Game-theoretic models of water allocation in transboundary river basins

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Abstract

The combined effects of climate change on river flow and growing water demand cause an increase of water scarcity in many river basins. In transboundary basins where water is scarce, this development is one of the drivers of both noncompliance with water allocation agreements and conflicts over the property rights to river water. An unresolved challenge is how cooperation in water allocation can be improved. Underlying this challenge are the issues of contested property rights to river water, and the design and stability of international water allocation agreements. The objective of this thesis is to analyse water allocation in transboundary river basins, focusing on the strategic interaction between riparian countries regarding their decisions on water use. The main methodology applied is game theory. I construct game-theoretic models to analyse cooperative agreements on water allocation, to assess strategic interaction when water is contested, and to design sharing rules for river water with attractive properties. The results show that increasing water scarcity may aggravate noncompliance with water allocation agreements, but that a careful agreement design suffices to provide stability. Existing claims and property rights to water are important determinants for both the probability of conflict over river water, and the outcome of negotiations on water allocation. In addition, it is impossible to single out a unique fair allocation of transboundary river water. Overall, this thesis provides insight into the strategic aspects that play an important role in the transboundary water allocation problem and its possible solutions.

Chapter 1

Introduction*

The 2009 World Water Day paid particular attention to transboundary waters, its theme was "Shared Water—Shared Opportunities". The accompanying brochure stated:[1]

> There is enough freshwater to meet everyone's needs. But the world's supply of freshwater is not evenly distributed and often not appropriately managed. Many countries are already facing increasing scarcity of freshwater. By 2025, 1800 million people will be living in countries or regions with absolute water scarcity, and two-thirds of the world's population could be under stress conditions.

This is an unpleasant message that has been broadly discussed in the media and scientific literature over the last years. Water scarcity, fed by impacts of climate change and increasing water demand, is an increasing threat to human welfare and economic development, constraining consumption and production possibilities.

On a national level, the reliable supply of water to meet the needs of households, agriculture, and industry is a crucial factor. Because the hydrological

*Section 1.1 of this chapter is based on Ansink et al. (2005). Anticipated climate, economic and policy changes and their impacts on European river basins. AquaTerra Deliverable I1.2, Wageningen University.

[1] The brochure can be found on-line at `http://www.unwater.org/worldwaterday/`. World Water Day is an annual event to celebrate freshwater, initiated at the 1992 United Nations Conference on Environment and Development.

reality often does not match these needs, transboundary cooperation may be required. The brochure covered this topic too:

> With every country seeking to satisfy its water needs from limited water resources (. . .), some foresee a future filled with conflict. But history shows that cooperation, not conflict, is the most common response to transboundary water management issues. Over the past 60 years there have been nearly 300 international water agreements and only 37 cases of reported violence between states over water.

In transboundary river basins, countries have been able, on some occasions, to establish property rights to water and thereby increase the overall benefits of water use. This is not the complete story, though. International agreements may not be complied with, conflict over water may occur anyway, and clear internationally accepted norms for the allocation of river water are lacking.

The turbulent history of water sharing in the Ganges basin by India (upstream) and Bangladesh (downstream) is a good illustration. After twelve years of negotiations, cooperation between the two countries started officially in 1972, with the establishment of the Indo-Bangladesh Joint Rivers Commission. In 1976, however, agreed-upon maximum diversions by India at the Farakka barrage were vastly exceeded, leading to serious environmental and economic damage in Bangladesh. Due to lack of internationally accepted rules for water sharing, intervention by the United Nations could only urge the parties to meet and "arrive at a fair and expeditious settlement". Short-term agreements were reached in 1977 and 1985 but were not successful, before the Ganges Treaty was signed in 1996. In the following season already, both countries were involved in a dispute because India allegedly exceeded its share allocated under the Ganges Treaty.[2]

In light of this illustration, the following recommendation in the brochure seems obvious:

> Work remains to be done to improve and implement these international agreements. In addition, more agreements are required. Of the world's 263 international river basins and transboundary aquifer systems, 158 do not have any type of cooperative management framework in place.

[2] See Bandyopadhyay (1995); Nishat and Faisal (2000); Tanzeema and Faisal (2001) for more background information on the sharing of the Ganges river.

Improvement and implementation are indeed necessary. Unresolved questions are, however, how cooperation can be improved, and how to design international agreements such that countries will not break them. Underlying these questions are the issues of contested property rights to river water and the design of attractive sharing rules for river water.

This thesis covers these aspects of water allocation in transboundary river basins, the theme of the 2009 World Water Day. It just as well covers the theme of the 2007 World Water Day, "Coping with Water Scarcity", and it touches on many other themes and issues that are important in the water literature and water management practice. The main source of the methodology applied to study this topic is game theory. Game theory is a branch of micro-economic theory that analyses behaviour in situations of strategic interaction. It is therefore well-suited to analyse the interaction between riparian countries regarding their decisions on water use. In chapters 2–5, I construct game-theoretic models to analyse cooperative agreements on water allocation, to assess strategic interaction when water is contested, and to design sharing rules for river water with attractive properties.

Before doing so, in the remaining sections of this introduction I provide evidence for the scarcity of water, both now and in the future. The current water scarcity is intensified by two global trends that are likely to accelerate in the coming decades: climate change effects on river flow and increasing water demand. Combined, these trends affect the balance of supply and demand of water, see section 1.1. Subsequently, in section 1.2, I will discuss the institutional setting of transboundary river sharing. Jointly, these two sections describe the factors that bring about increasing water scarcity and inefficient water allocation in transboundary river basins. I will discuss these factors now before moving on to a brief review of existing approaches and the specific objectives of this thesis in sections 1.3 and 1.4.

