^*}\frac{\partial q_2^*}{\partial s} < 0 \Rightarrow \frac{\partial SW^d}{\partial s} < 0$. ■

An increase in upstream reservoir capacity s enables the upstream riparian to produce more electricity in the second period where the marginal social welfare is relatively higher. Thus, it releases less water in the first period and more in the second period. Unfortunately, the change in the operation mode of the hydropower plant has negative ramifications downstream because it enhances the negative externality effects of 'too little' water in period one and 'too much' in period two. Graphically, this intervention would imply a leftward shift of the $(Q_1 - s)$−curve in Figure 3.2. As mentioned previously, a trade-off between the policy objectives of regional stability and basinwide welfare will occur if upstream gains outweigh downstream losses.

5. Evaluation of policy interventions

5.1 Policy ranking

On the basis of the comparative statics derived above we have ascertained the qualitative implications of three different policy interventions. These policies are ranked below in terms of their ability to reduce the negative externality. The rank of a particular intervention depends critically on the characteristics of the upstream riparian. More specifically, whether the hydropower plant is operating at an interior or a corner solution, and, whether condition (21) is satisfied or not.

Table 3.2 Ranking of policy interventions

Policy intervention	∂SW^u	∂SW^d	Externality	Welfare
1. UP HP efficiency (IN and (21))	> 0	> 0	Reduced	Higher
2. DOWN reservoir ($IN/ST/SU$)	$= 0$	> 0	Reduced	Higher
3. UP HP efficiency (ST/SU)	> 0	$= 0$	Same	Higher
4. UP reservoir (IN/SU)	$= 0$	$= 0$	Same	Same
5. UP reservoir (ST)	> 0	< 0	Increased	Uncertain
5. UP HP efficiency (IN not (21))	> 0	< 0	Increased	Uncertain

Note: IN = interior solution, ST = storage constraint binds, SU=supply constraint binds. Policy interventions 1 and 6 include the possibilities of moving from a corner solution to an interior solution, cf. Table 3.1.

An expansion in upstream hydropower efficiency is the qualitatively most attractive policy, but only at the interior solution and provided that the hydropower production function exhibits 'sufficiently high' returns to scale, i.e. condition (21) is satisfied. If this is not the case, then the second best policy is to expand downstream reservoir capacity. Expansion of upstream storage capacity is at best ineffective, at worst, exacerbates the externality problem. An intervention in an upstream state by a multilateral development bank would therefore wisely include a policy conditionality that prevents a unilateral expansion of upstream reservoir capacity without consultation with co-riparians. We also note that if (21) is not satisfied and the hydropower plant is operating at an interior solution then expanded hydropower efficiency emerges as the least attractive policy option. Thus, while this intervention guarantees a positive upstream impact, its downstream implications are uncertain unless accurate and reliable data can be obtained about the hydropower production function and the electricity demand function. If this is not possible, a risk-averse policy maker would prefer the 'safer option' of expanded downstream capacity. Policy conditionality, if effective, may help reduce risk if the multilateral development bank can credibly persuade the upstream hydropower plant to increase first-period water release, possibly in exchange for part-financing the intervention.

While these observations give policy makers an overview of the merits and demerits of alternative interventions they are not a shortcut to a detailed cost-benefit analysis. The above ranking necessarily ignores several important aspects, including economic (e.g. cost of investment), social impact (e.g. local population displaced by dam construction) and environmental impact (e.g. soil erosion caused by flow alterations). Such aspects must obviously be considered before a final policy decision is made.[10]

5.2 Direct or indirect intervention?

Our research was also motivated by the question of whether the downstream riparian is best assisted by an MDB through upstream or downstream intervention. In our context, this reduces to a question of whether DOWN should be assisted *indirectly* by increasing upstream hydropower efficiency, or *directly,* through an expansion in downstream reservoir capacity. This comparison is relevant only at the interior solution, since upstream intervention would otherwise be ineffective or counterproductive. Both investments have the same desirable property of reallocating irrigation water from period two to period one. Letting c_α and c_r denote the investment cost of improving hydropower efficiency and constructing a new reservoir, respectively, the cost-effectiveness of the two investments can be compared. We have the following result:

[10] Construction of large dams has become a hugely controversial issue in development debates because of their adverse environmental and social impact as argued by the grassroots organisations. As a consequence, traditional dam financers, such as the World Bank, typically hesitate to support dam construction these days (see Khagram (2004) for a discussion).

Proposition 6 *Indirect intervention (hydropower investment at the interior solution) is more cost-effective than direct intervention (downstream reservoir expansion) in terms of reducing the negative externality if and only if:*

$$\frac{b}{c_\alpha \Psi}\left(\frac{\partial f(q_1^*)}{\partial q_1} f(q_1^*) - \delta \frac{\partial f(q_2^*)}{\partial q_2} f(q_2^*)\right) > \frac{1}{c_r} \tag{24}$$

Proof. This result follows directly from the expression: $\frac{\frac{\partial q_1^*}{\partial \alpha}}{c_\alpha} > \frac{\frac{\partial (q_1^*+r)}{\partial r}}{c_r}$. Where $\frac{dq_1^*}{d\alpha}$ has been derived from total differentiation of (12) and $\Psi < 0$ is the variable defined in the proof of Proposition 3 (Equation 22). ■

The intuition behind this result is most easily derived by considering the case of constant returns to scale and setting $c_\alpha = c_r$. Condition (24) becomes $\frac{\delta a_2 - a_1}{b(1+\delta)}\alpha^{-2} > 1$, i.e. indirect intervention is likely to be more attractive than direct intervention when the difference between first- and second-period electricity demand is sufficiently large.

6. Case study: Syr Darya[11]

As highlighted in the introduction, the overall aim of this chapter is to provide an analytical framework within which various intertemporal river conflicts can be examined. To illustrate the relevance of the framework we consider here the case of the Syr Darya conflict in Central Asia. This section uses the theoretical insights developed above to examine the conflict-reducing impact of a range of infrastructure project currently under way in the Central Asian region. Before doing so, however, we present a detailed introduction to the Syr Darya conflict. Apart from aiding the analysis relevant to this chapter this sub-section is intended to prepare the reader for the analysis in Chapter 4 which also features the Syr Darya conflict.

[11] The background information provided in this section draws upon EIU (2004ab), ICG (2002), IMF (2003), Moller et al. (2005), O'Hara (1998, 2000ab), SPECA (2004), USDA (2004) and World Bank (2004a, 2004b, 2004c, 2004d, 2004e).

6.1 The Syr Darya conflict: Background

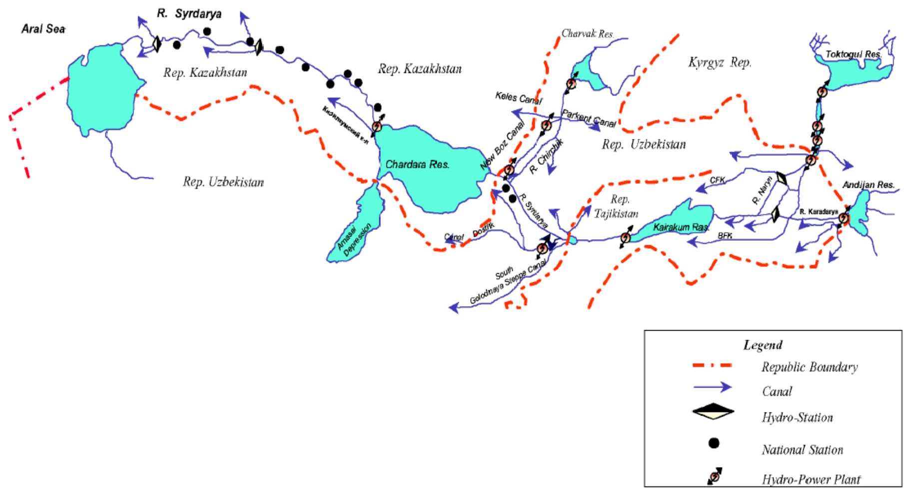
The collapse of the Soviet Union in 1991 left the newly independent Central Asian Republics (CARs) with a difficult transition task and inter-state relations that have not always been easy. Almost immediately a conflict arose over the use and allocation of the waters of the Syr Darya river with major economic and political ramifications for the region. Upstream Kyrgyzstan operates the huge Toktogul Reservoir to facilitate hydropower production while the downstream riparians, Uzbekistan and Kazakhstan, abstract water from the river to irrigate land dominated by cotton cultivation. The conflict stems from the diametrically opposed seasonal requirements for water in the different countries. Kyrgyzstan has the highest demand for electricity in the winter months thus generating an incentive to store summer inflows into Toktogul for release during the winter. In contrast the downstream countries want water to be released during the summer months so that they can irrigate their agricultural lands. Thus, the characteristics of the Syr Darya conflict are quite similar to those outlined in the theoretical model with the notable difference that there are two downstream riparians on the Syr Darya.

Water resources are of critical importance to the Central Asian economies.[12] Mountainous Kyrgyzstan has a substantial hydropower potential currently covering up to 80 percent of its domestic energy needs. Hydropower exports - through barter trade to other CARs and to Russia in cash - account for approximately ten percent of total exports with an estimated monetary value of US$ 46.8 million in 2001. In Uzbekistan, irrigated cotton production is the

[12] With a GDP of US$ 1.6bn. and a population of 5m, Kyrgyzstan is one of the poorest countries in the region. Uzbekistan is larger and slightly less poor. It has a GDP of US$ 9.7bn and a population of 25.3m. Kazakhstan is the most prosperous country in a poor region. Its GDP is US$ 24.2bn in a population of 14.8m.

most important economic activity in an agriculturally dominated economy. The country is the World's second largest cotton exporter with a market share of almost 10 percent.[13] Cotton exports totalled US$ 669 million in 2002, equivalent to 26.7 percent of total exports and around 60 percent of hard-currency export earnings. Finally, although the Syr Darya is of relatively low economic significance to the oil-dominated Kazakh economy, it is nevertheless of substantial regional importance. Cotton exports from South-Kazakhstan (one of the two provinces that the Syr Darya flows through) equalled US$ 104.6 million in 2002, or one percent of total Kazakh exports.

Map 3.1. The Syr Darya river



Note: Map not drawn to scale. Source: World Bank (2004a).

The Syr Darya, one of Central Asia's most important transboundary rivers, rises in the mountains of Kyrgyzstan. It has two main tributaries, the Naryn and the Kara Darya which merge in eastern Uzbekistan to form

[13] In addition to taking water from the Syr Darya Uzbekistan also uses significant volumes of irrigation water from the Amu Darya and the Zerefshen Rivers. The figures given in this section are for the country as a whole and not just production in the Syr Darya Basin.

the Syr Darya proper. From there the river flows into Tajikistan[14] before re-entering Uzbekistan and finally flowing in to Kazakhstan where it discharges into the remnants of the Aral Sea (see map 3.1).[15] Its annual discharge varies from 21 to 54 billion cubic metres (BCM) with a mean of 37 BCM. The flows of the Syr Darya and its tributaries are regulated by a series of reservoirs built during the Soviet period. The most important of these being the huge, multi-purpose Toktogul Reservoir built in the 1970s on the Naryn River in Kyrgyzstan. The reservoir which has an active storage capacity of 14.5 BCM was primary used to even out seasonal variations in river flows thereby maximising its irrigation potential. Toktogul also produces hydropower.

The different water requirements of the upstream and downstream republics has long been problematic.[16] During the Soviet period the decision on when and how much water was to be released from the upstream reservoir was made by the central planners in Moscow. Toktogul was operated under an irrigation regime whereby 75 percent of the annual discharge was released from the reservoir in the summer months (April-September). Releases during the winter months (October-March) accounting for the remaining 25 percent. Surplus hydropower generated in the summer was fed into the Central Asian Power System for use by the Uzbek and southern Kazakh regions. Since the Kyrgyz region lacked any significant fossil fuel resources, they were trans-

[14]Tajikistan plays only a minor, regulatory role on the Syr Darya due to its relatively low reservoir storage capacity and insignificant irrigation withdrawal rates. For this reason Tajikistan is not treated explicitly in this analysis.

[15]The tragedy of the shrinking Aral Sea is a disastrous side effect of intensive irrigation. This issue is outside the scope of this thesis.

[16]When Stalin delimited the borders of the CARs in the 1920s and 1930s he deliberately created water-rich and water-poor republics. This ensured that there was always competition between the upstream and downstream republics. Such competition worked to Moscow's advantage in two ways. First, disputes over water reinforced the national distinctiveness of the Republics, thus limiting the potential for regional cooperation which would threaten Soviet control. Secondly, as competition for water increased the Republics were forced to ask Moscow to intervene; a role it was more than willing to undertake.

ferred from the Uzbek and Kazakh republics to enable the Kyrgyz region to meet its winter demand for electricity and heat. After independence, the Soviet arrangement came under great strain. Fossil fuel prices rose quickly to world price levels and payments were increasingly demanded in hard currency. Households switched from expensive fossil fuel fired heating to electric heating, thus increasing winter electricity demand. Kyrgyzstan could not afford to import fossil fuels to generate electricity and started to increase winter discharges of water from Toktogul to meet its winter power demand and reduce summer releases to store water for the following winter. As a result, farmers in Uzbekistan and Kazakhstan faced irrigation water shortages in summer. Furthermore, the frozen waterways and canals were unable to handle the larger volume of water in winter, occasionally causing flooding on downstream territories.

In the absence of a central planner to solve this conflict, the newly independent CARs were forced to seek voluntary cooperative agreements. In February 1992 they signed the Almaty Agreement whereby the CARs agreed to the joint ownership and management of the region's water resources, while retaining sovereign control over crops and electric power obtained from them. The agreement further reiterated the need for cooperation. But this, as well as annual agreements for the release of water and exchange of electricity and fossil fuels, proved ineffective and could not arrest the increasing orientation towards power production of the Toktogul operation. Eventually in March 1998, Kazakhstan, Kyrgyzstan and Uzbekistan entered into a Long Term Framework Agreement which explicitly recognised that annual and multi-year irrigation water storage has a cost and that it needs to be compensated, either through a barter exchange of electricity and fossil fuels or in cash. However, the supply of fossil fuels generally fell short of agreed quantities and quality, forcing Kyrgyzstan to increase winter discharges. In wet years downstream states did not need the agreed volumes of summer discharges and this affected the export of electricity and the compensating quantities of fossil fuel transfers to Kyrgyzstan. The latter was thus exposed to a serious risk in meeting its winter demand for heating and power. To reduce this risk, Kyrgyzstan, on average, reduced summer releases to 45 percent of the annual discharges (and winter releases increased to 55 percent) during the 1990s.

Third-party agencies have been actively involved in resolving the conflict. The US Agency for International Development (USAID) played a critical role in brokering the 1998 Framework Agreement, for instance. The multilateral development banks (the World Bank in particular, and, to a lesser extent, the Asian Development Bank) have also been involved. Their contributions have tended to focus on facilitating political and technical dialogue between riparians with the ultimate purpose of brokering a regional agreement which maximises Syr Darya net benefits. In recent years, the prospects of reaching a regional agreement have diminished considerably as the co-riparians failed to conclude barter agreements for 2003 and 2004.[17] Increasingly disillusioned by these developments, the World Bank (2004b) recently revised its approach away from 'encouraging multi-country consensus and contractual agreements' towards 'national interventions' with the objective of 'promoting intra-state cooperation'. This change of strategy clearly increases the relevance of the type of interventions analysed in this chapter. Below we discuss a range of infrastructure projects currently under preparation (or construction) in the region and comment on their potential impact on the river conflict.

[17] The reasons for this failure are discussed in chapter 5.

6.2 The role of infrastructure projects

The Kyrgyz government, in an attempt to ensure energy self-sufficiency, is actively pursing the construction of two new hydropower plants on the Naryn cascade above the Toktogul reservoir (Kambarata I and II) that will have a combined capacity of 2,260 MW. The qualitative implications of this project, which could be completed by 2020, are broadly similar to those of increasing α in the model although it also offers the potential of electricity exports beyond the Central Asian region. The estimated cost of construction of US$ 2.3 billion, or approximately one and a half times the Kyrgyz GDP, implies that a co-financing scheme is essential. The World Bank would be an ideal facilitator and contributor to such a scheme, but it argues that the economic cost of 0.0717 US$/kwh is too high. Interestingly, downstream Kazakhstan, which is considerably richer than its co-riparians, has offered to invest in the Kambarata projects. Given the high cost of investment, this offer is likely to have been driven primarily by an intention to project a positive international image in the region (see LeMarquand, 1977). In return for this investment, the Kyrgyz authorities would have to allow Kazakh representatives to sit on the board of the Toktogul hydroelectric plant controlling downstream releases (EIU, 2004a).[18] Kyrgyz officials have so far rejected the proposal, possibly because they do not wish to surrender their sovereign right to control the water and because Toktogul represents the only source of regional influence of the Kyrgyz Republic. On the basis of the results developed in this chapter, however, it could be argued that it makes good sense for Kazakhstan to demand 'political influence' in exchange for co-financing. While the Kyrgyz Republic stands to benefit from this investment, Kazakhstan (and Uzbekistan) would benefit only if the Kyrgyz

[18]Such an arrangement is not uncommon. To illustrate, Egyptian officials are also represented at the Owen Falls Dam in Uganda (Waterbury, 2002).

Republic releases more water during summer and less during winter. As the theoretical analysis has demonstrated, an upstream riparian may only under certain conditions voluntarily choose to alter the release pattern in this manner. Recall that a positive downstream impact requires that two conditions are fulfilled: First, that the hydropower plant operates at an interior solution and secondly, that the hydropower production function exhibits 'sufficiently high' returns to scale. Unless this is the case, the co-financer must impose additional policy conditionality to make a positive downstream impact more likely.

An alternative project which aims to increase winter power generation in the Kyrgyz Republic involves the completion of a 400 MW thermal power plant, Bishkek II, by 2007. At a cost of US$ 200 million or 0.0255 US$/kwh, this project has better prospects of attracting external financial support, notably from the World Bank. A major drawback, however, is the increased Kyrgyz dependency on Uzbek natural gas. The Kyrgyz government is therefore hesitating to pursue this investment essentially because the relations between the two countries are strained, as a result of disputes over water and international borders. An increase in second-period electricity supply cannot be analysed explicitly in the model without further modifications. However, its implications for the negative externality are similar to that of a reduction in second-period hydropower demand, represented by the variable a_2.[19] Graphically speaking, an decrease in a_2 implies a downward shift in the SW_2 *curve*. By totally differentiating (12) and re-arranging we get $-\frac{dq_1^*}{da_2} = \frac{b}{\Psi}\delta\frac{\partial f(q_2^*)}{\partial q_1} > 0$ at the interior solution, i.e. the negative externality would be reduced. If the hydropower plant is operating at a corner solution

[19]This comparative static, however, does not adequately reflect the impact on upstream, and hence, basinwide social welfare.

then a decrease in a_2 has no impact on q_1^*, unless if the supply constraint becomes non-binding in which case q_1^* increases. Since the Toktogul reservoir generally operates at an interior solution, although the storage constraint is occasionally binding, the construction of Bishkek II has good prospects of promoting regional stability.

With respect to reservoir construction, a number of interesting and important developments have taken place in recent years. Most importantly, Uzbekistan has intensified efforts to increase its downstream water-regulating reservoir capacity which could provide additional storage of about 2.5 billion BCM of water downstream. As demonstrated in the model, this could absorb the equivalent additional release from Toktogul in winter and subsequently release the same quantity of water again in summer for downstream irrigation. These projects are self-financed, although the Uzbek government did apply for financial assistance from USAID and the US Department of Agriculture (USDA). This application was later withdrawn, however, because the Uzbek government did not agree to conduct an environmental impact assessment.[20] Finally, the Kazakh government is also contemplating the construction of a reservoir (Koksarai) west of Shymkent. This reservoir would cost US$ 200 million and have an active storage capacity of 3 BCM. The proposed increment to the combined active storage capacity of Uzbekistan and Kazakhstan may, according to some observers, be sufficient to eliminate the seasonal conflict.[21] Whether this would indeed be the case depends partly on the behavioural response of the co-riparians - an issue we take up in Chapter 4.