1.1 Water scarcity: supply and demand

Jointly, water supply and demand determine the level of water scarcity. The scarcity of water is sometimes measured by the concept of "water stress". Water stress is defined as the available water volume per capita per year and water stress is said to occur at levels below 1,000 m^3 per capita per year. Estimates of the number of people living in water-stressed river basins range from 1.4 to 2.1 billion (Vörösmarty et al., 2000; Alcamo et al., 2003; Bates et al., 2008). Clearly, water scarcity is an issue that affects a large share of the world's population. A number of trends in the supply and demand of water contribute to increasing water scarcity (cf. IPCC, 2007b; Nations, 2009a). Climate change is affecting various climate components that ultimately influence the supply of water through aquifers and water flow in river basins. Changes in driving forces related to demographic developments affect the demand for water from river basins. I will discuss the changes in supply and demand using these two trends of climate change impacts and increasing water demand, starting with climate change.

1.1.1 Climate change

Climate change refers to long-term changes in the average pattern of the weather, caused by natural or anthropogenic factors. In spite of the many uncertainties related to climate change itself as well as its consequences, three main effects of climate change on global water resources can be distinguished. These effects relate to atmospheric circulation, temperature, and precipitation (Arnell, 1999a,b; Allen et al., 2000). Jointly, they affect the quantity and variability of river runoff, the frequency and severity of extreme events, and the quality of water.

Atmospheric circulation is the main control behind many climate components including temperature, precipitation, and soil moisture, and is closely related to climate change and climate variability on a regional scale (Räisänen et al., 2004). Globally, temperature is steadily increasing, as measured by the global surface temperature (IPCC, 2007b). Projected effects of climate change on temperature in Europe show that temperatures in Europe since the late 20th century exceed those of any time during the last five centuries (Luterbacher et al., 2004). Overall, temperature has increased by 0.95°C over the last century, with large regional differences in the extent of warming (Klein Tank and Können, 2003). Precipitation levels have increased and are projected to increase over the coming decades because of climate change. Since the beginning of the 20th century, global land precipitation has increased considerably (IPCC, 2007b; Hulme et al., 1998; Schonwiese and Rapp, 1997). Next to precipitation levels, the frequency and intensity of extreme precipitation events have increased too (Easterling et al., 2000). These increases in extreme precipitation events are closely related to increases in mean precipitation (Groisman et al., 1999). Various climate models project a sharp increase in mean precipitation levels and the occurrence of extreme precipitation events, even in those areas where mean precipitation levels decrease (Räisänen et al., 2004). An additional effect is increasing mean winter precipitation which, combined with temperature increases, causes part of winter precipitation to fall as rain instead of snow (Arnell, 1999a,b).

River runoff changes are caused by the combined effects of temperature increase and changes in evaporation, soil moisture, and precipitation. Relatively small changes in temperature already have serious impacts on river runoff, mainly because of its effect on evaporation (Arnell, 1999b). This effect may even outweigh the effect of increased precipitation (Frederick and Major, 1997). In snow-dominated river basins, the amounts of snow and rain change when the temperature increases. The snow-pack season will be considerably shortened in many regions as a result of earlier and more rapid snow-melt (Arnell, 1999b). The consequences on river runoff are evident: winter runoff increases with higher peaks and the peak runoff (that normally occurs in spring) shifts to an earlier period in the year (Nijssen et al., 2001). Earlier snow-melt in basins with snow regimes gives room for faster and more intense drying of soil moisture in spring and summertime. As a consequence, changes in soil moisture storage will be positive in fall and winter and negative in spring and summer. This process has a close link to runoff levels in the respective seasons.

Floods and droughts are expected to occur more frequently and be more intense because of changing precipitation patterns (Arnell, 1994; Milly et al., 2002; Christensen and Christensen, 2003). The effect of more extreme high and low flow months within one year can be seen in many parts of the world and may explain part of the increase in flood frequency and intensity (Lehner et al., 2001). Climate models generally agree on a continuation of this trend (IPCC, 2007a).

The overall result of climate change on river runoff is a change in the mean runoff, an increase in runoff variability, both between seasons and between years, and an increase in the frequency of extreme events (cf. Voss et al., 2002; Milly et al., 2005). Many areas, especially in arid and semi-arid climates, will see an overall decrease in water availability (Alcamo and Henrichs, 2002; Arnell, 2004). This result adds to the already existing stochasticity and uncertainty in the availability of water resources (Krzysztofowicz, 2001; Montanari and Grossi, 2008). Clearly, climate change—whether it is caused by natural or anthropogenic factors—adds to this stochasticity and is not its single cause. In fact, Hulme et al. (1999) have shown that the impacts of natural climate variability on environment and society may be larger than the impacts of climate change (see also Shanahan et al., 2009).

Increases in temperature, floods, and droughts have a pronounced effect on water quality, through various hydrological and chemical processes. Higher water temperatures reduce oxygen concentrations and increase the release of phosphorus. The projected increase in extreme events, including floods and droughts, increases the amount of suspended solids, decreases the dilution capacity for contaminants, and enhances the transportation of pollutants (Bates et al., 2008). The result of these processes is a decrease in the availability of freshwater, further increasing water scarcity.

1.1.2 Water demand

Water scarcity is related to increasing water demand by various economic sectors, spurred by economic growth, urbanisation, technological innovation, population growth, and consumption patterns of this growing population (most notably their diet).