A complete ranking of the four infrastructure projects discussed above, akin to that presented in section 5.1, would be beyond the scope of this

[20]Personal communication, Mr Ken McNamara, USAID, Almaty 14/12/04.

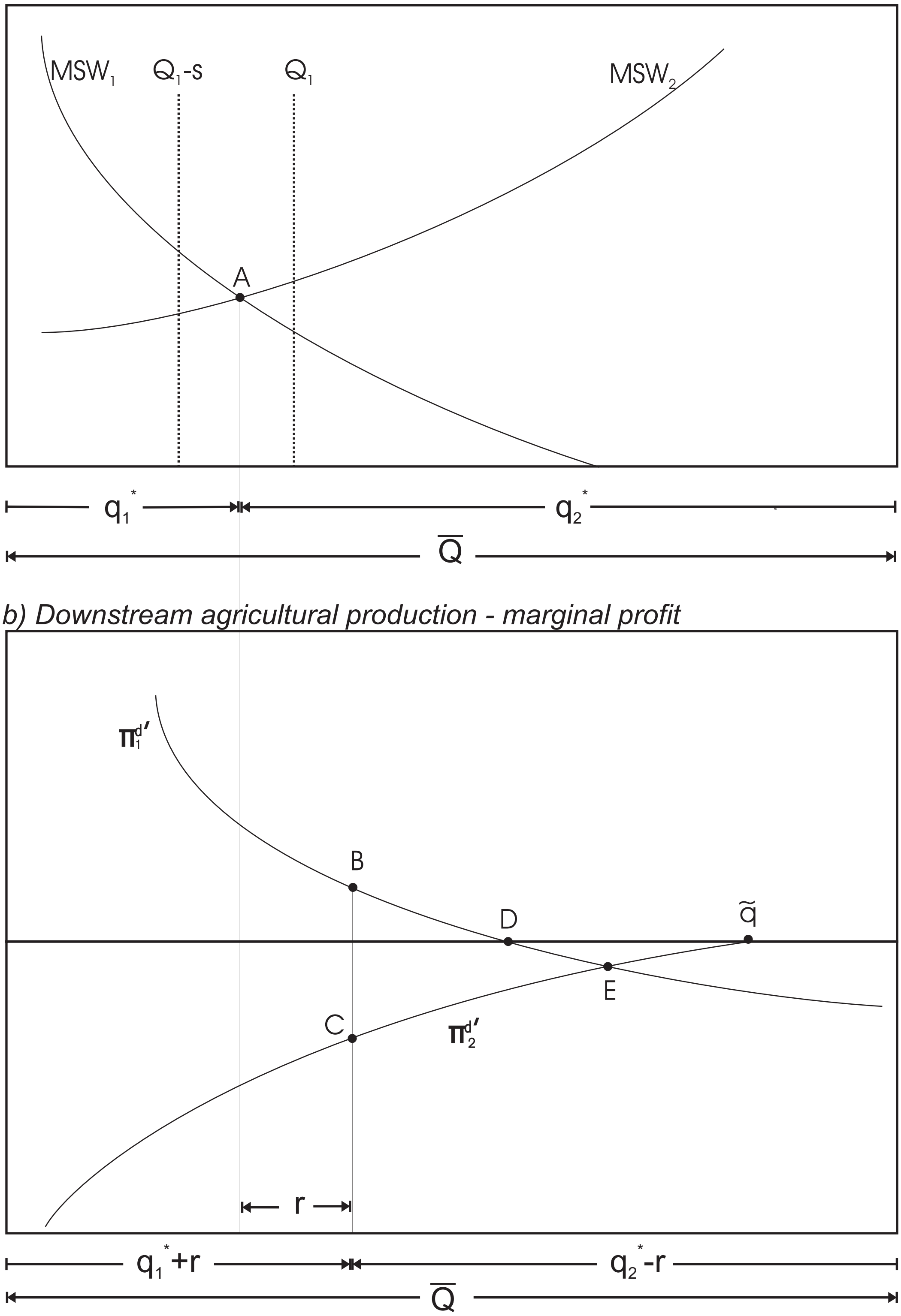
[21]Personal communication, Mr Leonid Dmitriev, Kazgiprovodhoz, Almaty 15/12/04.

chapter. Nevertheless, in conclusion, we do make a few partially comparative remarks. Based on the information available, the construction of the Bishkek II thermal power plant does emerge as one of the most attractive investments due its relatively low costs and good prospects for reducing the externality. Given their high relative cost, the Kambarata projects appear less attractive than the theoretical analysis would suggest, even if the Kyrgyz government should agree to surrender absolute political control over Toktogul. The merits of constructing downstream reservoirs, the Uzbek ones in particular, are analysed in-depth in the subsequent chapter.

7. Conclusion

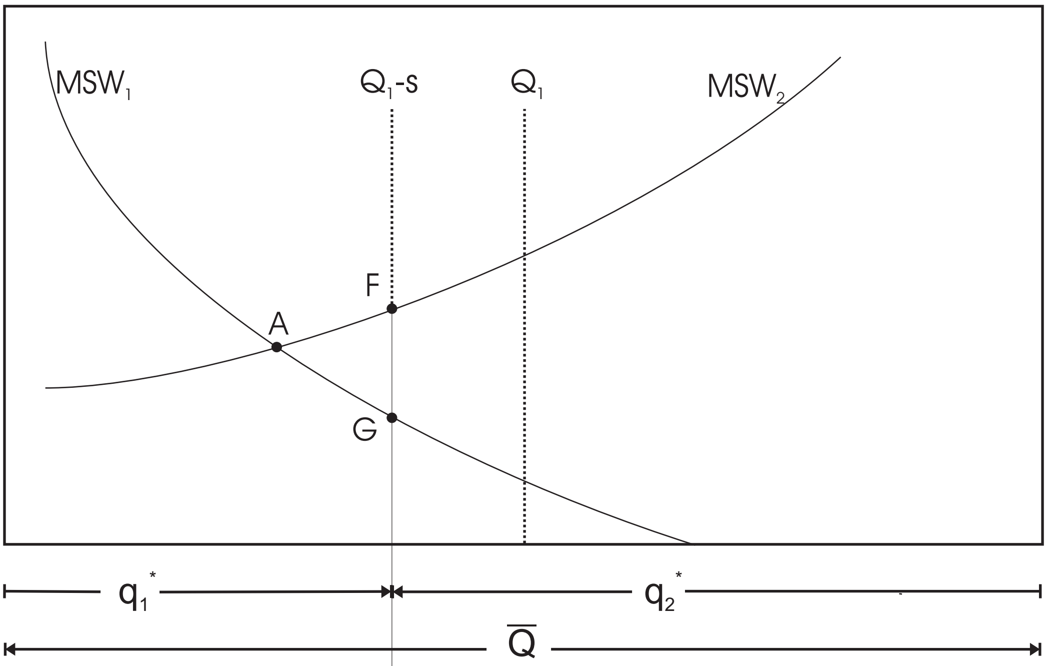
In this chapter we have analysed the potential conflict of interest embodied in upstream hydropower use and downstream irrigation use on a transboundary river. More specifically, we addressed the question of whether there is a role for multilateral development banks in reducing regional tension and improving basinwide social welfare. We identified two Pareto-improving policy interventions, both of which have the beneficial effect of reducing the unidirectional, negative externality caused by upstream regulation of the natural river flow. Investment in upstream hydropower efficiency is one such intervention, but it requires that the MDB (or any other co-financier) can credibly enforce policy conditionality. This is necessary, because the upstream riparian may face incentives which could undermine the positive impact on the downstream riparian. The MDB should reach an agreement with the upstream riparian about the amount by which first-period release must increase, although care should be taken not to demand too large increases in first-period release since otherwise the project might reduce upstream welfare. In addition, in exchange for co-financing, the upstream riparian must also agree not to expand its reservoir capacity since this increases the negative externality. The second type of intervention, expansion of the downstream reservoir capacity, involves less risk. This reduces the need for conditionality, but brings benefits only to the downstream riparian. The chapter also argued that the presence of a unidirectional externality presents policy options which could potentially be attractive. More specifically, we established the conditions under which an MDB could more effectively assist a downstream client through upstream intervention. Similar options are available on other transboundary rivers and should be explored further.

Figure 3.1 Noncooperative equilibrium (interior solution)
a) Upstream hydropower production - marginal social welfare



b) Downstream agricultural production - marginal profit

Figure 3.2 Noncooperative equilibrium (storage constraint binding)
a) Upstream hydropower production - marginal social welfare



b) Downstream agricultural production - marginal profit

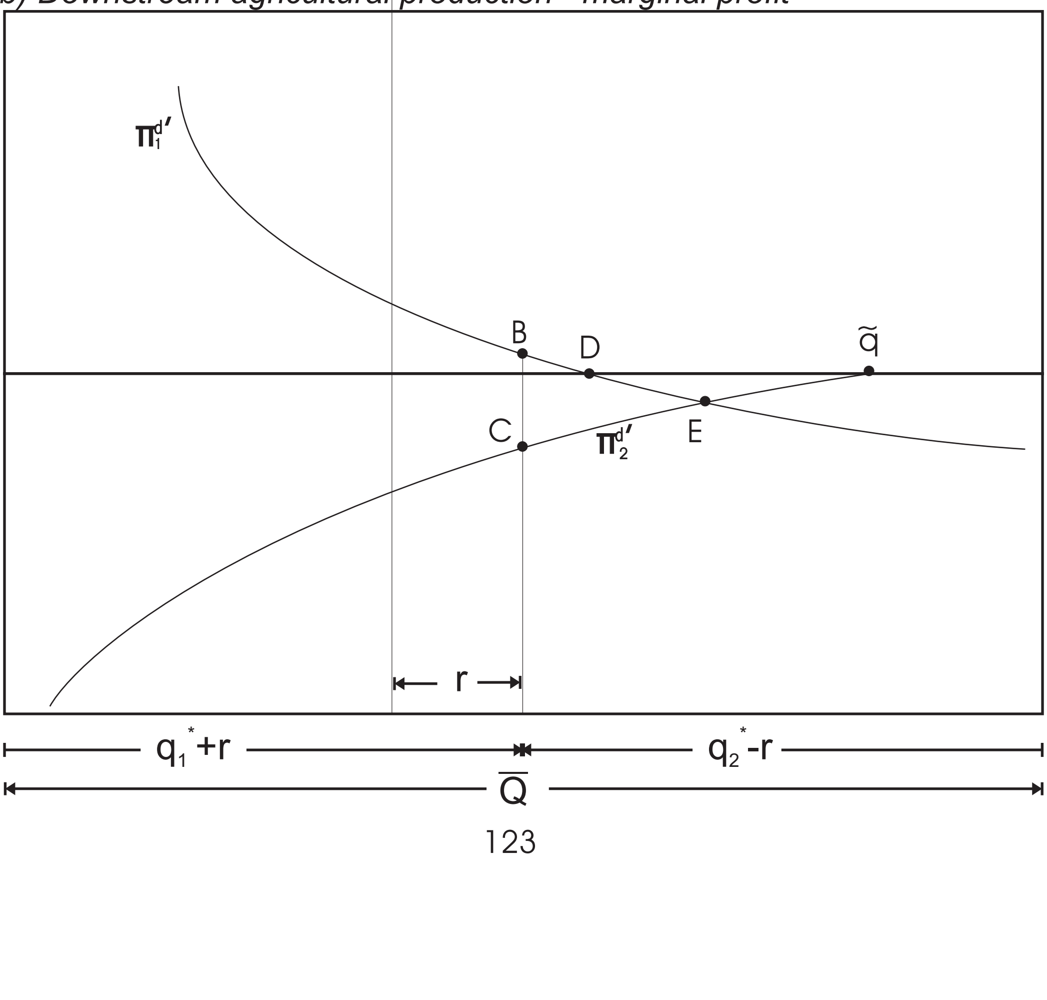
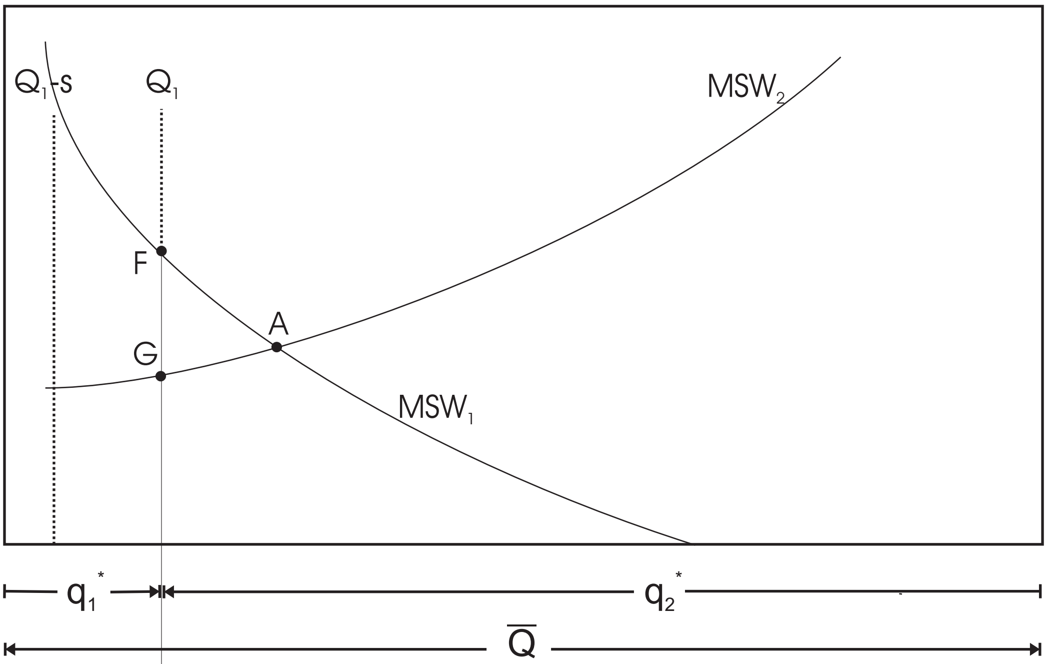


Figure 3.3 Noncooperative equilibrium (supply constraint binding)
a) Upstream hydropower production - marginal social welfare



b) Downstream agricultural production - marginal profit

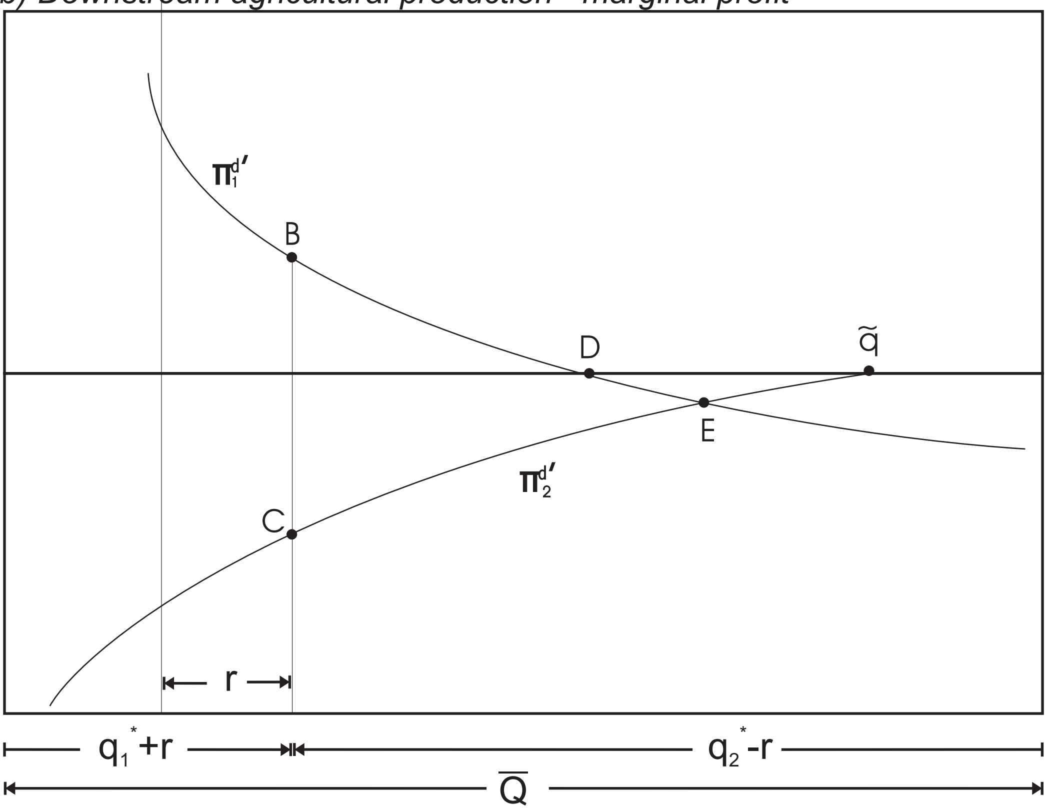
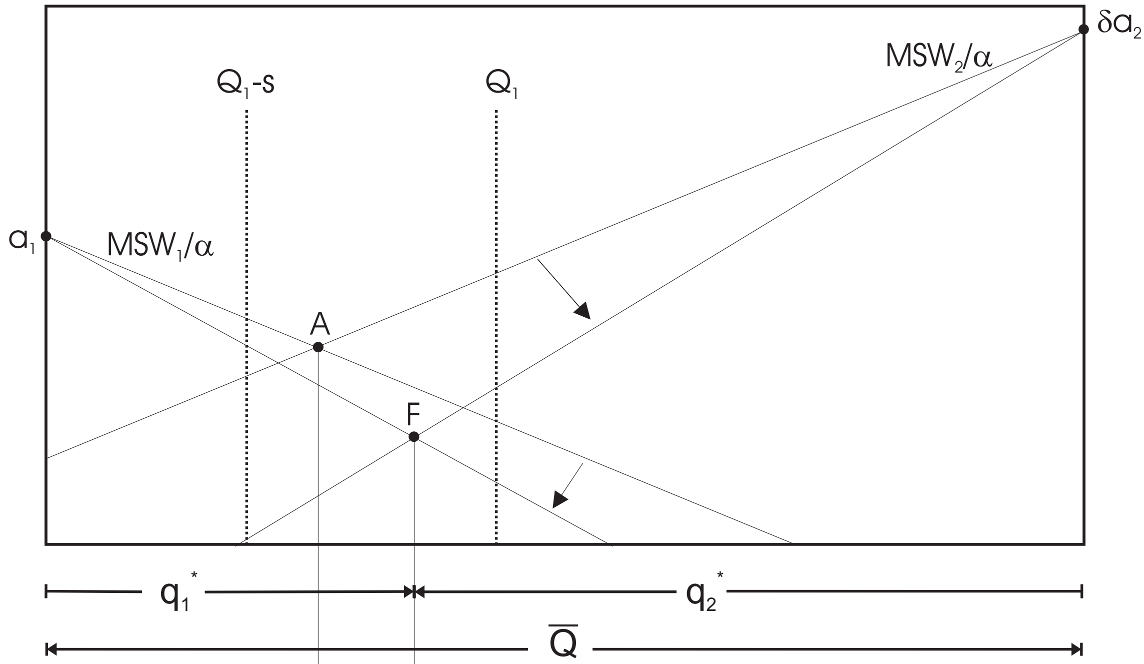