The four main economic sectors in terms of water demand are agriculture, industry, energy, and households. Each has its own characteristics and features different impacts on water quality and quantity, and each has different needs concerning water quality (Becker et al., 2000). It is important to distinguish between consumptive and non-consumptive use of water. For example, in the case of cooling of hydro-power plants, less than 10% of abstracted water is actually consumed. The vast majority of the abstracted water is redirected to the water cycle, ready to be used for other purposes. In the literature, the terms water use and water abstraction usually include both types of water use while "water consumption" refers to consumptive use only.

Agriculture is the largest water using sector, accounting for 70% of global water abstraction, ranging from 34% in the EU to 89% in South Asia (Shiklomanov and Rodda, 2003). Principal water uses by the agricultural sector include direct abstraction of groundwater and surface water for irrigation purposes and watering of livestock. The amount of irrigation water needed and the time of irrigation depends on the irrigation efficiency, water availability, crop type, and soil- and climatic conditions. Irrigated agriculture is the economic sector that will be affected most strongly by climate change. It is also the sector where changes in the production efficiency (i.e. irrigation effectiveness) have the strongest effects on overall water use (IPCC, 2007a). The combined effect of climate change and irrigation efficiency determines the trend in overall water use in agriculture. Using a global irrigation model with climatic predictions for the 2020s and 2070s, Döll (2002) finds that two-thirds of 1995 irrigation area will face modest increased water requirements by up to 8%. Over the period 1998–2030, the amount of irrigated land is projected to increase by 0.6% per year on average, compared with 1.5% over the period 1950–1990 (Nations, 2009a).

Industrial water use accounts for 21% of global water abstraction, ranging from 5% in Africa and South Asia to 51% in the EU (Shiklomanov and Rodda, 2003). Principal water using industries are ferrous and non-ferrous metallurgy, chemical and petroleum plants, machinery manufacture, and the wood pulp and paper industry. Actual water use in these industries is very much dependent on the water supply technology being used. Main water use purposes include process water, boiler feed water, and cooling water. Although economic growth correlates with water use in industry, technological progress (i.e. improvements in water use efficiency), possibly induced by water pricing (cf. Reynaud, 2003), may weaken this correlation. Water use efficiency reflects the amount of water used per unit of product. Scenarios developed by Alcamo et al. (2000) project an annual increase of water use efficiency in the industrial sector in the range from 1% to 3% up to 2025, mainly due to improvements in wastewater recycling. This progress in efficiency offsets prospected growth of the industrial sector. A similar result is reported by Cole (2004) in an analysis of the relation between economic growth and water use, where he finds an environmental Kuznets curve (i.e. an inverted U-shaped relationship).

Water use for energy production is largely non-consumptive. Except for an increased temperature of return water and possibly some biocide contamination, water use for the energy sector has no effects on water scarcity (EEA, 2001).

Household water use accounts for 10% of global water abstraction, ranging from 6% in South Asia to 19% in Latin America (Shiklomanov and Rodda, 2003). Principal water uses by households include the direct abstraction of water for domestic uses, municipal services, public gardening, and small industries (that are connected to public water supply). The amount of household water use depends on various factors, including climate, the efficiency of public supply systems, water use habits, technological change and socio-economic conditions. UN projections for global population indicate that the world population reaches 7 billion in 2012, up from the current 6.8 billion, and reaches 9 billion people by 2050 (Nations, 2009b). Almost all of this 2.3 billion increase occurs in developing countries, with population in developed countries only marginally increasing from 1.23 to 1.28 billion by 2050.

Two additional features of this increasing population are relevant. The first feature is urbanisation. UN projects for urbanisation indicate that the urban population will roughly double between 2007 and 2050, from 3.3 billion to 6.4 billion (Nations, 2008). Compared with the increase of total population, this implies a net migration from rural to urban areas. Several problems are related to urban water use. Urban water use per capita is higher than rural water use, due to different lifestyles (cf. Bates et al., 2008). Urban water use generally leads to pollution problems and reduced groundwater recharge , decreasing the amount of available freshwater (Gleick, 1998; Vörösmarty et al., 2000). In addition, urban water use creates very high local demand, which requires increased water transportation and infrastructure, leading to evaporation and conveyance loss (cf. Gleick, 1998; Thompson et al., 2000).

The second feature is the overall change in consumption patterns, habits, and diet with increasing income. Changing diet has the largest implication. As living standards increase, the consumption of meat and dairy products increases (meat consumption per capita has more than doubled in China since 1985) (Nations, 2009a). The production of meat and dairy is very water-intensive though. Liu et al. (2008) estimate for China that while it takes only 800–1,300 litres of water to produce a kilogram of cereals, it takes 2,400–12,600 litres of water to produce a kilogram of meat, a difference of a factor 2–10 (while, compared with cereals, meat has a lower energy content per kilogram on average). Similar changes occur in other growing economies (Nations, 2009a).

Comparing projected water use between sectors, Rosegrant and Cai (2002) conclude that water use will increase rapidly for industry and households, while agricultural water use will increase only slowly. In absolute levels, however, agriculture will remain the largest water user. As stated as one of the key messages in the United Nations World Water Development Report (Nations, 2009a):

> Steadily increasing demand for agricultural products to satisfy the needs of a growing population continues to be the main driver be-

hind water use. While world population growth has slowed since the 1970s and is expected to continue its downward trend, steady economic development, in particular in emerging market economies, has translated into demand for a more varied diet, including meat and dairy products, putting additional pressure on water resources.

Jointly, changes in supply and demand will cause increasing water scarcity (Vörösmarty et al., 2000; Arnell, 2004). Shiklomanov and Rodda (2003) estimate that total water use increases from 8.4% of global water resources in 1995 to 12.2% in 2025. Part of this increasing scarcity will be offset by shifts in international trade patterns, causing some regions to gain from this scarcity (Berrittella et al., 2007). Regional differences in the anticipated changes are to be expected because of specific regional climatic and economic conditions. Alcamo et al. (2007) find that the principal factor that causes increasing water scarcity is the increase in household water use caused by increasing household income. As a result, the major share (93%) of increased demand for water is projected to occur in developing countries, while only limited increases in water supply are feasible (Rosegrant and Cai, 2002). Overall, up to 2050 water scarcity increases in 62–76% of total global river basin area, and decreases in 20–29% (Alcamo et al., 2007). The next section discusses the institutional setting that has evolved in these water scarce river basins.

1.2 Institutional setting

The institutional setting of water allocation in transboundary river basins is strongly determined by the hydro-geographical context (cf. Saleth and Dinar, 2005; Dombrowsky, 2007). Relevant institutions in this setting include water rights, principles for sharing water, joint river basin committees, and water allocation agreements.

The hydro-geographical configuration of transboundary river basins is often so-called through-border, with one country being located upstream of the other. Alternative configurations include the case where a river forms the boundary between two countries and many hybrid configurations (Dinar, 2006). In this thesis, the focus is on river basins with a through-border configuration. This geographical setting causes an asymmetry between the countries in terms of being able to affect water use in the other country (Van der Zaag, 2007). Asymmetry may for instance lead to downstream foregone benefits—because the upstream country uses all available water—or physical damage as a result of low-quality irrigation return flows or flood management (Zawahri, 2008b). Note that factors other than geography, such as power distribution, also play a role in the relation between riparian neighbours (Dinar, 2006; Zeitoun and Warner, 2006).

The stochasticity and uncertainty of river flow, as discussed above, translates into ever-changing conditions for international water allocation. Various instruments have been applied by countries to allocate water under these conditions. Water allocation agreements are a common instrument, based on a large variety of underlying principles for water allocation. Many such agreements, however, are void because they are not sufficiently flexible to adjust to the hydrological reality (McCaffrey, 2003; Drieschova et al., 2008). This observation also holds for other instruments to allocate water (cf. Young and McColl, 2009).

There are two major institutional obstacles for international cooperation on water allocation. The first obstacle is the absence of well-defined property rights to water (Richards and Singh, 2001). This situation is caused by river water being a flowing resource. Two dominant and conflicting principles of water rights have emerged in international law (Salman, 2007; Dellapenna, 2007). One is "absolute territorial sovereignty", which says that every country has the right to all river water within its territory. The other is "absolute territorial integrity", which says that every country has the right to all river water within and upstream of its territory. In absence of well-defined property rights, water trade cannot resolve water shortages or inefficient allocation (Holden and Thobani, 1996).

Although formal property rights may be missing, history and custom often determine some kind of status quo water allocation. Such a process forms the basis for water rights in the US, called the doctrine of appropriative rights (Burness and Quirk, 1979). In an international setting, this doctrine is meaningless as there is no authority to enforce rights. The result is, in many river basins, the presence of overlapping or conflicting claims to water (Dellapenna, 2007). These claims can be based on a number of water sharing principles. Wolf (1999) provides an overview of these principles. They include principles based on historic use, based on water needs (e.g. irrigation requirements), water rights (e.g. the principles of sovereignty and integrity introduced above), or based on international water law (e.g. the Helsinki Rules (1966), the UN Watercourses Convention (1997), and the

Berlin Rules (2004)) (see also Wolf, 1999; Giordano and Wolf, 2001; Van der Zaag et al., 2002). The principles introduced above are often used in actual negotiation processes on water allocation (Beach et al., 2000; Daoudy, 2008). The Nile basin, for example, has ten riparian countries with Egypt and Sudan being the largest consumers of the Nile water. The claims of Sudan and Egypt are disputed by the other riparians. Egypt defends its claim by pointing to the principle of historic rights. Ethiopia and Sudan, upstream of Egypt, defend their claims based on the principle of "reasonable and equitable use", a notion introduced by the Helsinki Rules. In addition, Sudan defends its claim based on economic principles, because it has a comparative advantage in terms of available land (Just and Netanyahu, 1998). Clearly, contested claims to water provide the starting point for possible cooperation or conflict over water (Waterbury, 1997).

The second obstacle for international cooperation on water allocation is the above-mentioned lack of a supra-national authority (Barrett, 1994b). Such an authority would be helpful in monitoring and enforcing compliance to some contract that specifies the allocation of water. In absence of a supra-national authority, two work-around solutions are dominant in international water allocation. These are joint river basin committees and water allocation agreements.

Joint river basin committees (or international river basin organisations) often serve as a continuing negotiation table for decisions on water development that affect the other riparian(s). A prominent example of a successful committee is the Mekong Committee. The Mekong Committee was established in 1957 by the four lower riparian states with the UN as a third party, and was re-ratified in 1995 as the Mekong Commission. Its goal is to "promote, coordinate, supervise, and control the planning and investigation of water resources development projects in the Lower Mekong basin" (Beach et al., 2000). The Mekong basin is not facing severe water scarcity, but despite political instability, the committee has been successful in promoting joint river basin development (Jacobs, 1995). Other committees have formed in for instance the Danube, Meuse, Sénégal, and La Plata river basins, and on transboundary rivers in India/Bangladesh, Canada/US, and Mexico/US.

Dombrowsky (2007) has surveyed 86 joint river basin committees, and demonstrated their importance for international river basin management. Despite their prevalence, many river basin committees often lack institutional power. Almost half of the surveyed committees have no monitoring mechanism, and only a small minority has some kind of enforcement mechanism in place (although in an international setting, enforcement may be a meaningless concept) (Wolf, 1998; Dombrowsky, 2007).