Figure 3.4 Expanded hydropower efficiency (interior solution and CRS)
a) Upstream hydropower production - marginal social welfare



b) Downstream agricultural production - marginal profit

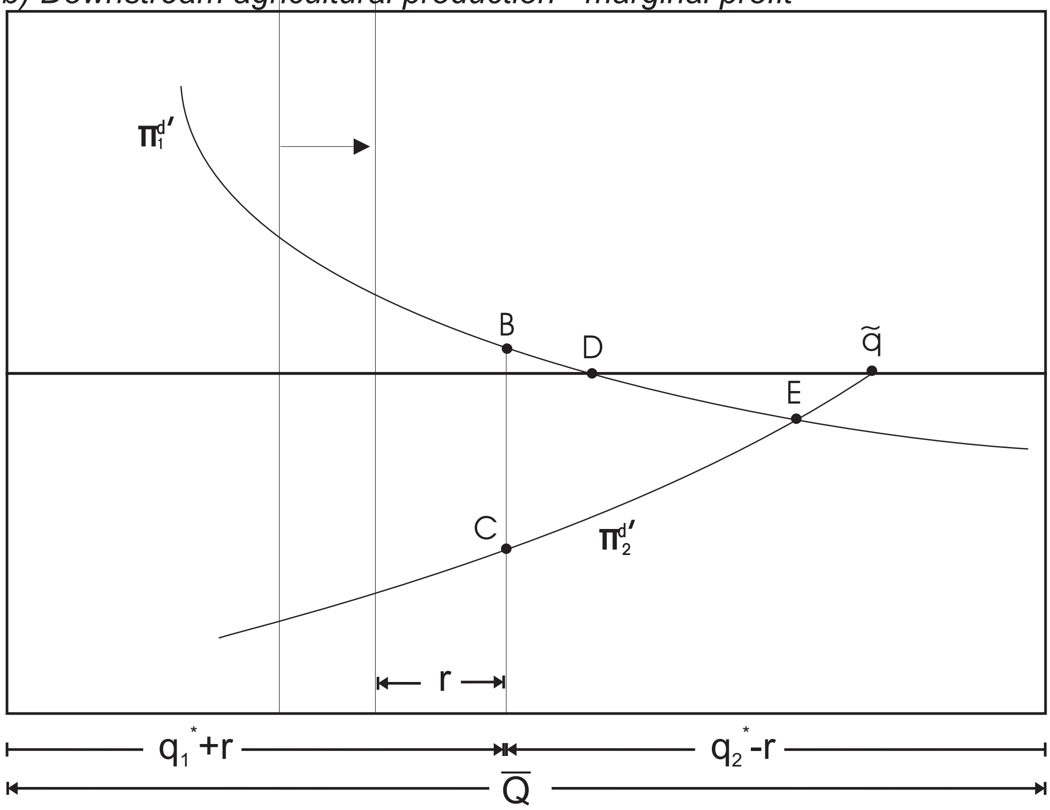
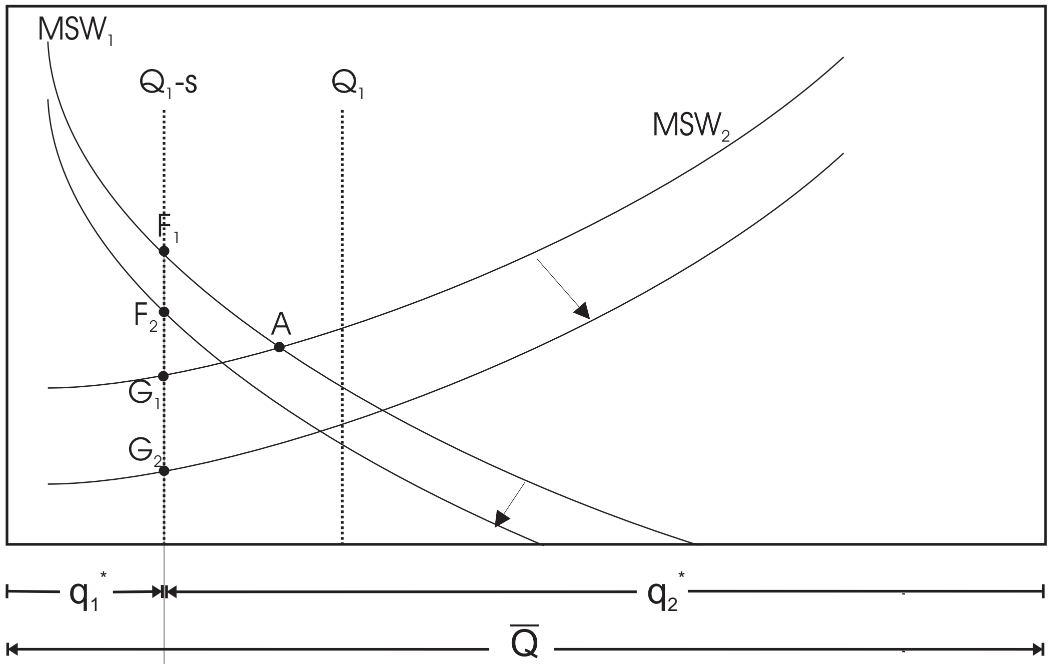


Figure 3.5 Expanded hydropower efficiency (supply constraint binding)
a) Upstream hydropower production - marginal social welfare



b) Downstream agricultural production - marginal profit

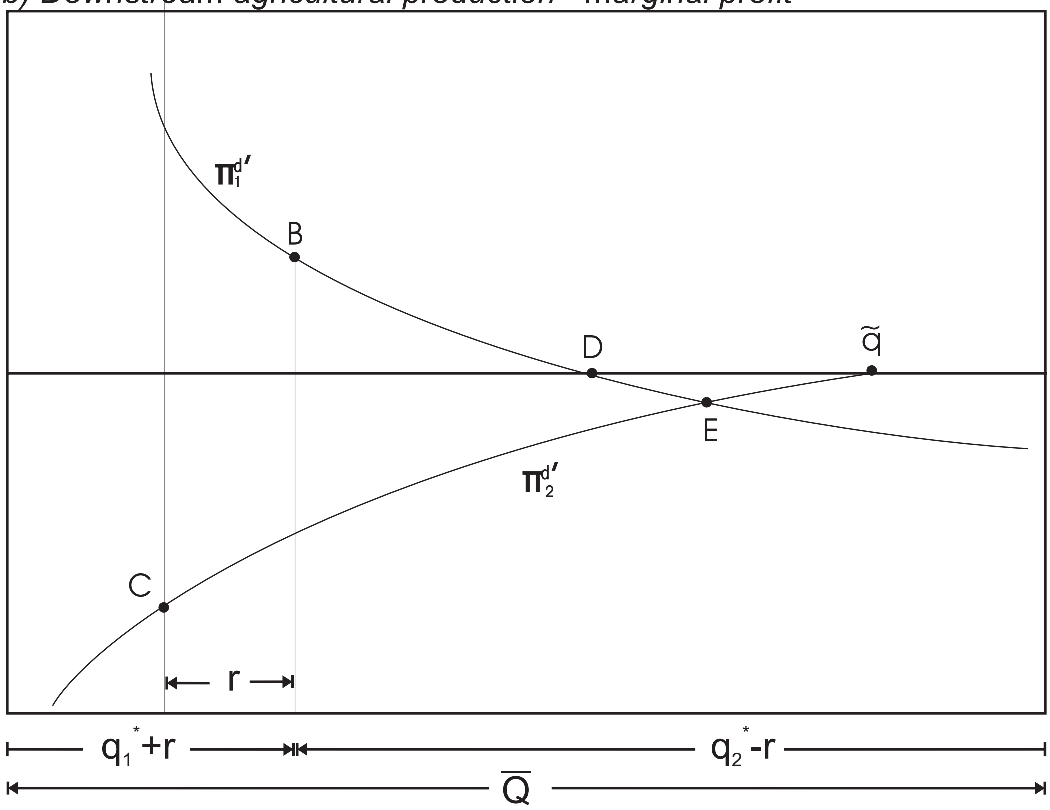
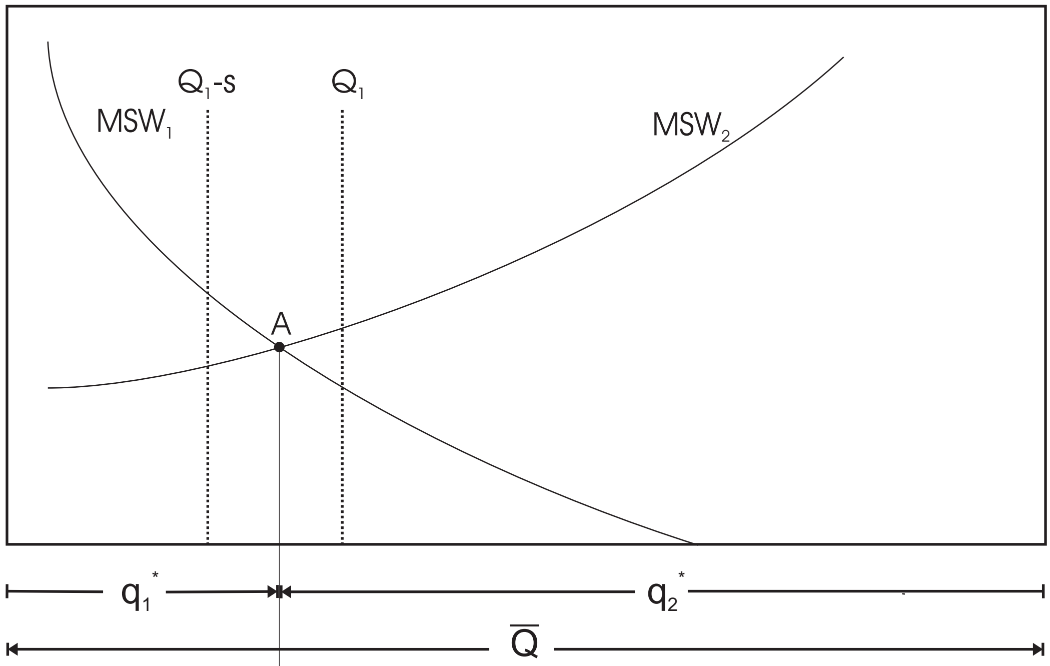
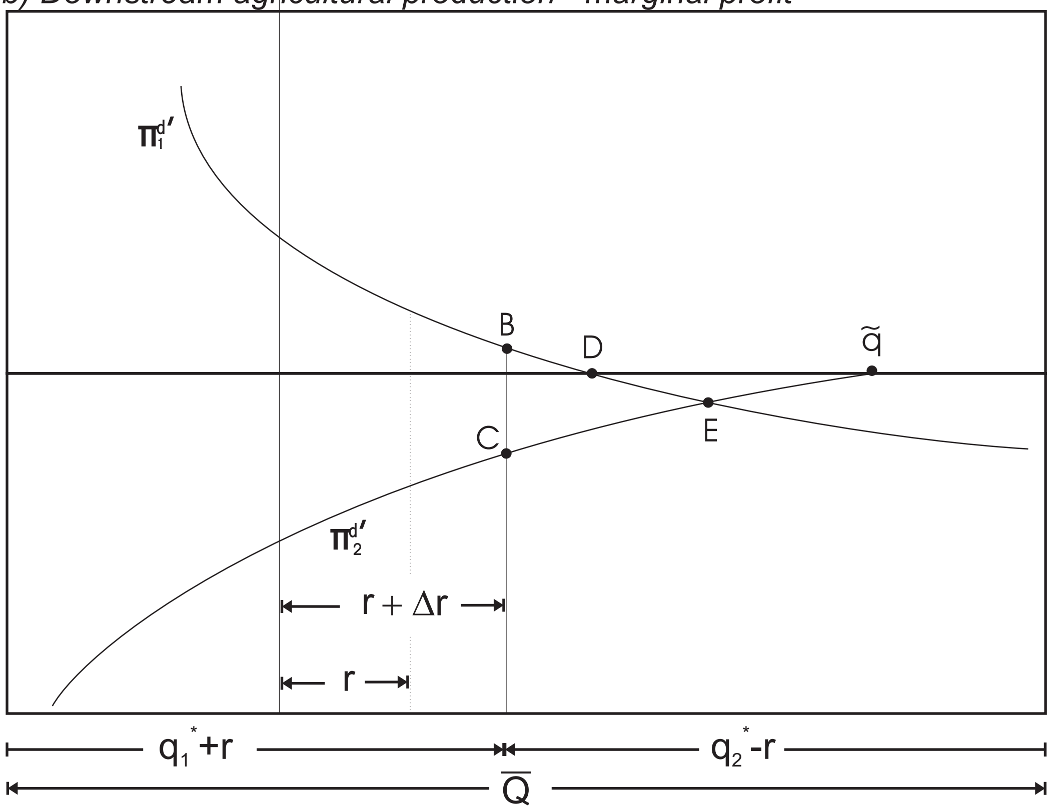


Figure 3.6 Expanded downstream reservoir capacity

a) Upstream hydropower production - marginal social welfare



b) Downstream agricultural production - marginal profit



Appendix E. Central Asia field trip

Chapters 3 and 4 were informed by a field trip to the Central Asian Republics of Kyrgyzstan and Kazakhstan conducted on 4-17 December 2004. In addition to the author of this thesis, the study team consisted of Lecturer Klaus Abbink (School of Economics) and Professor Sarah O'Hara (School of Geography)[1]. The trip was generously funded by the Asia Fund of the University of Nottingham. Its objective of was twofold: 1) To collect primary data otherwise inaccessible outside the region; 2) To assess the preferences and motivation of policy makers in the region. To meet these objectives we conducted semi-structured interviews with key stakeholders, including government representatives, development partners and academia (see Table E.1 for a list). The preparation for this trip was complicated by the fact that we did not have any professional or personal contacts in the countries we intended to visit. This made it difficult and cumbersome to secure entry visas. A planned visit to Uzbekistan was cancelled for this reason. In preparation we drew up a list of potential interviewees on the basis of reports and other material available on the internet and secured appointments via email and telephone. Fortunately, the trip itself went a lot smoother than its preparation. We successfully arranged and completed 16 interviews, most of which proved highly valuable. In terms of tangible outputs we obtained the following essential background information: a) The World Bank (2004a) Water and Energy Nexus Report; b) Flow data at the Toktogul reservoir compiled by JSC Kyrgyzenergo, and; c) Background notes detailing the progress of Uzbek reservoir construction. The most substantial intangible outcome of

[1]Unfortunately Sarah O'Hara was unable to participate in the trip.

the visit was the way in which the research objectives changed in light of our consultation with stakeholders. The original objective was to examine the effects of climatic change (and thus changes in water availability) on riparian cooperation. However, during our visit we were made aware of a more interesting development in the region, namely the construction of reservoirs in Uzbekistan and Kazakhstan. Since our ability to influence current policy debates in the region was an important objective of the research we decided to change our focus in this direction.

Table E.1.a List of stakeholders met in Bishkek

Date	Name	Position	Organisation
6/12	Natalia Charkova	Operations Officer, Infrastructure/Energy.	World Bank
6/12	Peter Graham	Project Manager	Tariff Policy and Utility Reform Project (DFID)
7/12	Bakyt Makhmutov	National Program Officer	Swiss Development Cooperation
7/12	Dyushen Mamatkanov	Director, Institute for Water Problems and Hydroelectric Power	Kyrgyz Academy of Science
7/12	Alexi Zyryanov	Engineer	JSC Kyrgyzenergo
7/12	Zharas Takanov	Programme Officer, Environment	United Nations Development Program
8/12	Kydykbek Beishekeev	First Deputy General Director	Water Economy Dept. Ministry of Agriculture and Water
8/12	Akylbek Tumenbaev	Vice Director, Executive Member	State Energy Agency
8/12	Cholpen Mambetova	Regional Cooperation Specialist	Asian Development Bank

Table D.1.b List of stakeholders met in Almaty

Date	Name	Position	Organisation
12/12	Tim Hannan	TA	United Nations Development Program
14/12	Paul Shaminder	TA	Asian Development Bank
13/12	Simon Kenny	Regional Program Co-ordinator	World Bank
15/12	Igor Steinberger	Engineer - hydrologist	Kazgiprovodhoz
15/12	Leonid Dmitriev	Chairman	Kazgiprovodhoz
15/12	Aliya Satubaldina	Project Manager	European Union

Chapter 4. The Syr Darya River Conflict - An Experimental Case Study[1]

In the previous chapter we adopted a noncooperative approach to hydropower-irrigation conflicts in general, and to the Syr Darya conflict in particular. We argued that the failure of riparians to conclude barter agreements in recent years has increased the relevance of externality-reducing interventions in what is presently a noncooperative environment. To some extent, this approach rests on the assumption that the barter agreement system which emerged in the 1990s has ultimately failed and that riparians will not seek to cooperate over water and energy in the future. While this assessment may well reflect current sentiments among riparian governments and international agencies it is also necessarily a short-sighted and static view. In comparison, this chapter is based on the premise that the policies and approaches of regional stakeholders may, for various reasons, change in the future. A cooperative approach is adopted in which the Syr Darya conflict is framed as a *trust game*. We examine whether cooperative outcomes emerge in a laboratory experiment with pay-off schemes derived from real data from the region. The aim of this exercise is to gain insights about the possible impact of Uzbek reservoir construction on cooperative behaviour on the Syr Darya.

[1]The analysis contained in this chapter draws upon a paper co-written with Klaus Abbink and Sarah O'Hara. The chapter builds on information presented in the case study analysis of chapter 3 (section 6). The reader is therefore advised to consult this text first.

1. Introduction

The failure of the Central Asian republics to conclude annual agreements in 2003 and 2004 can to some extent be attributed to above-average precipitation in those years.[2] More fundamentally, however, the collapse of the barter agreement system was due to a change in the Uzbek position towards a decisive unilateral stance. The most explicit expression hereof has been the decision to construct a series of re-regulating reservoirs. Uzbekistan is currently proceeding with the design of new water storage capacity of the Karamansay reservoir (0.69 BCM), as well as constructing the Razaksay (0.65-0.75 BCM) and Kangkulsay (0.3 BCM) reservoirs. These facilities together with the natural reservoir in the Arnasai depression (0.8 BCM) will provide additional storage of about 2.5 BCM.[3]

The impact of the Uzbek decision has been substantial for Kyrgyzstan and Kazakhstan. The Kyrgyz challenge is that even when the reservoirs are operated in the noncooperative 'power mode', hydropower production is insufficient to cover domestic winter electricity demand. In the absence of a regional agreement, the Kyrgyz government must aim to cover this deficit through a combination of domestic reforms and construction of new power-generating facilities - both of which represent daunting challenges. Kazakhstan, which had otherwise pursued a cooperative strategy towards

[2]Recall from chapter 3 that wet years reduce the downstream countries' need for water released from Toktogul and thus affects their willingness to compensate Kyrgyzstan for its additional discharge.

[3]Recognising the strategic importance of these reservoirs, the Uzbek government gave little away about its intentions and actions to co-riparians and donors. To illustrate, the World Bank only learnt about these reservoirs when representatives from a visiting, albeit unrelated, mission were taken to one of the construction sites. (Personal communication with Simon Kenny, World Bank, Almaty, 13 December 2004).

Kyrgyzstan, has had to come to terms with the fact that this strategy ultimately depended on Uzbek willingness to cooperate. Since the latter was not forthcoming, Kazakhstan has shown renewed interest in the construction of re-regulating reservoirs on its own territory. As mentioned in Chapter 3, plans exist for constructing a 3 BCM reservoir (Koksarai) near Shymkent at a cost of US$ 200 million, although no final political decision has been made to initiate construction.