In addition to these river basin committees, many basins have one or more water agreements in place. These agreements may cover many issues related to river basin development, such as hydro-power generation, navigation, and flood management (Wolf, 1998; Beach et al., 2000). More than a third of these agreements cover water allocation issues; 53 out of 145 agreements surveyed by Wolf (1998). The far majority is bilateral and lacks clear rules for how available water is to be shared (Wolf, 1998). This lack of clear sharing rules in international agreements contrasts with common practice in national agreements. International case study evidence shows that various forms of sharing rules occur frequently and that monitoring and enforcement is common (Dinar et al., 1997; Bennett and Howe, 1998). The reason for this difference is that enforcement is possible under national water allocation agreements. This also explains the occurrence of national or regional water markets (Rosegrant and Binswanger, 1994; Bjornlund, 2003; Brewer et al., 2008; Donohew, 2009).

Given the evidence on stochasticity and uncertainty of water supply in section 1.1, one would expect water allocation agreements to be flexible instruments.[3] The need for this flexibility has been advocated by many (Kilgour and Dinar, 2001; McCaffrey, 2003; Giordano and Wolf, 2003; Freebairn and Quiggin, 2006; Sgobbi and Carraro, 2009; Young and McColl, 2009). Few agreements, however, explicitly include flexibility, and water allocations are seldom clearly delineated in the agreements (Giordano and Wolf, 2003; Fischhendler, 2004). This results in agreements that are void when faced with the hydrological reality.

Despite the many river basins that do have one or both work-arounds (river basin committees or water agreements) in place, they still form a minority. In addition to the lack of flexibility, cooperating countries face a cascade of problems in the implementation of desired water allocation schedules. These problems occur from incomplete contracts, ambiguity in their implementation, and lack of monitoring and enforcement (cf. Barrett, 1994a; Fischhendler, 2008; Souza Filho et al., 2008). All in all, the results of cooperation in transboundary river water allocation are not always positive.

[3]An alternative solution to cope with stochasticity is to construct dams that allow inter-annual water storage, see for instance Strzepek et al. (2008).

An immediate result of failing transboundary cooperation is inefficient water allocation and the possible emergence of conflicts on water (Gleick, 1993, 2008; Dinar and Dinar, 2003; Dombrowsky, 2007; Wolf, 2007; Zawahri, 2008b). Inefficiency is caused by missing property rights so that water may not be used at its highest value. Conflicts may emerge when the actual allocation of water damages one of the countries' economies or is perceived as unfair. Some countries and river basins are more prone to conflict over river water than others (Toset et al., 2000; Stahl, 2005; Dinar, 2007). Yoffe et al. (2003) find that the occurrence of rapid institutional or physical changes in a river basin (e.g. dam construction) is the most likely cause of conflict. The presence of water agreements is an important factor in mitigating conflict (Yoffe et al., 2003). Espey and Towfique (2004) and Song and Whittington (2004) analyse characteristics of countries that are successful in agreement formation. One key result is that asymmetry in power between the riparians may prevent cooperation. This result is in line with the hydro-hegemony theory of Zeitoun and Warner (2006). This theory stresses the determinative role of power asymmetry for water allocation and conflict in river basins.

Some argue though, that conflict over water is a misconception, disqualifying the possibility of water wars as a "myth" (e.g. Barnaby, 2009). This line of reasoning is mainly based on data from the International Water Event Database of Oregon State University. This database contains information on all water-related international events from 1948 to 2005. 28% of these events are conflictive in nature and no war has ever been fought over water (Wolf, 1998; Yoffe et al., 2003). Hence, it is concluded that international relations over water are "overwhelmingly cooperative". Though this may be true, it does not imply that the 28% of events that are conflictive are unimportant or could not aggravate into more serious conflicts when water scarcity increases (Bernauer, 2002; Siegfried and Bernauer, 2007; Kundzewicz and Kowalczak, 2009).

Note that conflict does not necessarily refer to open conflict or even warfare. Various hybrid forms of cooperation and conflict exist or co-exist (Dinar et al., 2007; Zawahri, 2008a; Zeitoun and Mirumachi, 2008).[4] For general overviews

[4]Case studies of cooperation and conflict in specific river basins include the following: the Euphrates–Tigris (Zawahri, 2008a), the Columbia (Krutilla, 1967), the Jordan (Haddadin, 2000), the La Plata (Gilman et al., 2008; Kempkey et al., 2009), the Nile (Dinar and Alemu, 2000; Wu and Whittington, 2006), the Indus (Zawahri, 2009), the Ganges (Nishat and Faisal, 2000; Tanzeema and Faisal, 2001), the Senegal (Vick, 2006), the Orange (Conley and Van Niekerk, 2000; Turton, 2003; Kistin et al.,

of conflict and cooperation in river basins, see Gleick (1993); Beach et al. (2000); Wolf (2007). The next section covers existing approaches to analyse conflict and cooperation over water allocation in transboundary river basins.

1.3 Existing approaches

Existing approaches to the issue of water allocation in transboundary river basins use very different reference points. I first give a brief overview of three dominant approaches and their applicability to the issues addressed here. Then I focus on game-theoretic approaches as they are best suited to model and assess the strategic aspects of water allocation, and are therefore closest related to the methodology of this thesis.

The first approach is integrated water resources management (IWRM, sometimes called integrated river basin management) (Lee and Dinar, 1996). IWRM is a concept that was developed in the 1990s as a response to the engineering-dominated paradigms of water development and water management that it succeeds. The approach considers engineering, economic, social, ecological, and legal aspects of water management across four dimensions: (i) the water resource itself, (ii) the water users, (iii) the spatial scale, and (iv) the temporal scale (Savenije and Van der Zaag, 2008). When applied properly, IWRM can provide a sustainable and efficient management regime for the allocation of water. Applied to the issue of water allocation in transboundary river basins, however, decision-making based on IWRM is inherently complex due to a multitude of objectives and stakeholders. Moreover, IWRM is not a suitable approach to assess the strategic elements that play a large role in transboundary river basins.