To what extent do the new Uzbek reservoirs represent the long-awaited solution to the conflict? Several issues need to be addressed to answer this question. First, the fact that the cooperation record has been poor so far does not imply that this will be the case in the future. The March 2005 revolution in Kyrgyzstan and the forthcoming retirement of senior government officials in all the riparian states bring new players to the negotiation table.[4] It is possible that new players will act differently, making expensive reservoir construction obsolete. So the question arises whether the previous failure of cooperation is systematic or idiosyncratic. In other words, has cooperation failed because this is inherent to the problem, or because the decision makers in charge have been incapable of working together? Secondly, the capacity of the proposed new reservoirs is limited. While they mitigate the costs of uncoordinated behaviour, they do not eliminate the need for cooperation to maximise basinwide efficiency. If incentives to cooperate get even worse, not much may be gained.

The aim of this chapter is to address these questions. We designed a

[4]Many of the most senior officials in the water sector are near or have passed the official age of retirement.

model that estimates the economic impact of the new reservoirs on the riparian economies. In doing so we had to tackle two difficulties. First, the model needed to trace the real economic situation as accurately as possible, despite notoriously limited data availability. We collated data from a variety of sources and from a series of interviews with experts on location - government officials and representatives of donor agencies - to make estimates as informed as possible. Secondly, costs and benefits from the new reservoirs crucially depend on the ability of decision makers to cooperate, which is a behavioural issue. To examine this, we introduce a novel approach to the analysis of transboundary river conflicts. We used a model estimated from real data and designed a game that resembles the strategic environment in the Syr Darya river conflict. Controlled laboratory experiments were then conducted to study the likelihood of future cooperation. We re-create an analogous, although stylised, set of conditions where we can analyse the strategic environment of the Syr Darya conflict in different future scenarios. In two separate treatments, we simulate the economic scenario with and without the new Uzbek reservoirs under three representative hydrological regimes.

We find that Uzbek reservoirs do not represent the solution to the river conflict. Maximisation of basinwide efficiency continues to require riparian cooperation. Though they alleviate Uzbekistan's problems in low-water years the reservoirs are not sufficiently large to achieve Uzbek self-sufficiency in irrigation water. Moreover, the experimental results reveal that cooperation is indeed very hard to establish in the present strategic environment, especially in low-water years. Thus failure to cooperate should not solely be attributed to the unwillingness or incapability of current decision makers. Finally, we find that reservoirs improve the likelihood of cooperation only marginally.

The remainder of this chapter is organised as follows: Section 2 briefly reviews the relevant literature. Section 3 develops the model and its estimation. Section 4 describes the experimental design. Section 5 presents the experimental results. Section 6 concludes.

2. Literature review

Arguably, the central problem for the interstate agreements has been one of trust. Short of military action there are no means to enforce a contract between sovereign republics who are generally suspicious of each other. If Kyrgyzstan discharges additional water in summer, it must trust the downstream riparians to deliver fossil fuels in winter, otherwise it will face a severe problem of not being able to meet its energy demand in the subsequent winter. Hence, it incurs a temporary loss and relies on compensation from the downstream neighbours - without being able to enforce the reward. Uzbekistan and Kazakhstan, on the other hand, are less inclined to pass fossil fuels to Kyrgyzstan if they fear that the latter will deviate from the agreement by releasing large volumes of water in winter. The Syr Darya conflict therefore has the nature of a trust game, reminiscent of those that have been extensively studied in the experimental economics literature (e.g. Fehr *et al.* (1993), Berg *et al.* (1995), Dufwenberg and Gneezy (2000), Abbink *et al.* (2000), Fershtman and Gneezy (2001), Gächter and Falk (2002)).[5]

[5]Irlenbusch (2005a, 2005b) reports results from a slightly more complex game, but with

In trust (or reciprocity) games a first mover can send money to a second mover, who in turn can voluntarily reward the trustor by sending money back. The games are constructed such that by doing so, both players would be better off with respect to final payoffs, but in equilibrium no trust and no rewarding would be exhibited. Contrary to the theoretical prediction, the common finding of these studies is that first movers often show trust by passing money, and second movers often reward them by sending money back, even if the game is played only once and under completely anonymous conditions. In light of these findings the poor record of cooperation in the Central Asian river conflict looks surprising. However, the games in the literature use artificial payoff structures which differ from those underlying the 'Syr Darya river game', and involve only two players.[6]

The literature reviewed in Chapter 3 remains relevant for the analysis presented here, including our own contribution. In Chapter 3 we adopted a noncooperative analysis of the Syr Darya conflict by examining the conflict-reducing impact of a range of infrastructure projects. Construction of downstream reservoirs was found to reduce conflict by reducing the impact of the negative externality caused by upstream regulation of the natural river flow. Basinwide welfare increases directly as a consequence of the increase in downstream welfare. In comparison, the World Bank (2004a) takes a cooperative approach to the Syr Darya conflict by examining how side payments can be used to attain efficient outcomes. It demonstrates that net Syr Darya

the non-binding contracts that characterise the situation on the Syr Darya.

[6]With the notable exception of Dufwenberg and Gneezy (2000) the standard assumption in the literature is that the amount sent by the first mover is trippled by the experimenter and handed to the second-mover.

basin benefits are substantially higher when the Toktogul reservoir is operated in an 'irrigation mode' than under the 'power mode'. Developed before the collapse of the barter agreements, the report recommends a number of ways in which the existing regional cooperation mechanisms could be improved. These include *inter alia* proposals to use multi-year rather than annual agreements, a 'letter of credit'-scheme, and, the introduction of a monitoring and guarantee mechanism to ensure compliance with agreed obligations. Reception of these proposals by riparian governments, however, was largely negative (see World Bank 2004b for details).

Building on the work contained in World Bank (2004a) this chapter also explores the scope for cooperation in the Syr Darya conflict. Using similar assumptions about key economic variables we develop a more general economic model which is then used for laboratory experiments.[7] The major difference between our model and that in World Bank (2004a) is threefold: The first relates to different assumptions about water availability. We assume an average annual water outflow of around 13 BCM compared to 9 BCM used in the World Bank report. The latter figure has been discredited (and World Bank (2004b) concedes) because it is based on a non-homogenous data set for the 1911-2000 period compiled by BVO Syr Darya (a basinwide agency located in Tashkent) which under-records inflow since 1975. Secondly, the Bank report compares two different water allocations (irrigation and power mode) while we generalise the analysis by considering a continuum of allocations

[7]Experiments on games informed by real-world data are surprisingly rare. Some have been carried out in the course of consulting projects for spectrum auctions, but their results are often not published due to confidentiality concerns of the clients (an exception is Abbink *et al.* (2002)). In a different context, Güth *et al.* (2003) parameterise a bargaining game with data from a case study on the film industry.

within the historically relevant range. Thirdly, and as a consequence, we have introduced a range of capacity constraints to provide a realistic treatment of extreme scenarios. The subsequent section develops the model and estimates its parameters.

3. The Model

Before formulating the economic model we had to make some choices. First, since Uzbek reservoirs are at an advanced stage of construction we decided mainly to focus on these in the experiment, and not to include the Kazakh reservoirs because the government has not yet approved their construction. Further, we neglect the impact of winter flooding, though this is a much-discussed concern of the Uzbek and Kazakh governments. Reliable estimates of the damages of flooding proved impossible to obtain, but there are some indications that the economic costs of flooding are relatively small. The most substantial damage seems to be political, since flooding is a very visible event likely to stir public anger.

3.1 Payoff Functions

Kyrgyzstan

Electricity output in the summer season of year t, Y_t^s MWh, is given by the hydropower production function (for ease of notation we suppress the time variable t from this point onwards):

$$Y^s = \alpha q_{ky}^s \tag{1}$$

where $\alpha > 0$ is a productivity parameter and q_{ky}^s BCM is the Kyrgyz water release from the Toktogul Reservoir in the summer season. Kyrgyzstan must cover a domestic energy demand of E^s MWh in summer.[8] Due to technical losses, the gross power generation necessary to cover this demand is given by $\frac{E^s}{\nu^s}$ MWh, where $\nu^s \in [0;1]$ is an efficiency parameter. The Kyrgyz domestic energy deficit in the summer season, D^s MWh, is defined as follows:

$$D^s = \frac{E^s}{\nu^s} - \alpha q^s_{ky} \tag{2}$$

To cover this deficit Kyrgyzstan operates its thermal power plant, Bishkek I, fuelled by imported natural gas and coal. Bishkek I has a short-run marginal cost of C_I US\$/kWh and an operating capacity of K MWh. If the domestic energy deficit is larger than the capacity of Bishkek I, a second thermal power plant, Bishkek II, is operated. It has a short-run marginal cost of $C_{II} > C_I$ and an assumed unlimited capacity within the relevant range of the model. Conversely, in the case of a domestic energy surplus, Kyrgyz electricity is exported to Uzbekistan and Kazakhstan. Electricity payments are not modelled explicitly, but may implicitly constitute a part of the side payments between countries. The Kyrgyz gross payoff during summer (excluding side payments), measured in million US\$, is given as follows:

$$\begin{aligned} \pi^s_{ky} &= -MAX\{C_I D^s, 0\} \; for \; D^s \leq K \\ \pi^s_{ky} &= -C_I K - C_{II}(D^s - K) \; for \; D^s > K \end{aligned} \tag{3}$$

In winter, hydropower is produced using the same constant-returns-to-scale technology as expressed in (1). Denoting all seasonal variables by

[8]The specification of a constant electricity demand differs from the model in chapter 3 where demand was a function of the electricity price. In this chapter we assume that the Kyrgyz government is bend on covering a fixed electricity demand to avoid political protests during winter.

superscript w, the Kyrgyz domestic energy deficit in winter is given by:

$$D^w = \frac{E^w}{\nu^w} - \alpha q^w_{ky} \tag{4}$$

A domestic energy deficit is covered by the Bishkek I and II thermal power plants in the same manner as in the summer period. In case of a domestic energy surplus, Kyrgyzstan is assumed to have no export markets in the winter period.[9] The Kyrgyz gross winter payoff is written:

$$\begin{aligned} \pi^w_{ky} &= -MAX\{C_I D^w, 0\} \; for \; D^w \leq K \\ \pi^w_{ky} &= -C_I K - C_{II}(D^w - K) \; for \; D^w > K \end{aligned} \tag{5}$$

Denoting the side payment received by Kyrgyzstan from Uzbekistan for its water and electricity services by S_{ky} the Kyrgyz total payoff (in million US$) is:[10]

$$\pi_{ky} = I_{ky} + \pi^s_{ky} + \pi^w_{ky} + S_{ky} \tag{6}$$

The intercept of the payoff function, I_{ky}, is not specified and can be chosen arbitrarily, since our economic analysis only aims at comparing payoffs in different scenarios.[11] If it is omitted, then a zero Kyrgyz payoff corresponds to a situation in which the domestic energy deficit is non-negative in both seasons.

[9]Since Kyrgyz winter electricity exports are associated with additional water releases in winter, downstream countries would effectively be importing a negative externality in addition to electricity if winter exports were allowed in the model.

[10]In the model, Kazakhstan does not issue a side payment directly to Kyrgyzstan (as it does in reality), but rather to Uzbekistan. This is done to ensure that Uzbekistan has an incentive to release water to Kazakhstan. In reality, the Uzbek incentive to release water to Kazakhstan is mainly political, i.e. Uzbekistan does not want to upset international relations with its downstream neighbour.

[11]In the experiment, the intercept values of all three payoff functions were set at an appropriate level (see section 4.2 for details).

Uzbekistan

Uzbek payoff relates only to the summer period and can be divided into two components: irrigation and electricity. Uzbek irrigation supply for cotton production is available from two main sources: summer water released by Kyrgyzstan, q^s_{ky}, and water available in the new Uzbek reservoirs, R, which are filled in the winter period where $R < q^w_{ky}$. Uzbekistan releases some of this water to Kazakhstan, $q_{uz} \leq q^s_{ky} + R$, and withdraws the residual, $q^s_{ky} + R - q_{uz}$, for cotton production. Of its total water withdrawals, only a share $0 \leq \beta_{uz} \leq 1$ is used for cotton irrigation with the residual $1 - \beta_{uz}$ used for other crops, the production of which is assumed non-profitable.[12] The economic value of irrigation water for cotton production is P US$/KCM. While we have not explicitly modelled an agricultural production function, it would be unrealistic to expect that marginal benefits are always positive, especially for high levels of water input. It is therefore assumed that if irrigation input reaches an optimum point, O_{uz}, then the marginal value of irrigation water is zero.[13] Uzbek gross irrigation benefits (in million US$) are thus written:

$$P\beta_{uz}MIN\{(q^s_{ky} + R) - q_{uz}, O_{uz}\} \tag{7}$$

We now turn to the Uzbek electricity benefits. Suppose that Kyrgyzstan

[12] This simplifying assumption implies that agricultural benefits of irrigation are limited to the cotton sector. World Bank (2004a) employs a similar assumption.

[13] Clearly this represents a substantial simplification of a more realistic cotton production function with diminishing returns to scale (and possibly a negative marginal product). The practical significance of this for the experimental results, however, seems neglible. A considerable amount of time was devoted to estimating representative production functions on the basis of available data. The implied economic value of water of these calculations (22-177 US$/m^3 or 57-146 US$/m^3 depending on the approach), however, was much higher than the price quoted in the World Bank report (20-50 US$/m^3) (see chapter 5 section 4 for details). The estimations were not considered sufficiently reliable and therefore not used in the analysis.

runs a domestic energy surplus in summer and that a share of this surplus is exported to Uzbekistan. In this case Uzbekistan can import electricity at a lower cost than were it to produce this electricity domestically. The gross benefit of electricity imports is valued at the opportunity cost of operating a coal fired power plant in Uzbekistan, the short-run marginal cost of which is C_{uz} US$/kWh. After accounting for the technical loss of transmitting electricity through the Uzbek power grid, electricity available for import equals $-\rho D^s$, where $0 \leq \rho \leq 1$ is an efficiency parameter. Due to technical constraints in the transmission grid, electricity exports cannot exceed X MWh. The exported electricity is shared between Uzbekistan and Kazakhstan. Denoting Uzbekistan's share by $0 \leq \gamma \leq 1$, its electricity benefits are:

$$MAX\{C_{uz}\gamma\rho MIN\{-D^s, X\}, 0\} \tag{8}$$

Denoting the side payment from Kazakhstan to Uzbekistan by S_{uz}, we can write the Uzbek payoff as follows:

$$\begin{aligned} \pi_{uz} &= I_{uz} + P\beta_{uz} MIN\{(q^s_{ky} + R) - q_{uz}, O_{uz}\} \\ &\quad + MAX\{C_{uz}\gamma\rho MIN\{-D^s, X\}, 0\} + S_{uz} - S_{ky} \end{aligned} \tag{9}$$

As with the Kyrgyz payoff function the intercept does not have any meaningful interpretation. If intercept and side payments are omitted and there are no reservoirs ($R = 0$) and then a zero payoff corresponds to a situation in which Kyrgyzstan releases no water at all in summer.

Kazakhstan

Like Uzbekistan, Kazakhstan also benefits from irrigation and electricity in the summer period. The Kazakh payoff-function is similar to that of

Uzbekistan and is given by the following expression (where Kazakh variables are denoted with subscript ka):

$$\begin{aligned} \pi_{ka} &= I_{ka} + P\beta_{ka} MIN\{q_{uz}, O_{ka}\} \\ &\quad + MAX\{C_{ka}(1-\gamma)\rho MIN\{-D^s, X\}, 0\} - S_{uz} \end{aligned} \tag{10}$$

where I_{ka} is the unspecified intercept of the Kazakh payoff function.

3.2 Estimating the model

Having defined the payoff functions of the three riparians the next step is to use real data to estimate the model. Analytically, this procedure is straightforward since it simply involves the use of numerical values for all exogenous variables and parameters. In practical terms, however, the compilation and selection of relevant data constituted a significant challenge.

Water availability is a key determinant of riparian payoff. We use primary data collected by JSC Kyrgyzenergo for the 1988-2003 period (see Appendix F, Table F.1). Water inflow is a stochastic variable determined by nature while water outflow is a reflection of political decisions made by Kyrgyzstan. The presence of what is, in effect, two stochastic variables (summer and winter inflows) adds complications to the experimental design. We thus make the simplifying assumption that Kyrgyz winter release is residually determined, $q^w_{ky} = \overline{Q} - q^s_{ky}$ where $\overline{Q}$ denotes annual inflow. This is equivalent to assuming that annual inflow equals annual outflow.[14] While this is true in the medium to long term it is a restrictive assumption on an annual basis. Thus while in practice the Toktogul Reservoir is large enough to enable multi-annual regulation, our analysis focuses exclusively on the seasonal conflict.

[14]Ambec and Doucet (2003) make a similar assumption.

Table F.2 (Appendix F) summarises the assumed values of the remaining exogenous variables and parameters. A few assumptions deserve special mention: First, we have set the economic value of irrigation water at US$ 20/KCM (1,000 cubic meters). According to the World Bank (2004a), the value of irrigation in Central Asia is estimated as being in the region of $20-$50 per KCM. To produce conservative benefit estimates we choose the lower bound of this estimate. Secondly, optimal irrigation input was calculated on the basis of total land under cotton in Uzbekistan and Kazakhstan, including additional land introduced in the medium term. Our results are consistent with those provided by Antipova *et al.* (2002) who estimate a total downstream irrigation need of 6.5 BCM. Thirdly, to capture the effect of increased marginal cost of thermal power production beyond the capacity of Bishkek I, we used cost figures for Bishkek II. The Bishkek II plant, however, currently exists only at the design stage and although it could be completed by 2007 the Kyrgyz government is yet to approve its construction.

3.3 Properties of the model

The payoff functions of the three riparians in equations (6), (9) and (10) can be expressed as cost and benefit functions if the intercepts and side payments are omitted. The costs of cooperating are borne entirely by Kyrgyzstan and are defined as:

$$C(q^s_{ky}, \overline{Q}) \equiv -\pi_{ky}(q^s_{ky}, \overline{Q}) \tag{11}$$

The benefits of cooperation accrue jointly to Uzbekistan and Kazakhstan:

$$B(q^s_{ky}) \equiv \pi_{uz}(q^s_{ky}) + \pi_{ka}(q^s_{ky}) \tag{12}$$

This reformulation of the model turns out to be quite useful in illustrating its properties. In the following we use $\overline{Q} = 13$ as a benchmark and assume, for illustrative purposes, that water is shared equally between the two downstream riparians, i.e. $q_{uz} = \frac{q^s_{ky}}{2}$.[15]

Figure 4.1 Marginal costs (MC) and marginal benefits (MB), $\overline{Q}$= 13.

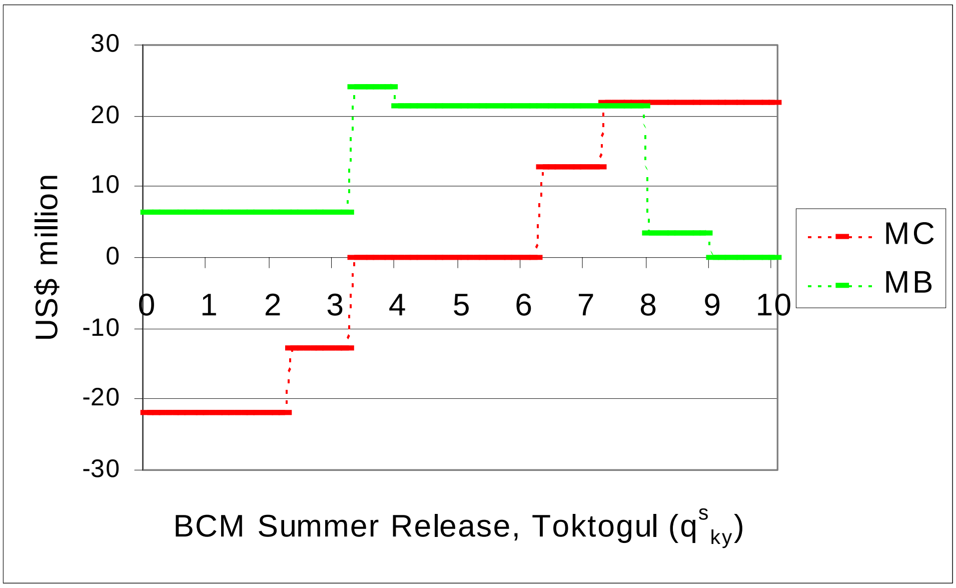


Figure 4.1 illustrates the marginal costs and benefits as a function of q^s_{ky}. Marginal costs and benefits are constant, piecewise linear and each schedule has five steps. Consider first each of these steps on the marginal benefit curve starting from the left: (1) For low values of q^s_{ky}, downstream marginal benefits are limited to cotton irrigation. (2) Marginal benefits increase for higher values of q^s_{ky} as the associated Kyrgyz energy surplus enables import of

[15]This assumption (also used in World Bank (2004a)) does not affect the properties of the model in any significant way. It merely affects the size of total benefits and the distribution of those benefits between Uzbekistan and Kazakhstan. Equal water sharing produces conservative benefit estimates because the potential for downstream optimisation is not neccessarily exploited. Note that the variable q_{uz} is endogenous in the experiment.

cheaper summer electricity by downstream countries. (3) Marginal benefits then fall slightly as Kazakh irrigation demands are saturated. (4) They fall substantially when the capacity constraint of electricity exports becomes binding. (5) Marginal benefits eventually reach zero as Uzbekistan receives sufficient irrigation water.

Marginal costs are determined by summer as well as winter effects. Low values of q_{ky}^s are associated with a domestic energy deficit in summer (and a surplus in winter) while the reverse is the case for high values of q_{ky}^s. The five steps on the marginal cost curve are characterised as follows: (1) For low q_{ky}^s-values, Kyrgyzstan operates both thermal power plants in summer (Bishkek I and II). Each additional water unit q_{ky}^s released reduces the cost of operating these plants, thus marginal costs are negative (i.e. Kyrgyzstan incurs a marginal benefit). (2) As q_{ky}^s increases Kyrgyzstan only requires to operate Bishkek I and marginal costs increase, but remain negative. (3) Marginal costs equal zero when the primary energy balance is non-negative in both seasons. (4) For higher levels of q_{ky}^s marginal costs (of operating Bishkek I) become positive since a high summer release causes a winter energy deficit. (5) Marginal costs peak when Bishkek II also needs to be operated in winter. Finally, we note that net benefits of cooperation are maximised at the intersection between the marginal cost and marginal benefit schedules.

The properties of the theoretical model depend critically on the two treatment variables: water inflow ($\overline{Q}$) and Uzbek reservoirs (R). Consider first model sensitivity to changes in $\overline{Q}$ within the historically relevant interval: $[10; 16]$. A change in $\overline{Q}$ affects the cost function but not the benefit function, cf. equations (11) and (12). The noncooperative equilibrium is non-unique and thus defined as an interval of q^s_{ky}-values (Table 4.1 refers). The start interval is always $q^s_{ky} = 3.3$ because this value is sufficient to eliminate the domestic energy deficit in summer. The end interval - which is increasing in $\overline{Q}$ - is determined by the point where Kyrgyzstan incurs a domestic energy deficit in winter. The cooperative optimum is typically unique and increasing in $\overline{Q}$ because higher overall water availability reduces the Kyrgyz marginal costs in winter and shifts the right-hand part of the marginal cost schedule downwards. Cooperation typically involves a higher Kyrgyz summer discharge, q^s_{ky}, than noncooperation, except in high-water years where the two may be identical. This implies that the downstream riparians have a higher marginal productivity of water than Kyrgyzstan. Table 4.1 also illustrates the intuitive property that basinwide gains from cooperation are highest when water is scarce.[16]

Uzbek reservoirs are represented by the second treatment variable, R, which thus far has taken the value zero. To consider the economic impact of reservoir construction we simply set this value to 2.5. The economic impact of the new reservoirs is as follows: First, Uzbek cotton benefits, and thus basinwide new benefits, increase by up to 8.8 million US$ depending on $\overline{Q}$. By and large, the basinwide gain from Uzbek reservoirs is decreasing in $\overline{Q}$, i.e. reservoirs are most useful in low-water years. Secondly, Uzbek reservoirs

[16]Note that the value of basinwide gains depend on the selection of the non-unique, noncooperative equilibrium. Table 4.1 produces conservative estimates because we assume that the equilibrium with the highest release is selected. This is also the most efficient one. Equilibria with lower releases do not benefit Kyrgyzstan but harm the downstream countries.

may make cooperation slightly less attractive.[17]

To maximise basinwide efficiency, it is necessary for riparians to cooperate (with or without reservoirs), except when water is abundant. In this sense the reservoirs do not establish Uzbek self-sufficiency in irrigation water, i.e. Uzbekistan could increase its benefits by cooperating. For a normal water year we compute a cooperative surplus equal to US$ 9.0 million per year.

Table 4.1. Model results for alternative values of the treatment variables

$\overline{Q}$	10	11	12	13	14	15	16
Noncooperative							
equilibrium (q^s_{ky})	3.3	3.3-4.2	3.3-5.2	3.3-6.2	3.3-7.2	3.3-8.2	3.3-9.2
Cooperative							
optimum (q^s_{ky})	4.2	5.2	6.2	7.2	7.9	8.3	9.0*
Basinwide gains from							
reservoirs (million US$)							
- Noncooperative**	8.8	8.7	8.8	8.8	6.3	2.8	0.0
- Cooperative	8.8	8.7	8.7	6.3	3.9	2.4	0.0
Basinwide gains of co-							
operation (million US$)							
- Without reservoirs	9.5	9.0	9.0	9.0	6.4	0.0	0.0
- With reservoirs	9.5	9.0	8.9	6.5	4.0	0.0	0.0

*$q^s_{ky} = 9.0$ without reservoirs but $q^s_{ky} \in [7.9; 9.2]$ with reservoirs.

**Refers to the highest noncooperative water release.

[17] The effect of the new reservoirs on figure 4.1 is that Uzbek irrigation demands are saturated earlier as q^s_{ky} increases. For $Q = 13$, Uzbek and Kazakh demands are met simultaneously at $q^s_{ky} = 4$ and thus the marginal benefit curves in the third and fourth step are each reduced by US$3.5 million.

4. Design and Procedures

4.1 The stage game

Having formulated the payoff functions we now turn our attention to the strategic environment. The Syr Darya river conflict is characterised by negotiations between governments of the three countries and the problem of their subsequent implementation. Consequently, we design a game that consists of two parts. First, in a negotiation part the three players - each representing a country - are given the opportunity to make a contract on a combination of water releases and possible side payments. This contract, however, is non-binding, as there is no way in which a country can be forced to obey (leaving aside the unlikely possibility of military intervention). In a second part of the game the players decide on the water releases and side payments they actually implement.

In the real conflict negotiations take place annually in trilateral negotiations. In the experimental design we attempt to model such a scenario. However, to make it playable in the laboratory we needed to impose a certain structure on the negotiations, which takes into account that laboratory time is limited. We simplified the bargaining process by randomly giving one of the players the opportunity to make a proposal and asking the other players to accept or reject. The proposal consists of the following four elements:

1. Kyrgyz water discharge from Toktogul in summer, q^s_{ky}.
2. Uzbek water discharge to Kazakhstan in summer, q_{uz}.
3. A compensation payment from Uzbekistan to Kyrgyzstan, S_{ky}.

4. A compensation payment from Kazakhstan to Uzbekistan, S_{uz}.

The inflow is exogenously given and known.[18] Uzbekistan can release to Kazakhstan any quantity of water up to what it receives from Kyrgyzstan. The compensation payments are amounts of money. This rule represents a simplification of conduct of play in the real conflict, where Uzbekistan refuses to make any monetary payments in exchange for water or to attach a price on water (services) - a demand from the Kyrgyz side. In practice, however, Uzbekistan has implicitly agreed to pay compensations through an inflated price for the electricity it receives from Kyrgyzstan in summer. For the experiment simplicity is important, such that we decided not to model these additional behavioural complexities.

At the first stage of the game, one player makes a proposal to the other two players. We chose to draw the proposer at random in each round of the game (each with a probability of one third), in the absence of a natural candidate.[19] After the proposal is specified, its terms are communicated to the other two players. These players are then simultaneously asked to accept or reject it. Note that since the contract is not binding, the negotiation part

[18]In practice there is an additional complexity since the inflow level is a stochastic variable (see appendix table E.1). Agreements are generally made before knowing the actual inflow level. However, since most of the inflow into Toktogul comes from glacier and snow melt in spring, the year's inflow is largely known when Kyrgyzstan makes a decision on releases. Hence, the governments could make agreements contingent of the inflow if they wished (though so far they did not). We therefore model the realised inflow in a given year as known.

[19]One may argue that the downstream country is the most natural candidate, since the downstream riparian wishes to change the status quo and alter the behaviour of the upstream player. However, always making Kazakhstan the proposer seems somewhat at odds with the reality of the conflict, in which the strongest conflict of interest is between Uzbekistan and Kyrgyzstan.

of the game is merely ‘cheap talk’ in the game theoretic sense. It may be used to co-ordinate the players’ behaviour, but it cannot be enforced and does not restrict the players in their subsequent actions.

After the proposal has been either accepted or rejected, the players make the decisions for real. As the first mover Kyrgyzstan decides on a release of water from Toktogul (q^s_{ky}). At the next stage Uzbekistan makes two decisions at once. It chooses which quantity of water to release to Kazakhstan (q_{uz}), and an amount of money to pay to Kyrgyzstan (S_{ky}). At the final stage of the game, Kazakhstan decides on a side payment to make to Uzbekistan (S_{uz}). At all stages all players are informed about all players’ decisions at preceding stages.[20]

4.2 The conduct of the experiment

Since the payoff functions developed from the available real-world data are complex, they needed to be presented in the simplest possible way. We used tables that list the payoffs obtained by each combination of water releases from Kyrgyzstan to Uzbekistan and from Uzbekistan to Kazakhstan. Depending on the range of feasible releases these payoff tables could quickly become very large and incomprehensible. Therefore, the number of choices was restricted. Water discharges had to be in integer numbers. We further cut the strategy space in a way that Kyrgyzstan could pass any integer number from 3 to 9 units. Releases outside this range are historically irrelevant and did not seem to be plausible choices. The resulting payoff tables

[20]There are some information problems due to neglect of metering stations and a generally secretive attitude of the Central Asian governments. At the aggregate level, however, the relevant information is largely available.

consisted of 49 lines and four columns. The first three columns showed the payoffs for each of the three players, the last column the sum of the three payoffs (enabling participants to identify efficient outcomes). The payoff tables can be found in Appendix G.

For the specification of the payoff values from the payoff functions we had to make some choices. First, we adopted the principle that 'a dollar is a dollar', thus we did not account for a different marginal utility of money in the three countries. Those could arise from their different population sizes or GDP levels. Such corrections, however, would have been somewhat arbitrary (for example, in Kazakhstan water benefits apply to the South Kazakhstan and Qyzlorda provinces only). Further, such considerations do not seem to play a significant role in the actual policy debate. Secondly, in the theoretical model payoffs are formulated in additional costs of water release for Kyrgyzstan and additional benefits for the downstream riparians. In the experiments absolute payoffs needed to be implemented, thus the unspecified intercepts of the payoff functions had to be defined. We decided to choose the intercepts in a way which was experimentally most suitable, rather than derive them from some real-world benchmark (such as GDP). As a benchmark we chose the least inefficient noncooperative equilibrium outcome without reservoirs in the normal water year ($\overline{Q} = 13$), where Kyrgyzstan discharges 6 and Uzbekistan releases 1 (see next section 4.3), since this is currently the most relevant scenario in reality. Payoffs were adjusted in a way that each player gets 370 talers (the experimental currency unit) in this scenario. From there we calculated all other payoffs using the cost and benefit functions derived earlier. Each taler difference between two numbers in the payoff tables corresponds to US$ 100,000 per year in the real game. Note that side payments would be added or subtracted from these figures, such that a wide range of payoff combinations was achievable.

The experiment was conducted at the *Centre for Decision Research and Experimental Economics* (CeDEx) of the University of Nottingham. The software for the experiment was developed using the *RatImage* programming package (Abbink and Sadrieh, 1995). Subjects were recruited by e-mail from a database of students, who had previously registered at CeDEx as potential participants in experiments. Each subject participated in only one session, and no subject had participated in experiments similar to the present one. The subjects were undergraduate students from a wide range of disciplines. The majority of participants were British. Among the substantial fraction of foreign students the largest group was Chinese. Virtually all subjects were aged between 19 and 25, with a balanced gender distribution.[21]

In each session subjects interacted in fixed groups of three subjects. The role of a participant as representing Kyrgyzstan, Uzbekistan or Kazakhstan did not change throughout the experiment. This set-up reflects the repeated-game character of the real situation. Subjects were not told who of the other participants were in the same group, but they knew that the composition of the groups did not change. Each session began with an introductory talk.

[21]Ideally we would have wished to conduct the experiment with participants from a Central Asian cultural background. However, few students from that region are enrolled at Nottingham University, and in Central Asia we did not have access to a computerised laboratory. Experiments conducted with participants from different cultures sometimes show differences (Roth *et al.* (1991), Willinger *et al.* (2003)), sometimes not (Brandts *et al.* (2000), Lensberg and Van der Heiden (2000)). Typically the differences are not large and do not lead to radically different conclusions.

The experimenter read aloud the written instructions (see Appendix H). The language used in the instructions was semi-natural. The situation was framed as that of a 'resource being passed' from one player to the other, but we did not label the players as the three countries they represented. Since we did not expect many students to be familiar with the Syr Darya river conflict, we were concerned that an entirely natural framing would cause confusion. On the other hand we did not expect a benefit from completely disguising the situation using abstract terms as this would have made the instructions more difficult to understand.[22]

We conducted 24 rounds of the stage game.[23] These were divided into three phases of eight rounds, using the different inflow levels of 10, 13, and 16 to represent low, normal and high water levels, respectively. The order of the three phases was varied in a way that each water level was played in each of the phases in the same number of sessions. The different levels of inflow implied different payoff distributions, but otherwise the structure of the game remained the same in each phase.

[22]The evidence from the literature is ambigous regarding the effect of context or instruction framing. Burnham, McCabe, and Smith (2000) report less trustful choices in a reciprocity game when the other player is called 'opponent' rather than 'partner'. Abbink and Hennig-Schmidt (2002), on the other hand, find no significantly different behaviour between a neutrally and a naturally worded version of a bribery experiment. A similar example can be given for tax evasion experiments: Baldry (1986) reports more evasion when the task is presented neutrally (as a gambling opportunity) while Alm, McClelland, and Schulze (1992) find no significant difference.

[23]Subjects were informed about the number of rounds for reasons of transparency and practicality. This creates a deviation from the real situation which resembles an infinitely repeated game. Contrary to the real-life decision makers, subjects could theoretically solve the 24-round supergame by backward induction and be guided by this solution. However, since such behaviour is not typically observed in other experiments (and greatly at odds with the existing evidence from trust games), it seems unlikely to be the case in our setting.

Subjects were granted a capital balance of 1,000 talers at the outset of each session. The total earnings of a subject from participating in the experiment were equal to the capital balance plus the sum of all the payoffs he or she made during the experiment minus the sum of that subject's losses. A session lasted for about two hours (including time spent to read the instructions). At the end of the experiment, subjects were paid their total earnings anonymously in cash, at a conversion rate of one pound sterling for 400 talers. Subjects earned between £3.44 and £39.10 with an average of £21.95, which is considerably more than students' regular wage in Nottingham.

We conducted three sessions with each treatment (with and without Uzbek reservoirs). The treatments differ in the payoff tables, but not in the structure of the game. Each session comprised of 12, 15, or 18 subjects, where the variation is due to show-up rates. Subjects interacted with each other within groups but not across groups so that each group of three countries can be considered a statistically independent observation. In total, we gathered 15 independent observations in the treatment without reservoirs and 16 in the treatment with Uzbek reservoirs.

4.3 Game-theoretic considerations

Using the payoff tables shown in Appendix G, the subgame perfect equilibria (Selten (1965, 1975)) of the stage game can easily be identified with a backward induction argument. It is straightforward to see that in a non-cooperative equilibrium no side payments are made. At the last stage a side payment only reduces Kazakhstan's payoff. Since the other players' decisions have been taken, Kazakhstan cannot gain anything from making a final payment. Analogously, Uzbekistan does not gain from making a side payment to Kyrgyzstan, since Kyrgyzstan's decision is already made.

The equilibrium choices with respect to water releases can be obtained from the payoff tables. Since Kyrgyzstan foresees that it will not receive compensation payments, its payoff is not affected by the choices being made downstream. Thus it will simply release the quantity that maximises its own payoff.[24] For example, in the benchmark case of $\overline{Q} = 13$ without reservoirs, Kyrgyzstan can release anything from 4 to 6 units (BCM) in an equilibrium and earn 370 talers (see Appendix Table G.3). Uzbekistan then chooses the quantity to pass to Kazakhstan given this behaviour. If Kyrgyzstan has chosen, for example, 6 units, then Uzbekistan passes on 0 or 1 units to Kazakhstan.[25] Thus, the combinations $(q^s_{ky}, q_{uz}) = (4,0), (5,0), (6,0)$ and $(6,1)$, combined with no side payments, constitute subgame perfect equilibria of the game. In comparison, the socially efficient allocations are those which maximise total payoff. Such allocations need to be sustained by side payments in order to be individually rational. Table 4.2 illustrates the subgame perfect equilibria and socially efficient allocations for all six scenarios.

[24]This feature eases the game-theoretic analysis, as we do not require a full-fledged backward induction analysis.

[25]Note that passing on zero does not imply that the Syr Darya is dry at the Uzbek-Kazakh border. We examine only the Naryn cascade, but as mentioned in chapter 3, the river is also fed from other sources notably the Kara Darya. Since other sources are generally unregulated, their inflow levels are not strategic variables in the game and thus excluded.

Table 4.2 Equilibria and social optima of the game (q^s_{ky}, q_{uz}).

Treatment	Subgame perfect equilibria	Social optima
$\overline{Q} = 10$, N	(3,0)	(6,2)
$\overline{Q} = 13$, N	(4,0), (5,0), (6,0), (6,1)	(7,2)
$\overline{Q} = 16$, N	(4,0), (5,0), (6,0), (6,1), (7,0)...,(7,2),(8,0), ..., (8,3), (9,0), ..., (9,4)	(8,2), (8,3), (9,2), ..., (9,4)
$\overline{Q} = 10$, R	(3,0), (3,1)	(4,2)
$\overline{Q} = 13$, R	(4,0), ..., (4,2), (5,0), ..., (5,3), (6,0), ..., (6,4)	(7,2), ..., (7,5)
$\overline{Q} = 16$, R	(4,0), ..., (4,2), (5,0), ..., (5,3), (6,0), ..., (6,4), (7,0), ..., (7,5), (8,0), ..., (8,6), (9,0), ..., (9,7)	(8,2), ..., (8,6), (9,2), ..., (9,7)

Note: N = No reservoirs; R = Reservoirs.