The second approach is hydro-economic modelling. This approach considers the complete river basin as one entity in which the most favourable options for water use are to be selected, constrained by water availability, physical feasibility, minimal flow requirements, and water use technology. Models developed under this approach typically focus on benefits to different economic sectors, including agriculture and industry. Heinz et al. (2007), Brouwer and Hofkes (2008), and Kragt and Bennett (2009) provide concise overviews of this strand of the literature. Two modelling approaches co-exist: the holistic and the compartment approach (Brouwer and Hofkes, 2008). The choice for either of the two

2008), and the transboundary rivers on the Iberian Peninsula (Thiel, 2004).

approaches is a trade-off between information transfer difficulties in the compartment approach versus the necessary simplified hydrological and economic modelling in the holistic approach (McKinney et al., 1999). The holistic approach fully integrates the hydrological and economic aspects in one integrated model; Braat and Van Lierop (1987) pioneered this approach. An example of the holistic approach is provided by Rosegrant et al. (2000), who develop an integrated economic-hydrologic model to assess water use at the basin scale under different management instruments (see also Cai et al., 2003). The model considers hydrologic, agronomic, and economic factors in a spatial model of water conveyance to different economic sectors. Other examples include Booker and Young (1994), Draper et al. (2003), Jenkins et al. (2004), Cai and Wang (2006), and Gürlük and Ward (2009). The compartment approach keeps the two aspects in separate models but allows the output of one model to be used as input in the other. An example of the compartment approach is Lefkoff and Gorelick (1990a,b), who combines an economic, a hydrologic, and an agronomic component in one integrated simulation model. The model is used to examine the effect of various agricultural practices on profits, and the hydrologic and economic effects of introducing a water market.

Related studies are the following. Albersen et al. (2003) apply capital accumulation theory to hydrological process-based models, which allows to price all stocks and flows in the model using Lagrange multipliers. This approach generates the data needed for a river basin authority to allocate water to its highest value use (see also Ward, 2009). Chakravorty and Umetsu (2003), in a spatial model of water use and re-use, focuses on the effects of upstream distribution losses on basin-wide water use. Their results indicate the preferred upstream and downstream water use technology (surface water abstraction vs. groundwater pumping) and significant increases in water use and output when water use is optimised in the basin. Clearly, basin-wide optimisation increases overall benefits of water use substantially. A related strand of the literature focuses on how these benefits may induce basin-wide cooperation. Both Sadoff and Grey (2002) and Fisher and Huber-Lee (2009) develop frameworks to understand and distribute the gains of optimisation over the countries in the basin. Again, however, this approach does not capture the importance of strategic behaviour by the riparian countries.

The third approach is the use of water markets, an instrument to implement basin-wide optimisation. In theory, the use of markets for water creates an efficient water allocation, even in transboundary river basins (cf. Howitt, 1994; Hearne and Easter, 1996). Institutional impediments may, however, hamper a fully functioning market (Giannias and Lekakis, 1997; Carey et al., 2002; Donohew, 2009). Moreover, because of the large water losses related to the transport of water, transfers of water across river basins are rare, and water markets are usually confined to the riparian countries only. Hence, markets are extremely thin. In addition, advocates of international water markets ignore the problem of undefined property rights to water (Brennan and Scoccimarro, 1999) and the lack of enforcement mechanisms, as discussed in section 1.2.

Other approaches focus on the engineering, economic, or legal aspects of water allocation. An example is the theory of hydro-hegemony, briefly mentioned in section 1.2. This positive theory provides an explanation for the situation of water allocation as we see it today. From a normative point of view, the principles for water allocation listed in section 1.2, may provide a good starting point for the allocation of water. An overview of modelling approaches for river basin management is provided by Chapman et al. (2007). It is clear that the many aspects of water allocation each ask for a specific approach.

Because in this thesis, the strategic aspects of water allocation are central, we now focus on the final approach: game-theory applied to water allocation in transboundary river basins. This approach models riparian countries as agents who interact with each other in their decisions on water use and related issues. Both cooperative or non-cooperative game-theoretic models have been used to model this type of interaction and its outcomes. This confined strand of the literature developed since the 1980s and has a modest number of applications to the issue of water allocation in transboundary river basins, listed below.[5]

Early work was done by Stone (1980) who analysed the case of two countries sharing a river that flows from country A to country B and then back to A. Water use decisions are analysed using "resource transformation curves" that present the relation between border flow volume and net benefits of water use. Using a case study, Stone (1980) shows that side payments can improve welfare in both countries and that conflicting interests are not necessarily present. Dufournaud (1982) applies metagame theory in his analysis of net benefits to riparians of

[5]A related strand of the literature uses game theory to analyse strategic interaction in transboundary water pollution (cf. Fernandez, 2002b; Ni and Wang, 2007; Fernandez, 2009; Gengenbach, 2009).

joint water development projects in the Columbia (see Krutilla, 1967) and lower Mekong river basins. In the case of the Columbia river basin, the analysis compares pay-offs to Canada and the US and argues that the inclusion of benefits from future joint ventures rationalises seemingly irrational choices made by these countries. In the case of the Lower Mekong river basin, the analysis shows that cooperation between the four countries involved would have been beneficial to all. Nevertheless, the risk that one of the countries at some point in time decided to withdraw from the project (for political reasons) made each country opt for sovereign development.