The table shows that for the case of abundant water ($\overline{Q} = 16$), there is no conflict between own-payoff maximisation and cooperation, since the socially efficient outcomes are also equilibria of the game. In normal ($\overline{Q} = 13$) or low water years ($\overline{Q} = 10$), maximisation of joint payoff requires the players to deviate from the noncooperative equilibrium. The construction of the Uzbek reservoir widens the range of equilibria and, in some cases, the range of socially efficient allocations. Interestingly, the reservoirs do not alter the scope for cooperation. Still, in the case of low and normal water years the players can improve their payoffs by agreeing on a solution that is not an equilibrium.

5. Results

In this section we present the results of the experimental data. Our main focus is the efficiency implications of the new Uzbek reservoirs and the possibility of cooperation under the two regimes. For readability we will continue to label the players with the names of the countries they represent, though in fact they were experimental participants.

5.1 Kyrgyz discharges from Toktogul

The economic efficiency of the outcome crucially relies on cooperation between Kyrgyzstan and Uzbekistan. We therefore first examine the behaviour of the participants representing the Kyrgyz side. Table 4.3 shows the relative frequency with which the different levels of water release occur in the experimental data.

Table 4.3 Relative frequency of Kyrgyz choices regarding Toktogul release

Kyrgyz quantity passed	3	4	5	6	7	8	9
$\overline{Q} = 10$, N	**0.562**	0.298	0.083	0.050	0.008	0.000	0.000
$\overline{Q} = 13$, N	0.050	0.142	0.083	**0.383**	0.333	0.008	0.000
$\overline{Q} = 16$, N	0.017	0.075	0.050	0.117	0.008	0.258	**0.475**
$\overline{Q} = 10$, R	**0.586**	0.188	0.164	0.023	0.023	0.016	0.000
$\overline{Q} = 13$, R	0.023	0.102	0.039	**0.500**	0.234	0.094	0.008
$\overline{Q} = 16$, R	0.047	0.102	0.031	0.078	0.055	0.305	**0.383**

Note: The modal frequencies are set in bold face.

In low water years we observe that the noncooperative choice is dominant in the data. Recall that with $\overline{Q} = 10$ (no reservoirs) the noncooperative release is 3 units and the socially efficient choice is 6 units (see Table 4.2). The choice generating the efficient solution is made in only 5 percent of the cases, while in more than half of the rounds we observe the noncooperative release.

Thus the subjects representing Kyrgyzstan did not show much trust in their downstream counterparts. This may be surprising given the high incidence of trustful choices in previous experiments on reciprocity games. A possible explanation is the high risk that Kyrgyzstan must take when deviating from the noncooperative (3 units) to the socially efficient choice (6 units). Under this scenario Kyrgyzstan renounces 477 talers (US$ 47.7 million), and to gain maximum benefits relies on receiving at least as much as a side payment from Uzbekistan (see Table F.1). To make such a high payment Uzbekistan would also need to trust Kazakhstan to cooperate. Given that the total benefit from cooperation (the pie that can be divided among the two players on top of the noncooperative payoffs) is only 189 talers (US$ 18.9 million), it is quite plausible that the players representing Kyrgyzstan in the laboratory deemed cooperation too risky.

Though the new reservoirs reduce Kyrgyzstan's risk of cooperation considerably for $\overline{Q} = 10$ (the socially optimal release is then only 4 units and requires Kyrgyzstan to renounce only 61 talers), the effect on the likelihood of cooperation is minor. While the frequency of socially optimal releases increases significantly from 5.0 to 18.8 percent ($\alpha = 0.025$ one-sided, Fisher's two-sample randomisation test) it is still below one fifth, and there is an absolute majority of noncooperative choices. Thus even with the reduced risk for Kyrgyzstan the payoff structure of the game imposes substantial hurdles to riparian cooperation.

In normal water years ($\overline{Q} = 13$) noncooperative choices are also most frequent, and we even observe a substantial fraction of spiteful decisions (releases of 4 or 5 units, which yield the maximum payoff for Kyrgyzstan but harm Uzbekistan). These may be acts of punishment against the Uzbek player in response to default on side payments. Taking together the three equilibrium options (4, 5 and 6 units) we observe noncooperative behaviour in more than 60 percent of the cases. However, the prospect for cooperation is not as bleak as in low-water years. Without reservoirs the socially optimal release (7 units) is realised in one third of the rounds, making this the second most frequent option. These results are independent of the new reservoirs, which do not have a statistically significant effect on cooperation.

When water is abundant ($\overline{Q} = 16$) participants usually do not find it difficult to sustain one of the efficient outcomes (a release of 8 or 9 units). However, note that in high water years there is no conflict between individual payoff maximisation and efficiency, such that this result does not hint at strong efforts to cooperate. In high-water years the new reservoirs are practically obsolete, and consequently they do not have a significant effect on the experimental results.[26]

5.2 Uzbek compensation to Kyrgyzstan

In order for all three countries to benefit from cooperation Uzbekistan needs to compensate Kyrgyzstan for its additional summer release of water. Table 4.4 shows Uzbekistan's median side payment to Kyrgyzstan, conditional on the quantity of water that Kyrgyzstan has released in summer. It emerges that Uzbekistan's reluctance to make sufficient payments is a source of cooperation failure. This is particularly pronounced in low water years

[26]Note that the Uzbek reservoirs are too small to enable multi-year regulation, i.e. to store water inflows in high-water years and release it in low-water years.

($\overline{Q} = 10$) without reservoirs. Recall that Kyrgyzstan renounces 477 talers (US$ 47.7 million) when moving from noncooperation to the social optimum. The experimental Kyrgyzstan players who did so, however, received in the median a mere 25 talers (US$ 2.5 million) back as compensation. In the presence of Uzbek reservoirs Kyrgyzstan typically did not receive any reward for releasing the efficient 4 units. This explains the low level of cooperation we observe in low water years despite the fact that reservoirs make cooperation less risky. For $\overline{Q} = 13$ Kyrgyzstan must forego 98 talers to sustain a socially optimal outcome (with and without reservoirs), but the median Uzbek compensation payment also falls short of this (45.5 talers without reservoirs and 92.5 talers with reservoirs). Finally, in high-water years we also observe some use of side payments. Although Kyrgyzstan receives the same payoff in the interval 4 to 9 units, its decision greatly affects Uzbekistan. Therefore, Uzbekistan may choose to use side payments to reward Kyrgyzstan for non-spitefulness thereby sustaining high releases.

Table 4.4 Median compensation payment from Uzbekistan to Kyrgyzstan

Kyrgyz quantity passed	3	4	5	6	7	8	9
$\overline{Q} = 10$, N	0	0	15.5	25	0	-	-
$\overline{Q} = 13$, N	0	0	0	2	45.5	100	-
$\overline{Q} = 16$, N	0	0	0	0	25	80	41
$\overline{Q} = 10$, R	0	0	90	205	0	10	-
$\overline{Q} = 13$, R	0	0	20	0	92.5	170	0
$\overline{Q} = 16$, R	5	0	5	1	0	50	50

Note: In talers. -No observations.

5.3 Downstream collaboration

The downstream riparians, Uzbekistan and Kazakhstan, rely on Kyrgyzstan's behaviour in order to achieve maximum payoffs. However, even without Kyrgyzstan's good will they often have room for improving their payoffs by cooperating. For each subgame (defined by Kyrgyzstan's release) we can identify a noncooperative equilibrium and a socially optimal allocation (although these may coincide). In the payoff tables, each subgame is identified as a block of cells (marked with a thin line) with identical Kyrgyz water discharge. Noncooperative equilibria for the sub-game are those rows within each block that maximise Uzbek payoff. The social efficient allocation is characterised as the Uzbek choice(s) maximising total payoff within the block. To illustrate, suppose that in a normal water year without reservoirs Kyrgyzstan has chosen to release 6 units (see Table G.3). Uzbekistan's payoff is then maximised if it passes either 0 or 1 units. Thus both choices constitute noncooperative equilibria for the subgame with a Kyrgyz release of 6 units. The social optimum for this subgame, is for Uzbekistan to pass 2 units.

As illustrated in Table 4.5, Uzbekistan's choice can fall into one of four categories depending on whether it is a social optimum and/or a noncooperative equilibrium or neither. The table shows that efforts to cooperate between the downstream riparians have been modest. Social optima which are not equilibria have only been implemented in very few rounds. Noncooperative equilibrium play is therefore the dominant outcome. In the treatment with reservoirs, virtually all of Uzbekistan's decisions fall into that category. Since social optima often coincide with equilibrium choices in the subgames, this behaviour is not always inefficient. In at least 43 percent of cases the most efficient downstream solution was realised.

Table 4.5 Frequency of Uzbekistan's passed quantities

Treatment	Social optimum, but not equilibrium	Equilibrium, but not social optimum	Social optimum and equilibrium	Neither social optimum nor equilibrium
$\overline{Q} = 10$, N	0.050	0.075	0.717	0.158
$\overline{Q} = 13$, N	0.075	0.325	0.417	0.183
$\overline{Q} = 16$, N	0.034	0.184	0.683	0.100
$\overline{Q} = 10$, R	0.000	0.547	0.430	0.023
$\overline{Q} = 13$, R	0.000	0.500	0.492	0.008
$\overline{Q} = 16$, R	0.000	0.336	0.664	0.000

5.4 The contracts and their adherence

In all six variants of the game participants find it difficult to come to an agreement, and if they do these agreements are frequently broken (Table 4.6).[27] When water is scarce ($\overline{Q} = 10$) an agreement is made in only about a third of the rounds, and from these more than three-quarters are broken. The record is best when water is abundant and there is no conflict between short-run self-interest and cooperation. Still, even in those years a majority of contracts are not adhered to. In this case, however, the high rate of broken contracts may just reflect that contracts are not considered necessary and therefore taken less seriously. Recall that in high water years there is a range of socially optimal choices. If the allocation implemented is different from the one that has been agreed on this then does not necessarily have negative consequences for the players.

[27] Any deviation from the agreement constitutes a breach.

Table 4.6 Frequency of agreements (in percent)

Treatment	Years with agreement	Broken agreements
$\overline{Q} = 10$,N	0.308	0.730
$\overline{Q} = 13$, N	0.525	0.714
$\overline{Q} = 16$, N	0.625	0.533
$\overline{Q} = 10$, R	0.414	0.830
$\overline{Q} = 13$, R	0.508	0.754
$\overline{Q} = 16$, R	0.648	0.614

The high frequency of noncooperative choices raises the question of whether, and to what extent, subjects proposed a social optimum in the non-binding agreements. Table 4.7 reveals that the socially efficient allocation was proposed at least once in the majority of cases (column 1). Nevertheless, the social optimum was implemented much less frequently, particularly in low water years (column 2). A similar picture emerges when comparing the total frequency of socially efficient proposals and their implementation (columns 3 and 4).

Table 4.7 Social Optima (SO): Proposals and implementation.

	(1) Groups proposing SO at least once	(2) Groups implementing SO at least once	(3) Frequency of SO proposals	(4) Frequency of SO implemented
$\overline{Q} = 10$, N	10/15	1/15	0.175	0.016
$\overline{Q} = 13$, N	14/15	11/15	0.408	0.283
$\overline{Q} = 16$, N	14/15	15/15	0.725	0.608
$\overline{Q} = 10$, R	9/15	5/15	0.141	0.067
$\overline{Q} = 13$, R	13/16	7/16	0.375	0.195
$\overline{Q} = 16$, R	16/16	14/16	0.781	0.477

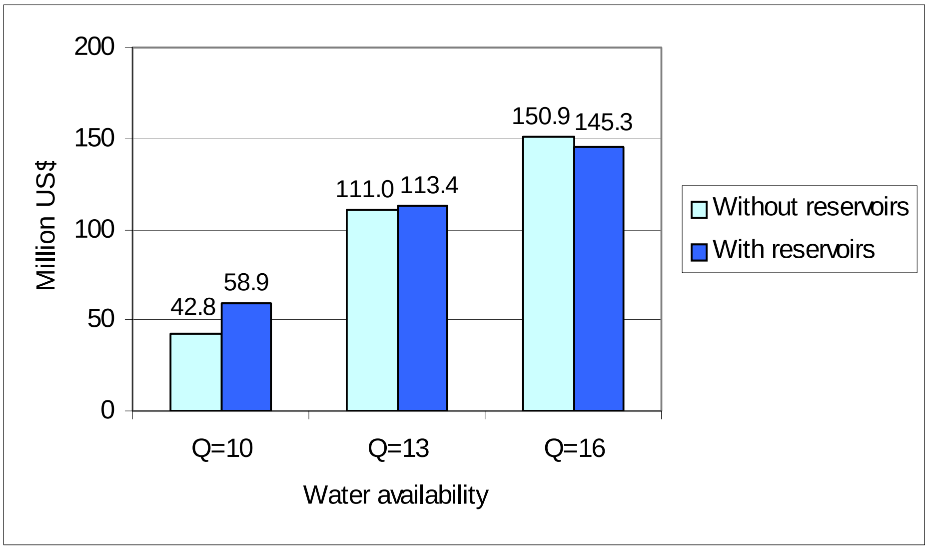
5.5 Payoff and social efficiency

Figure 4.2 shows the payoff (in US$ equivalents) for the six treatments of the experiment. Recall that the intercept terms of the payoff functions are unspecified. This implies that only differences between every two bars are meaningful, while the absolute values are partly determined by our choice for the experimental payoff tables.

As expected, high-water years lead to greater economic returns - a finding which is significant for all pairwise comparisons between two water levels in a given treatment ($\alpha < 0.0001$, binomial test). The impact of reservoirs, however, is limited to low-water years. In those years reservoirs increase the median total payoff significantly ($\alpha < 0.0001$, Fisher's two-sample randomisation test) by 161 talers (corresponding to US$ 16.1 million in reality).[28] The slight rise in normal water years is not significant. When water is abundant we even observe a slight decrease in social efficiency, but this difference is not significant and likely due to random variation.

[28]This figure is higher than the theoretical value in table 4.1. The difference stems mainly from the restrictive assumption on water sharing in that table which we drop later in the experimental design.

Figure 4.2 Median total payoff in million US$ equivalents



The total payoff gained by the three players jointly also gives a measure of the social efficiency of the experimental outcomes. Table 4.8 compares median payoff with the payoff in the socially optimal and the noncooperative allocations. We find that the experimental payoff was typically similar to that under noncooperation. The social optimum was only attained when this coincided with the noncooperative equilibrium. This suggests a low level of overall social efficiency which the reservoirs had little impact on.

Table 4.8 Median Payoff (talers) compared to theoretical benchmarks

Treatment	Median payoff	Noncooperative (least inefficient)	Social optimum
$\overline{Q} = 10$, N	428	428	617
$\overline{Q} = 13$, N	1,110	1,110	1,246
$\overline{Q} = 16$, N	1,509	1,509	1,509
$\overline{Q} = 10$, R	589	589	711
$\overline{Q} = 13$, R	1,134	1,166	1,246
$\overline{Q} = 16$, R	1,453	1,509	1,509

5.6 Analysis of individual behaviour

A more detailed analysis of individual behaviour enables us partly to examine alternative player strategies and partly to identify characteristics of cooperative behaviour. Importantly, we find that in three-quarters of the cases the socially optimal allocation is sustained by a system of side payments which splits total profit almost equally between players. Conversely, socially optimal allocations which are not equitable are almost always unstable. Thus, perceptions of fairness emerge as an important determinant of cooperative behaviour in this experiment.

Behaviour in low-water years is largely noncooperative. Interestingly, the experimental Kyrgyz players often attempt to cooperate. The compensationary side payment from Uzbekistan, however, is generally too low and this discourages Kyrgyzstan from cooperating in subsequent rounds. A similar picture emerges for Uzbek-Kazakh cooperation, although due to low water availability, Kazakhstan can only participate meaningfully if Uzbekistan receives sufficient water from Kyrgyzstan. Only one group attains social optimality occasionally, but the players representing Kyrgyzstan earn less than their noncooperative payoff. The presence of reservoirs does not change these observations substantially apart from the fact that more groups (6) occasionally attain the socially optimal outcome, although none of them are able to sustain it. This may partly be because of inadequate compensation and partly because of an uneven split of total profit.

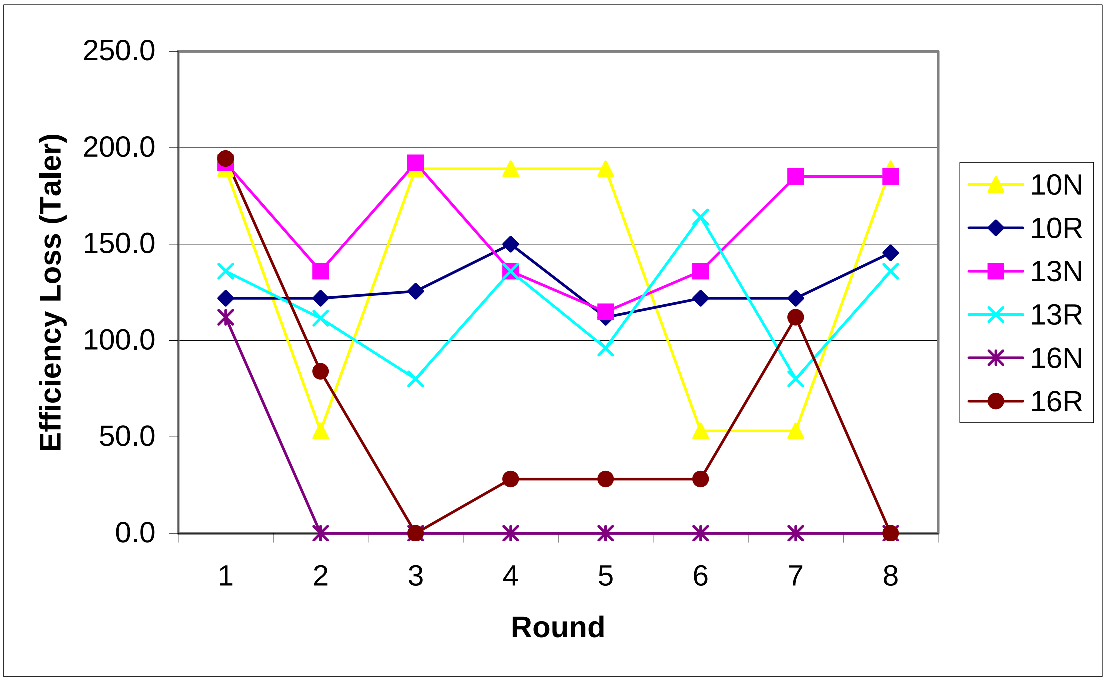
Noncooperative behaviour is also the norm in normal water years, although attempts to cooperate are relatively more successful. Behaviour can be broadly classified into three different categories (irrespective of the reservoir variable). In at least one third of the groups, the social optimum is never attained. To some extent this is the result of spiteful Kyrgyz behaviour - a strategy which has the (possibly intended) effect of increasing Kyrgyzstan's relative rather than total payoff. Kazakhstan typically plays no role here. In another sub-set (25 to 47 percent of groups, depending on the reservoir variable) we observe the occasional, albeit not systematic attainment of the social optimum. Total payoff in the socially efficient allocation is split unevenly and this may be one reason why it is unstable. In most of these groups the Kyrgyz subjects pass the optimal quantity without being adequately compensated by Uzbekistan. This then triggers a punishment from Kyrgyzstan which, ultimately, leads to cooperation break-down. Uzbekistan does not need a side payment to pass the optimal quantity to Kazakhstan, yet the latter's payoff depend positively hereof. This gives Uzbekistan the power to extract side payments for passing high quantities and to punish if they are not forthcoming. Uzbek players occasionally punished Kazakhstan by releasing sub-optimal quantities, but this was a successful strategy in only half the cases. A final, but smaller, subset of groups (33 to 45 percent) successfully sustain the socially optimal allocation. These groups are often characterised by attaining the efficient outcome early in the game and by splitting total profit in an equitable manner.

In high water years Kyrgyzstan does not lose from passing the optimal quantity to Uzbekistan, although it may expect to be rewarded for this as it holds the means of punishment. As before, outcomes can be classified in three different categories. Three to four groups fail to attain social efficiency entirely. This may sometimes be caused by unsuccessful attempts by Kyrgyzstan to coerce the Uzbek player into making higher side payments. Six groups attain optimal outcomes occasionally, but not persistently. Again, payoffs are not evenly split in the social optimum. Kyrgyz punishment continues to be a relatively impotent source of power. Finally, six groups succeed in attaining social efficiency early in the game and four of these implemented the equal payoff allocation.

5.7 Evolution of behaviour

To analyse the evolution of behaviour, Figure 4.3 illustrates the median efficiency loss (maximum payoff - actual payoff) over time.

Figure 4.3 Evolution of play: Median efficiency loss



There are clear signs of a systemic first-round effect: Median payoff in the second round is at least as high as in the first round in all six treatments. Subsequent rounds exhibit no systemic trends, except in high water years where efficiency tends to increase or remain constant. There are also some signs of a last-round effect: Increased efficiency loss in the last round is observed in half of the treatments.

While Figure 4.3 illustrates the evolution of the game, it masks important differences in the first- and last-round effects. It does not distinguish between groups that played this phase (of eight rounds) for the first (or the last) time in the experiment and those that did not. Table 4.9 produces separate figures for these two types of groups. First-round effects are more prevalent in groups which played it for the first time in the experiment. The same effect prevails for other groups, although it is less pronounced. Thus subjects needed some time to familiarise themselves with the experiment (and to some extent with new payoff tables as a new phase was initiated) in order to coordinate their behaviour towards less inefficient outcomes. Last-round effects tend to occur as some players use backward induction and realise that the best strategy in the last round of the experiment (and the game) is noncooperation. Interestingly, last-round effects were much less pronounced for groups playing the 24^{th} round in the experiment as opposed to groups that were playing the 8^{th} or 16^{th} round. Thus, subjects generally tended to ignore the negative reputational impact of such behaviour and this may have undermined the scope for cooperation in subsequent phases.

Table 4.9 Median efficiency loss (taler)

	Groups playing phase for the first or the last time.				Other groups			
Round	1	2	7	8	1	2	7	8
$\overline{Q} = 10$, N	67	53	189	189	189	189	53	135
$\overline{Q} = 13$, N	325	192	115	112	154	68	189	278
$\overline{Q} = 16$, N	626	105	0	0	18	0	28	217
$\overline{Q} = 10$, R	122	122	178	178	122	122	122	126
$\overline{Q} = 13$, R	136	80	96	136	108	136	68	136
$\overline{Q} = 16$, R	228	200	56	284	277	0	112	0

6. Conclusion

We examined the likely impact of new Uzbek reservoirs on the Syr Darya economies. This impact crucially depends on two issues. First, the reservoirs change the seasonal distribution of water availability in downstream Uzbekistan and Kazakhstan for any given release by Kyrgyzstan. Thus, payoffs from Kyrgyz water releases to the three countries have to be re-estimated. Second, the changed parameters may change the likelihood of regional cooperation. We designed a strategic game to address these issues. Costs and benefits of water releases are computed using data from the region. We then set up a laboratory experiment using the obtained payoff functions.

The theoretical analysis reveals that regional cooperation is still required for basinwide net benefits to be maximised. In this sense the reservoirs do not achieve the goal of Uzbek self-sufficiency. The experimental results strongly suggest that failure to cooperate is systematic. Inefficient noncooperative outcomes prevail in our experiments, in line with past behaviour in the river conflict, but in contrast to most trust games reported in the experimental literature. The difference with the literature can be explained as follows. In our experiments, the payoff structure is such that players often run high risks, but receive a relatively modest gain. Moreover, for cooperation to prevail it requires the simultaneous trust of three players. In the experimental literature, on the other hand, payoffs are much more favourable to cooperation and trustful behaviour is required by only two players.

We also find that experimental participants fail to set up mutually beneficial agreements (particularly in low-water years) and if agreements are made they are frequently broken. Thus our results suggest that failure to implement cooperative agreements should not be attributed to current decision makers' unwillingness alone. Cooperation failure is inherent to the structural features of the river conflict. Thus our results leave us pessimistic about decision makers being able to play the game more cooperatively in the future. Rather, they suggest to change the structure of the game, notably the sequence of water release and compensation payments that appears to make cooperation so difficult. While there are physical limits to synchronising water release and compensation in a barter scheme (due to prohibitive storage costs of energy and fuel), sophisticated instalments schemes using money payments may help to reduce the risks to trustful behaviour.[29] Once

[29] In this sense, our data call for a further development of a 'letter of credit' scheme as suggested in World Bank (2004a). Under this proposal, the water services charge paid by downstream riparians to Kyrgyzstan would have a fixed and a variable component where the latter is a function of the rainfall level. Uzbekistan and Kazakhstan would open a letter of credit for the water services charge, and the fixed charges could be drawn down in 6 equal monthly installments based on certification by the BVO (a monitoring agency) that agreed volume of water had been released in summer. The variable charge could be drawn down in one installment at the end of the winter based on BVO certification that winter discharges did not exceed the agreed levels. This arrangement could be backed by guarantees provided by a Guarantee Fund contributed by bilateral and multilateral donors.

these mechanisms are developed, new experiments can be designed to test their likely effectiveness.

The enhanced basinwide efficiency effect of the new reservoirs originates mainly from Uzbekistan's reduced dependency on Kyrgyz summer releases, and is limited to low-water years. A possible effect of enhanced cooperation can be detected statistically, but it is relatively small. As an overall effect of the new reservoirs we observe a median efficiency gain of the equivalent of an annual US$ 16.1 million for the low-water years, and no significant effect for normal and high-water years. Though this figure can naturally not be precise, it may provide an order of magnitude for a cost-benefit analysis of constructing the reservoirs. The benefits need to be weighed against the high construction costs. For these no official Uzbek figures are available, but they are estimated in the order of several hundred million dollars.

Of course, our findings have their limits. Though we have made every effort to trace the real economic framework as accurately as possible, no economic model (experimental or theoretical) can guarantee that no salient features of the real situation are lost or distorted when simplifying the economic environment. Undeniably the laboratory environment adds some artificiality as well. Despite these caveats we believe that the experimental methodology widens the scope for economic case studies, when behavioural influences are known to be relevant but natural data are unavailable.

Further, for the first experimental study on the Syr Darya river conflict we had to restrict the analysis to a few representative scenarios. Many future developments are uncertain today. In the long run, population growth, economic development, or world market demand for cotton may alter the parameters of the real-life situation. There are also worries that the glaciers and snow fields that feed the Syr Darya will shrink because of climate change. As a consequence, inflow would rise in the short run (because the melting water is added to the natural inflow), but fall in the long run (as glaciers are depleted). This increased scarcity of water could reinforce the conflict in the future. The relevant long-term future scenarios are also affected by strategic decisions outside our economic analysis. If construction plans for the Kambarata I and/or II hydropower plants are eventually realised an entirely different situation would arise. Kambarata I could enable the Kyrgyz Republic to produce winter electricity (and export it) by discharging water into the Toktogul Reservoir rather than into the territories of the downstream countries. Kambarata II is a run-off-the river scheme and it does therefore not have any beneficial downstream impact, but it has relatively better prospects of being completed as it is cheaper, smaller and because construction is more progressed. Further research would be needed to incorporate the structural changes in the parameters that any of these plants may produce.

Appendix F. Data used for model estimation

Table F.1 Historical flow data (BCM), Toktogul Reservoir, 1988-2003.

Year	Total Inflow	Total Outflow	Summer Inflow	Summer Outflow	Winter Inflow	Winter Outflow
1988	16.52	12.24	13.46	8.80	3.06	3.44
1989	10.13	14.97	7.34	10.97	2.79	4.00
1990	12.99	11.60	10.25	7.09	2.74	4.51
1991	10.74	13.16	7.93	8.51	2.81	4.65
1992	12.05	12.19	9.05	6.55	3.00	5.64
1993	13.64	10.59	10.61	4.41	3.03	6.18
1994	15.24	14.52	12.08	6.72	3.16	7.80
1995	10.89	14.62	7.88	6.33	3.01	8.29
1996	13.70	14.53	10.94	6.16	2.76	8.37
1997	10.83	13.68	8.09	6.08	2.74	7.60
1998	14.49	11.16	11.50	3.68	2.99	7.48
1999	14.47	13.47	11.01	5.07	3.46	8.40
2000	12.62	15.18	9.19	6.48	3.43	8.70
2001	12.56	15.15	9.29	5.91	3.27	9.24
2002	16.67	11.38	13.51	3.65	3.16	7.73
2003	15.67	14.16	12.00	4.90	3.67	9.26
Average	13.33	13.29	10.26	6.33	3.07	6.96
Relative	100%	100%	77.0%	47.7%	23.0%	52.3%
Minimum	10.13	10.59	7.34	3.65	2.74	3.44
Maximum	16.67	15.18	13.51	10.97	3.67	9.26
SD	2.09	1.56	1.96	1.91	0.28	1.94

Note: Summer: April-September and Winter: October-March.

Source: Primary data provided by JSC Kyrgyzenergo, Bishkek.

Table F.2 Assumed values of exogenous variables and parameters

Name	Description	Unit	Value	Source
α	Hydropower efficiency	kWh/m^3	0.86	1,3
E^s	Net energy demand, summer	GWh	2,550	1
E^w	Net energy demand, summer	GWh	4,950	1
ν^s	Technical transmission efficiency, summer	percent	90.0	1
ν^w	Technical transmission efficiency, winter	percent	85.0	1
K	Generation capacity, Bishkek I	GWh	876	1
C^I	Short-run marginal cost, Bishkek I	US$/kWh	0.0150	1
C^{II}	Short-run marginal cost, Bishkek II	US$/kWh	0.0255	2
C_{uz}	Short-run marginal cost, Uzbekistan	US$/kWh	0.0230	1
C_{ka}	Short-run marginal cost, Kazakhstan	US$/kWh	0.0210	1
ρ	Technical power transmission efficiency	percent	94.0	1
γ	Share of electricity exported to Uzbekistan	percent	50.0	1
X	Maximum hydropower export volume	GWh	4,000	4
P	Economic value of irrigation water	US$/kcm	20	1
O_{uz}	Optimal irrigation input for Uzbekistan	BCM	4.5	1,3
O_{ka}	Optimal irrigation input for Kazakhstan	BCM	2.0	1,3

Sources: (1) World Bank (2004a); (2) World Bank (2004b); (3) Antipova et al (2002), and; (4): Peter Graham, Tariff Policy & Utility Reform Project, DFID Bishkek (personal communication, 9 February 2005).

Table G.1 Payoff table for Q=10 without reservoirs

Units passed by player 1	Units passed by player 2	Player 1's payoff	Player 2's payoff	Player 3's payoff	Total payoff
3	0	333	12	83	428
3	1	333	-58	139	414
3	2	333	-128	195	400
3	3	333	-198	195	330
4	0	272	148	144	564
4	1	272	78	200	55
4	2	272	8	256	536
4	3	272	-62	256	466
4	4	272	-132	256	396
5	0	76	277	229	582
5	1	76	242	285	603
5	2	76	172	341	589
5	3	76	102	341	519
5	4	76	32	341	449
5	5	76	-38	341	379
6	0	-144	370	314	540
6	1	-144	370	370	596
6	2	-144	335	426	617
6	3	-144	265	426	547
6	4	-144	195	426	477
6	5	-144	125	426	407
6	6	-144	55	426	337
7	0	-364	463	399	498
7	1	-364	463	455	554
7	2	-364	463	511	610
7	3	-364	428	511	575
7	4	-364	358	511	505
7	5	-364	288	511	435
7	6	-364	218	511	365
7	7	-364	148	511	295
8	0	-583	549	478	444
8	1	-583	549	534	500
8	2	-583	549	590	556
8	3	-583	549	590	556
8	4	-583	514	590	521
8	5	-583	444	590	451
8	6	-583	374	590	381
8	7	-583	304	590	311
8	8	-583	234	590	241
9	0	-803	549	478	224
9	1	-803	549	534	280
9	2	-803	549	590	336
9	3	-803	549	590	336
9	4	-803	549	590	336
9	5	-803	514	590	301
9	6	-803	444	590	231
9	7	-803	374	590	161
9	8	-803	304	590	91
9	9	-803	234	590	21

Table G.2 Payoff table for Q=10 with reservoirs

Units passed by player 1	Units passed by player 2	Player 1's payoff	Player 2's payoff	Player 3's payoff	Total payoff
3	0	333	117	83	533
3	1	333	117	139	589
3	2	333	47	195	575
3	3	333	-23	195	505
4	0	272	183	144	599
4	1	272	183	200	655
4	2	272	183	256	711
4	3	272	113	256	641
4	4	272	43	256	571
5	0	76	277	229	582
5	1	76	277	285	638
5	2	76	277	341	694
5	3	76	277	341	694
5	4	76	207	341	624
5	5	76	137	341	554
6	0	-144	370	314	540
6	1	-144	370	370	596
6	2	-144	370	426	652
6	3	-144	370	426	652
6	4	-144	370	426	652
6	5	-144	300	426	582
6	6	-144	230	426	512
7	0	-364	463	399	498
7	1	-364	463	455	554
7	2	-364	463	511	610
7	3	-364	463	511	610
7	4	-364	463	511	610
7	5	-364	463	511	610
7	6	-364	393	511	540
7	7	-364	323	511	470
8	0	-583	549	478	444
8	1	-583	549	534	500
8	2	-583	549	590	556
8	3	-583	549	590	556
8	4	-583	549	590	556
8	5	-583	549	590	556
8	6	-583	549	590	556
8	7	-583	479	590	486
8	8	-583	409	590	416
9	0	-803	549	478	224
9	1	-803	549	534	280
9	2	-803	549	590	336
9	3	-803	549	590	336
9	4	-803	549	590	336
9	5	-803	549	590	336
9	6	-803	549	590	336
9	7	-803	549	590	336
9	8	-803	479	590	266
9	9	-803	409	590	196

Table G.3 Payoff table for Q=13 without reservoirs

Units passed by player 1	Units passed by player 2	Player 1's payoff	Player 2's payoff	Player 3's payoff	Total payoff
3	0	333	12	83	428
3	1	333	-58	139	414
3	2	333	-128	195	400
3	3	333	-198	195	330
4	0	370	148	144	662
4	1	370	78	200	648
4	2	370	8	256	634
4	3	370	-62	256	564
4	4	370	-132	256	494
5	0	370	277	229	876
5	1	370	242	285	897
5	2	370	172	341	883
5	3	370	102	341	813
5	4	370	32	341	743
5	5	370	-38	341	673
6	0	370	370	314	1,054
6	1	370	370	370	1,110
6	2	370	335	426	1,131
6	3	370	265	426	1,061
6	4	370	195	426	991
6	5	370	125	426	921
6	6	370	55	426	851
7	0	272	463	399	1,134
7	1	272	463	455	1,190
7	2	272	463	511	1,246
7	3	272	428	511	1,211
7	4	272	358	511	1,141
7	5	272	288	511	1,071
7	6	272	218	511	1,001
7	7	272	148	511	931
8	0	76	549	478	1,103
8	1	76	549	534	1,159
8	2	76	549	590	1,215
8	3	76	549	590	1,215
8	4	76	514	590	1,180
8	5	76	444	590	1,110
8	6	76	374	590	1,040
8	7	76	304	590	970
8	8	76	234	590	900
9	0	-144	549	478	883
9	1	-144	549	534	939
9	2	-144	549	590	995
9	3	-144	549	590	995
9	4	-144	549	590	995
9	5	-144	514	590	960
9	6	-144	444	590	890
9	7	-144	374	590	820
9	8	-144	304	590	750
9	9	-144	234	590	680

Table G.4 Payoff table for Q=13 with reservoirs

Units passed by player 1	Units passed by player 2	Player 1's payoff	Player 2's payoff	Player 3's payoff	Total payoff
3	0	333	117	83	533
3	1	333	117	139	589
3	2	333	47	195	575
3	3	333	-23	195	505
4	0	370	183	144	697
4	1	370	183	200	753
4	2	370	183	256	809
4	3	370	113	256	739
4	4	370	43	256	669
5	0	370	277	229	876
5	1	370	277	285	932
5	2	370	277	341	988
5	3	370	277	341	988
5	4	370	207	341	918
5	5	370	137	341	848
6	0	370	370	314	1,054
6	1	370	370	370	1,110
6	2	370	370	426	1,166
6	3	370	370	426	1,166
6	4	370	370	426	1,166
6	5	370	300	426	1,096
6	6	370	230	426	1,026
7	0	272	463	399	1,134
7	1	272	463	455	1,190
7	2	272	463	511	1,246
7	3	272	463	511	1,246
7	4	272	463	511	1,246
7	5	272	463	511	1,246
7	6	272	393	511	1,176
7	7	272	323	511	1,106
8	0	76	549	478	1,103
8	1	76	549	534	1,159
8	2	76	549	590	1,215
8	3	76	549	590	1,215
8	4	76	549	590	1,215
8	5	76	549	590	1,215
8	6	76	549	590	1,215
8	7	76	479	590	1,145
8	8	76	409	590	1,075
9	0	-144	549	478	883
9	1	-144	549	534	939
9	2	-144	549	590	995
9	3	-144	549	590	995
9	4	-144	549	590	995
9	5	-144	549	590	995
9	6	-144	549	590	995
9	7	-144	549	590	995
9	8	-144	479	590	925
9	9	-144	409	590	855

Table G.5 Payoff table for Q=16 without reservoirs

Units passed by player 1	Units passed by player 2	Player 1's payoff	Player 2's payoff	Player 3's payoff	Total payoff
3	0	333	12	83	428
3	1	333	-58	139	414
3	2	333	-128	195	400
3	3	333	-198	195	330
4	0	370	148	144	662
4	1	370	78	200	648
4	2	370	8	256	634
4	3	370	-62	256	564
4	4	370	-132	256	494
5	0	370	277	229	876
5	1	370	242	285	897
5	2	370	172	341	883
5	3	370	102	341	813
5	4	370	32	341	743
5	5	370	-38	341	673
6	0	370	370	314	1,054
6	1	370	370	370	1,110
6	2	370	335	426	1,131
6	3	370	265	426	1,061
6	4	370	195	426	991
6	5	370	125	426	921
6	6	370	55	426	851
7	0	370	463	399	1,232
7	1	370	463	455	1,288
7	2	370	463	511	1,344
7	3	370	428	511	1,309
7	4	370	358	511	1,239
7	5	370	288	511	1,169
7	6	370	218	511	1,099
7	7	370	148	511	1,029
8	0	370	549	478	1,397
8	1	370	549	534	1,453
8	2	370	549	590	1,509
8	3	370	549	590	1,509
8	4	370	514	590	1,474
8	5	370	444	590	1,404
8	6	370	374	590	1,334
8	7	370	304	590	1,264
8	8	370	234	590	1,194
9	0	370	549	478	1,397
9	1	370	549	534	1,453
9	2	370	549	590	1,509
9	3	370	549	590	1,509
9	4	370	549	590	1,509
9	5	370	514	590	1,474
9	6	370	444	590	1,404
9	7	370	374	590	1,334
9	8	370	304	590	1,264
9	9	370	234	590	1,194

Table G.6 Payoff table for Q=16 with reservoirs

Units passed by player 1	Units passed by player 2	Player 1's payoff	Player 2's payoff	Player 3's payoff	Total payoff
3	0	333	117	83	533
3	1	333	117	139	589
3	2	333	47	195	575
3	3	333	-23	195	505
4	0	370	183	144	697
4	1	370	183	200	753
4	2	370	183	256	809
4	3	370	113	256	739
4	4	370	43	256	669
5	0	370	277	229	876
5	1	370	277	285	932
5	2	370	277	341	988
5	3	370	277	341	988
5	4	370	207	341	918
5	5	370	137	341	848
6	0	370	370	314	1,054
6	1	370	370	370	1,110
6	2	370	370	426	1,166
6	3	370	370	426	1,166
6	4	370	370	426	1,166
6	5	370	300	426	1,096
6	6	370	230	426	1,026
7	0	370	463	399	1,232
7	1	370	463	455	1,288
7	2	370	463	511	1,344
7	3	370	463	511	1,344
7	4	370	463	511	1,344
7	5	370	463	511	1,344
7	6	370	393	511	1,274
7	7	370	323	511	1,204
8	0	370	549	478	1,397
8	1	370	549	534	1,453
8	2	370	549	590	1,509
8	3	370	549	590	1,509
8	4	370	549	590	1,509
8	5	370	549	590	1,509
8	6	370	549	590	1,509
8	7	370	479	590	1,439
8	8	370	409	590	1,369
9	0	370	549	478	1,397
9	1	370	549	534	1,453
9	2	370	549	590	1,509
9	3	370	549	590	1,509
9	4	370	549	590	1,509
9	5	370	549	590	1,509
9	6	370	549	590	1,509
9	7	370	549	590	1,509
9	8	370	479	590	1,439
9	9	370	409	590	1,369

Appendix H. Instructions for the experiment

General information

We thank you for coming to the experiment. The purpose of this session is to study how people make decisions in a particular situation. During the session it is not permitted to talk or communicate with other participants. If you have a question, please raise your hand and the facilitator will come to your desk to answer it. During the session you will earn money. At the end of the session the amount you have earned will be paid to you in cash. Payments are confidential. We will not inform any of the other participants about the amount you have earned. In the following, all amounts of money are denominated in talers, the experimental currency unit.