The issue of stability of water allocation agreements has received some attention. Dufournaud and Harrington (1990) explicitly included the temporal and spatial distribution of benefits and costs of a joint water development project, using cooperative game theory, and analysed the stability of cooperation. Kilgour and Dinar (1995, 2001) developed a model of flexible water allocation between riparian states in the context of variable flow rates, to identify whether stable agreements are possible. An application to the Ganges river basin shows that such a flexible agreement may bring about significant welfare improvements.

Examples of game-theoretic applications to specific river basins are the following. Rogers (1969, 1993) analyses cooperation between India, Bangladesh, and Nepal in a joint water supply protect, focusing on flood protection and irrigation water storage. Dinar and Wolf (1994) combine physical, economic and political aspects in their analysis of coalition formation in trading of Nile water and water saving technologies in the western Middle East (Egypt, Israel, West Bank, and Gaza). Frisvold and Caswell (2000) assess water management on the Colorado and Rio Grande rivers along the US-Mexico border, using bargaining theory. Kucukmehmetoglu and Guldmann (2004) use cooperative game theory to analyse stable water allocations in the Euphrates and Tigris river basins (Turkey, Syria, and Iraq). Bhaduri and Barbier (2008a,b) assess the feasibility of water transfers in a game-theoretic analysis of cooperation in the Ganges basin.

Compared to non-cooperative game theory, cooperative game theory has been applied to a lesser extent. A notable recent exception is Dinar et al. (2006) who developed cooperative approaches to water allocation, given stochastic river flow. The only axiomatic[6] approach to water allocation in river basins is by Ambec and

[6]Axiomatic studies use "axioms" or "properties" to uncover or select desirable solutions in a multi-agent interaction (Thomson, 2001).

Sprumont (2002). Their approach to water allocation in an (international) river basin is a compromise between the principles of absolute territorial sovereignty and absolute territorial integrity. This approach is discussed at length in the chapters to come.

Two recent review papers on game theory and water allocation have appeared. Parrachino et al. (2006) review the applicability of cooperative game theory to water allocation, while Carraro et al. (2007) review the non-cooperative approaches.

Although existing game-theoretic models of water allocation in transboundary river basins have analysed a fair range of topics and river basins, many issues remain to be researched. To mention a few, the stability of agreements is a topic that has not been settled completely yet. Also, these analyses do not demonstrate which factors cause actual negotiations on water allocation to be so cumbersome and lengthy. In addition, the axiomatic approach has hardly been used to design attractive sharing rules for water and makes for a wide open research area. The objectives addressed in this thesis are described in the next section.

1.4 Objectives

In this thesis I analyse water allocation in transboundary river basins. The focus of the thesis is on the strategic interaction between riparian countries in their decisions on water use. This interaction determines on the one hand the preconditions for official negotiations and agreements. On the other hand, interaction occurs in the process of negotiation and bargaining over water itself. Both aspects of this interaction will be covered.

To be specific, given the background information on water scarcity and the institutional setting in sections 1.1 and 1.2, and given the existing approaches reviewed in section 1.3, in this thesis I have four objectives that aim to answer some of the open questions in this research area. These objectives are described below.

Stability of water allocation agreements The evidence provided in section 1.2 demonstrates the lack of stability of water allocation agreements. When climate change effects on river flow occur, as described in section 1.1, agreements need to be flexible. Many, though, are not. It is unknown what happens when agreements with inflexible sharing rules are tested for their resilience against the impacts of climate change. The objective is therefore to assess the stability of water allocation agreements when climate change affects river flow.

The methodology to meet this objective is to construct a game-theoretic model of water allocation in order to analyse the stability of three sharing rules for water allocation in a two-country setting. Two of these sharing rules allocate a fixed amount of water to one country. The third sharing rule allocates water proportionally. In addition, the analysis considers two types of side payments; one is constant, based on average river flow, and one is flexible, based on actual river flow. This methodology allows to assess the stability of a wide range of currently existing designs of water allocation agreements.

Design of self-enforcing agreements on river water Given that many types of agreements are not stable, an open question is how to design an *ex ante* stable agreement. Such an agreement is called self-enforcing. Self-enforcing agreements have been analysed for many other topics, including the economics of climate change (cf. Nagashima et al., 2009). A particular feature of agreements on river water, however, is the hydro-geographical setting, as discussed in section 1.2. The objective is therefore to analyse self-enforcing water allocation agreements.

The methodology to meet this objective is to construct a two-country repeated extensive-form game of river water allocation with stochastic river flow. Before the start of the first stage game, the outcome of a bargaining game determines the agreement specifications: water allocation and side payments. In each stage game, as water flows from one country to the other, the countries act sequentially in using water and making side payments. In doing so, they decide to cooperate or defect; that is to comply with specified agreement actions or not. This methodology allows to assess under what conditions such agreements are self-enforcing.

Bargaining over contested water rights With growing population and increasing water demand, as discussed in section 1.1, the competition for water in transboundary river basins is getting fiercer. Countries make claims to a share of the water as we saw in section 1.2. This leads to situations where water rights are contested and a source of conflict. Conflict seems a costly option compared to settlement of the conflict and defining property rights to water. Yet, conflict occurs in many river basins. The question is why? The objective is therefore to design a theory for continued conflict and undefined property rights to water.

The methodology to meet this objective is the analysis of a conflict model in which water rights are contested. In the model, countries decide whether to bargain over the allocation of contested river water or not. If not, they engage in conflict. In the conflict, countries spend their resources on production, which also requires water, or on fighting to secure part of the contested water. This methodology allows to assess for which model parameters countries prefer not to bargain an efficient allocation, but to engage in conflict.