The participants in this session are divided into groups of three participants. These groups play completely independently. The composition of the groups remains the same throughout the experiment. You do not know which of the other participants are in your group. There are three types of players in this game: Player 1, player 2, and player 3. Participants play the same role throughout the experiment. The experiment consists of twenty-four rounds with the same decision situation. Each round is structured as explained below.

Payoff structure

In each round the three players must divide a resource. At the end of each round the players receive a payoff depending on how the resource has been divided. The division of the resource takes place as follows:

Player 1 receives a quantity of the resource. Player 1 can then pass on some quantity of the resource to player 2. After player 2 has received a share of the resource, he or she can pass on some quantity of this share to player 3.

Player 1's payoff from the resource depends on two factors: (1) how much of the resource is available, and (2) how much of the resource is passed on to player 2.

Player 2's payoff depends on the quantity of the resource received from player 1 minus the quantity passed on to player 3.

Player 3's payoff depends on the quantity of the resource received from player 2.

The payoff of the three players is listed in the enclosed table.

The three player's payoff also depends on the payments they make to each other in exchange for the resources received. This is explained in more detail below.

The decision situation

Each of the twenty-four rounds consists of two stages. The first stage is the negotiation stage. The second stage is the implementation stage.

The negotiation stage

In the negotiation stage the players can make a non-binding agreement over (1) the division of the resource, and (2) payments they make between each other. This is done in the following steps:

Step 1: One of the three players is selected to be the proposer. This selection is random and each player is selected to be the proposer with probability one third.

Step 2: The selected player makes a proposal which specifies the following aspects:

- How many units of the resource player 1 passes on to player 2. All integer numbers between three and nine are feasible.
- How many units of the resource player 2 passes on to player 3. Feasible are all integer numbers between zero and the maximum possible (i.e. the number of units passed from player 1 to player 2).
- How many talers player 2 pays to player 1. All integer numbers from 0 to 1,000 are feasible.
- How many talers player 3 pays to player 2. All integer numbers from 0 to 1,000 are feasible.

Step 3: Each of the two other players (apart from the proposer) decides whether to accept or reject the proposal.

Note that an agreement made in the negotiation stage is not binding. It does not commit the players to act in any particular way at the implementation stage.

The implementation stage

In the implementation stage the division of the resource as well as payments between players are implemented. This is done in the following steps:

Step 4: Player 1 decides how many units of the resource to pass on to player 2. This integer number must be between three and nine (both inclusive).

Step 5: Player 2 decides how many units of the resource to pass on to player 3. Feasible are all integer numbers between zero and the total amount of units received from player 1.

Step 6: Player 2 decides how many talers to pay player 1. All integer numbers from 0 to 1,000 are feasible.

Step 7: Player 3 decides how many talers to pay player 2. All integer numbers from 0 to 1,000 are feasible.

Phases

The experiment is divided into of three phases, each consisting of eight rounds. Each round is played exactly the same way as described above. The rounds differ in the quantity of the resource that is available.

The players' payoffs vary with the available quantity of the resource. Therefore a different payoff table is used for each phase. At the outset of a new phase you will be given the relevant payoff table. Please note that the payoff table lists the payoffs of the players excluding the payments made between them.

Payoffs

You start with an initial capital of 1,000 talers. Your payoff from each round will be added to this amount. At the end of the session the talers are converted into Pound Sterling at an exchange rate of £2.50 per 1,000 talers. The minimum payoff is £3.

Chapter 5. Conclusion

In this thesis we have examined three issues arising from transboundary river sharing: 1) the equity-efficiency trade-off; 2) the role of multilateral development banks (MDBs) in reducing hydropower-irrigation conflicts, and; 3) cooperative behaviour on the Syr Darya river. The purpose of this final chapter is to bring together the issues raised in chapters 2-4, to highlight lessons learnt and to consider possible future directions for the research programme. The chapter is organised as follows: Section 1 summarises the key findings of the thesis. Section 2 contains a comparative analysis of the three core chapters. Section 3 highlights some limitations of the research findings and the methodology used. Section 4 suggests areas of future research.

1. Summary of findings

Chapter 2 explored the relationship between equity and efficiency on a transboundary river. This was done in a theoretical model by comparing riparian profit in the noncooperative allocation with that in the equal quota cooperative agreement. We found that the noncooperative approach is socially inefficient when water is scarce due to decreasing marginal productivity of water. Moreover, if the upstream riparian uses its optimal quantity the downstream riparian suffers disproportionately. In comparison, the equal quota allocation is at least as efficient as noncooperation when riparians are identical or when the downstream riparian is relatively cost-effective and generates a cooperative surplus if water is sufficiently scarce. The equity-efficiency trade-off is found to be relatively insignificant, in magnitude as well as prevalence, limited to some special cases where the upstream riparian has a high relative cost advantage and water is very scarce.

At a more general level, the analysis aimed to provide an analytical framework for examining the efficiency implications of any exogenously defined sharing rule. The proposed policy algorithm sheds light on some of the key steps involved in making economically rational decisions about how to reach a water sharing agreement. Encouragingly, the algorithm is roughly similar to the approach taken by the World Bank in its involvement with governments sharing transboundary rivers.[1]

Chapter 3 looked at the role of multilateral development banks (MDBs) in reducing regional tension over upstream hydropower use and downstream irrigation use. Our findings were based on a theoretical model with two riparians in which we derived the comparative static properties of the noncooperative equilibrium. We found that regional stability and basinwide social efficiency can, under certain conditions, be improved through externality-reducing and Pareto-improving investments, such as enhancement of upstream hydropower efficiency and expansion of downstream reservoir capacity. Investments in upstream hydropower efficiency should be made only under two conditions: a) that the upstream riparian agrees to increase water releases in the downstream vegetation season, and; b) that the upstream riparian commits itself not to expand its reservoir capacity further. The aim of both conditions is to reduce any potential harm that the upstream riparian may impose on its downstream neighbor. We also considered the possibility that a downstream client state could be more effectively assisted by an MDB through

[1] This was pointed by Aaron Wolf, Oregon State University, as he reviewed an earlier version of chapter 2 (personal communication 3 March 2003).

upstream intervention. This policy option is particularly attractive if there are substantial seasonal variations in upstream power demand.

More generally, the analysis facilitated the evaluation of a range of relevant policy interventions. By narrowing down the policy objectives to only two dimensions (externality impact and basinwide welfare) we showed that it was possible to rank these interventions. Using this approach, some policies could be eliminated (i.e. upstream reservoir expansion) while others would be relevant only under certain conditions (i.e. upstream hydropower efficiency). These conditions included hydropower production technology and the possibility of binding supply/storage constraints.

Finally, in Chapter 4, we examined cooperative behaviour in the Syr Darya river conflict. In laboratory experiments, subjects played a multiround three-player trust game with non-binding contracts. This game represented a simplified version of the existing system of annual barter agreements. Costs and benefits of alternative water releases were computed using best available data from the region. An important research objective was to establish the economic impact of Uzbek reservoirs. From Chapter 3 we learnt that construction of a downstream reservoir can reduce the impact of the negative externality and improve downstream welfare by increasing irrigation water availability and reducing the risk of flooding. This result was developed in a noncooperative setting, however. It therefore excluded the possibility that Syr Darya riparians could resume cooperation over water releases in the future in which case behavioural responses may become important. The laboratory experiments conducted are well-suited for addressing this issue. A possible effect of enhanced cooperation can be detected statistically in the experimental data, but it is relatively small. As an overall effect of the new reservoirs we observe a median efficiency gain of US$ 16.1 million per year in low-water years, and no significant effect for normal and high-water years. The experimental results also suggest that the causes of noncooperation on the Syr Darya are systematic rather than idiosyncratic. Inefficient noncooperative outcomes prevail in our experiments, in contrast to most trust games reported in the experimental literature. This difference can be explained as follows. In our experiments, the payoff structure is such that players often run high risks, but receive a relatively modest gain. Moreover, for cooperation to prevail it requires the simultaneous trust of three players. In the experimental literature, on the other hand, payoffs are much more favourable to cooperation and trustful behaviour is required by only two players.

Chapter 4 also demonstrated how economic analysis can contribute to understanding the incentives for cooperation on transboundary rivers. Recall the study by Wolf *et al.* (2003) reported in the introductory chapter. That study identified the determinants of conflict and cooperation using multivariate regression analysis on a data set containing all international river basins in the world. The behavioural experiments reported in Chapter 4 represent an alternative methodology to identifying these determinants for an individual basin. Specifically, we examined the impact of two determinants: Uzbek reservoirs and water availability. In fact our results that noncooperation occurs in years with low water flow provides evidence in support of the Neo-Malthusian hypothesis (see Chapter 1). In comparison, Wolf *et al.* (2003)

found little evidence of this tendency in their cross-sectional data analysis. Thus, while water scarcity cannot be said to generally cause noncooperation, it does play an important role on some transboundary rivers, such as the Syr Darya.

2. A comparison of the three contributions

The essays contained in this thesis do have many similarities in terms of approach and methodology, but there are important differences as well. Table 5.1 compares the three chapters in terms of a range of defining characteristics. Chapters 2 and 3 both consider river problems in a theoretical model involving two riparians and share a normative analytical approach. Chapters 3 and 4 deal with hydropower-irrigation conflicts and with Syr Darya. Finally, chapters 2 and 4 both take a cooperative approach.

Table 5.1 Comparative analysis of the three core chapters

	2. Sharing transboundary rivers fairly and efficiently	3. Hydro-irrigation conflicts and the role of MDBs	4. The Syr Darya conflict - an experimental case study
Objective	Identifies a fair and efficient alternative to noncooperation	Ranks externality-reducing policies and compares upstream vs. downstream intervention	Investigates riparian cooperative behaviour
Methodology	Microeconomic theory	Microeconomic theory	Experimental economics
Approach	Cooperative	Noncooperative	Cooperative
Analysis	Normative	Normative	Positive
Generality of results	Analytical framework	Analytical framework with case study	Case study only
Riparians	Two	Two	Three
Conflict type	Quantity sharing	Inter-temporal	Inter-temporal
Water-related activity	Irrigated agriculture	Irrigated agriculture and hydropower	Irrigated agriculture and hydropower
Policy relevance	Aids negotiators in implementing an exogenous sharing rule.	Ranks qualitative properties of policy interventions.	Informs regional stakeholders of the impact of Uzbek reservoirs.

3. Limitations

It is inevitable that any study concentrates on certain aspects of a problem to the exclusion of others and this thesis is no exception. In this section we briefly highlight a number of important issues which have been excluded from the analysis.

1. Water is essential for all life on this planet. It follows that water has multiple uses. This thesis focuses on water as an input in the

production of a marketable output with economic value. More specifically, it deals exclusively with water use for agricultural irrigation and hydropower production. As a consequence there are other economic aspects of transboundary water use which have been ignored, notably water for industrial use, navigation and tourism. Access to clean water and sanitation also has an impact on labour productivity (through reduced illness), but again, such aspects are ignored here.

2. A number of important issues related to geography deserve mention. First, by focusing exclusively on rivers with an upstream-downstream geography the thesis ignores other relevant types of geography. In the case of river basins shared by only two countries, the most important exception is border rivers, i.e. rivers which form the international border between two countries. Recall from the introductory chapter that 176 of the 261 international river basins of the world have only two riparians. Seventy-six of these rivers are in fact border rivers and the analysis contained in chapters 2 and 3 is therefore not relevant for these rivers (albeit the remaining 100 rivers are). Secondly, the thesis deals exclusively with rivers with a so-called I-geography, i.e. where the water flows from an upstream country to a mid- or downstream country. For rivers with 3 or more riparians, there is a range of possible geographies. Consider, for instance, the Y-geography with two countries upstream and one country downstream. The lack of readily available statistics classifying transboundary rivers according to their geography makes it difficult to assess the extent of this omission. Finally, while two-riparian upstream-downstream rivers have been well-covered

in chapters 2 and 3 and three-riparian rivers touched upon in Chapter 4 the thesis has little to say about rivers that are shared by 4 or more riparians. In sum, the analysis contained here is of high relevance to some, albeit not all transboundary rivers in the world.

3. The stochastic nature of the annual volume of river water is an important issue that deserves mention here. Kilgour and Dinar (1995) is one of the few contributions that treat this physical fact explicitly in their theoretical analysis. They point out that 'river flow is well known to be affected by weather, for example, and fluctuations of 25% above or below the mean annual flow volume are quite common' (ibid. p. 4). Different levels of water availability are considered throughout the thesis, but the stochastic nature is often omitted. In chapters 2 and 3 we assume that water flow is exogenously determined or perfectly forecast. The range of water flow plays a role in the policy algorithm of Chapter 2, but is not modelled explicitly. The experimental design in Chapter 4 originally involved a stochastic resource availability, but this aspect was eventually omitted because of the complexities involved in negotiation the sharing of a resource, the size of which is stochastically determined.

4. Policy analysis takes a central role in the thesis. We consider, however, only a limited set of these objectives here to the exclusion of others. Our attention has been on the objectives of economic efficiency, equity and regional stability. An important omission, however, which should be mentioned here is the lack of consideration of environmental sus-

tainability. This omission stems from our principal analytical interest in river conflicts rather than in water as a scarce resource.

5. As in the case of stochastic flows, there is a tendency in the literature to ignore the issue of water quality (Sigman, 2002 is a notable exception). Arguably, a transboundary river agreement may fail for reasons related to water quality as well as quantity. Whether an upstream country has pure water is determined by that country alone, whereas the purity of the downstream country's water is determined by both countries. Water quality is particularly relevant when countries use irrigation water because return flows have a high salinity content and thus the quality of the water decreases the further downstream the fields are located. Irrespective of this, this thesis is based on the assumption that water quality is homogenous throughout the river basin.

4. Directions for future research

In conclusion, we highlight directions for future research. We address two questions: First, if this research had to be conducted again, how could it have been done differently? Secondly, if the research programme were to continue which directions could it usefully take?

What could have been done differently?

In answering this question we focus exclusively on two methodological issues encountered in the experimental analysis contained in Chapter 4. The first relates to the desirability of exploring the multi-year regulation ability of the Toktogul reservoir. Recall that this ability was ignored using the assumption that annual inflow equals annual outflow. By relaxing this assumption, the Kyrgyz player would have been equipped with an extra variable, namely the storage reservoir, the volume of which would pass from year to year (round to round). In this case, a minimum and a maximum storage capacity would also have needed to be included. By considering Toktogul's multi-year ability the validity of our findings would have been increased. Why was this assumption made then? Basically, because the real-life situation was complex and the experiment had to be simple, there was a great demand for simplifying assumptions. In actual fact, the subjects learnt the game faster than anticipated (see section section 5.8 in chapter 4). In hindsight, therefore, adding an extra variable to the game would probably have been possible without to great a cost in terms of complexity added.

The second issue relates to the cotton production function in the experimental analysis. Ideally, this production function would have been estimated empirically using real data from the region. As a consequence, considerable amounts of time and effort went into this process. Two different approaches were taken. The first approach, based on 'macro' data regressed Uzbek cotton yields against summer releases from Toktogul. In the second approach, 'micro' data was used by regressing cotton yields in the Uzbek province of Ferghana with water use within the Yazavan district of that province. Both approaches relied on relatively few observations based on annual time series data from the 1990s. Although, the OLS regression results were robust (high R^2 and significant t-values), the estimated value of water turned out to be unrealistically high. Depending on the total water availability (we estimated a quadratic production function), the micro approach yielded 22-177

US$/KCM while the macro approach yielded 57-146 US$/KCM. In comparison, the World Bank (2004a) quotes a study which estimates the value of water at 20-50 US$/KCM in the Central Asian region. As a consequence, we decided to use a linear production function with a saturation point using the lower bound of that estimate (US$20/KCM) to produce conservative benefit estimates. What were the reasons for the differences in the estimation of the economic value of water? First, there was a considerable discrepancy between the geographical location of the independent and the dependent variables. Ideally, the relationship between cotton yields and water input should be studied on the farm level, but unfortunately we did not have access to this type of data. Secondly, there was a lack of data for other relevant explanatory variables, notably precipitation. Finally, the number of observations was too small to allow accurate estimations.

Directions for future research

As a starting point, future research could aim to address some of the limitations of the methodological approach taken, as outline in section 3. This includes testing the robustness of theoretical results in chapters 2 and 3 with respect to: a) different types of geography; b) the stochastic nature of water and; c) water quality. Moreover, one could also consider what would happen if each country had, say, two water-using sectors thereby allowing for more flexibility in water sharing.

In Chapter 3 we analyse what is essentially a dynamic problem using a static two-period model. As mentioned above this is made possible through the assumption that total inflow equals total outflow. While a static model is entirely suitable for our purposes it is possible that a dynamic model may yield further insights and challenge the general validity of some of the theoretical findings. This thus represents one possible route for further research. Moreover, it could also be thought of merely as a process towards the much more ambitious objective of developing a comprehensive economic model of the Syr Darya river basin using mathematical programming akin to the many US case studies reported in Chapter 3. Substantial analytical work of this kind has already been conducted with the support of USAID as reported in Antipova *et al.* (2002). A major drawback of their work (from the perspective of an economist) is that the optimisation criterion used is to minimise the cost of covering Kyrgyzstan's domestic energy demand as opposed to the preferred criterion of maximising basinwide social welfare.

Finally, the introduction of experimental economics to the study of transboundary river conflicts also represents a possible avenue for future research. This methodology opens the possibility of examining behavioural responses to changes in important parameters on the river. Examples include changes in government policy, proposed investments or climatic change. In addition, experiments can shed light on existing conflicts by examining whether their causes are systemic or idiosyncratic. Finally, as mention above, experiments constitute an alternative methodology to identifying the determinants of cooperation on individual rivers. Follow-up experiments on other transboundary river conflicts therefore seem relevant where these conflicts can be framed in game-theoretic terms.

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