Sharing rules for river water An axiomatic approach for the allocation of river water to riparian countries starts with the formulation of the desired axioms. These axioms capture reasonable or desirable features of an outcome of interaction between the countries. The specific hydro-geographical setting of river basins, discussed in section 1.2 provides a challenging basis for the application of axioms. The objective therefore is to construct an axiomatic approach for the design of sharing rules for river water.

The methodology to meet this objective comes from the bankruptcy literature, an axiomatic approach to solve the allocation of a resource among agents when there is not enough to satisfy all demands. There are two additional features in the setting of transboundary water allocation before sharing rules from this literature can be applied. One is that the resource is distributed over the agents in the form of rainfall and tributaries. The other is the linear ordering of the countries along the river. Both features do not occur in bankruptcy problems and should therefore be resolved appropriately. This methodology allows to characterise an appropriate redistribution of the endowments of river water that countries receive, based on a well-established axiomatic approach from a different strand of literature.

1.5 Reading guide

Chapters 2–5 of this thesis each answer one of the four objectives introduced above. Chapter 2 assesses the stability of water allocation agreements. Chapter 3 analyses the design of self-enforcing agreements on river water. Chapter 4 designs a theory for continued conflict and undefined property rights to water.

Chapter 5 constructs an axiomatic approach for the design of sharing rules for river water. Finally, in chapter 6, I draw some overall conclusions.

This thesis provides four distinct approaches to analyse water allocation in transboundary river basins. Each of these approaches is grounded in game theory, but—depending on parameter values—the outcomes of these approaches on the allocation of water may differ substantially. One could question which approach is the right one to meet the overall objective of this thesis. This question does not have a straightforward answer. Instead, it may be more informative to delineate the differences in the approaches used in the four subsequent chapters.

These differences are of course manifold, but the chapters can roughly be classified based on three criteria. The first distinction between chapters can be made based on the strategic interaction that was discussed in the beginning of section 1.4. Chapter 4 deals with the preconditions for official negotiations by analysing the role of lacking property rights over water. The other three chapters (except maybe for chapter 2) concern the process of negotiation and bargaining over water itself. The second distinction is the practical focus of the chapters. Chapters 2 and 3 focus on agreement design and its effects on agreement stability. Chapters 4 and 5, however, focus on the role of claims in the allocation of transboundary river water. The third distinction concerns the methodological starting point of analysis. Chapters 2 and 4 are positive, describing the current situation in transboundary water allocation and its consequences for the efficiency and stability of water use. Chapters 3 and 5 are more normative. In these chapters, based on economic theory, an "ideal" water allocation agreement is developed and sharing rules with attractive properties are constructed.

Although supplementary to each other, each chapter can be read in isolation of the other chapters. The order of the chapters is according to my own sequence of research ideas on water allocation in transboundary river basins. I expect it to be a logical order.

Chapter 2

The stability of water allocation agreements*

We analyse agreements on river water allocation between riparian countries. Besides being efficient, water allocation agreements need to be stable in order to be effective in increasing the efficiency of water use. In this chapter we assess the stability of water allocation agreements using a game-theoretic model. We consider the effects of climate change and the choice of a sharing rule on stability. Our results show that a decrease in mean river flow decreases the stability of an agreement, while an increased variance can have a positive or a negative effect on stability. An agreement where the downstream country is allocated a fixed amount of water has the lowest stability compared to other sharing rules. These results hold for both constant and flexible non-water transfers.

*This chapter is based on Ansink and Ruijs (2008). Climate change and the stability of water allocation agreements. *Environmental and Resource Economics 41*(2), 249–266.

2.1 Introduction

When countries share a river, they compete over available water resources. The upstream country has the first option to use water, which may obstruct the overall efficiency of water use (Barrett, 1994a). Cooperation between upstream and downstream countries—in the form of a water allocation agreement—may increase the efficiency of water use. Whether cooperation is stable, however, depends on the design of the water allocation agreement. The stability of water allocation agreements is the subject of this chapter.

In the 20$^{\text{th}}$ century, 145 international agreements on water use in transboundary rivers were signed; 53 of these agreements cover water allocation issues (Wolf, 1998). The majority of these water allocation agreements do not take into account the hydrologic variability of river flow (Giordano and Wolf, 2003). This is a shortcoming because variability is an important characteristic of river flow. This variability will even increase in many river basins when the effects of climate change on temperature and precipitation proceed as projected by climate simulation models (IPCC, 2007b). These effects are expected to increase the variability of the annual and seasonal flow patterns as well as the frequency of extreme events in many river basins (Arnell, 1999b; Chalecki and Gleick, 1999; Voss et al., 2002; Räisänen et al., 2004). Recognition of flow variability in the design of water allocation agreements can increase the efficiency of these agreements.

Several studies have addressed this issue for two common sharing rules for water allocation: proportional allocation and fixed flow allocation (for an overview of sharing rules, see Dinar et al., 1997). Fixed flow allocations are most common (Wolf, 1998) but tend to be less efficient when flow variability increases. Bennett et al. (2000) compared the efficiency of fixed flow allocations with proportional allocations and found that, in many situations, proportional allocations are more efficient. Kilgour and Dinar (1995, 2001) developed a sharing rule that ensures a Pareto-efficient allocation for every possible flow volume, where the level of compensation paid by receivers of water is subject to annual bargaining. Obviously, compared with a proportional or fixed flow allocation, this flexible allocation is more efficient, but it requires accurate predictions of annual river flow and flexibility in compensation payments. In a case study of the Colorado river, Mendelsohn and Bennett (1997) found that the loss of efficiency related to a change in mean river flow (e.g. because of climate change) is higher for a proportional allocation than for a fixed allocation, the main reason being that the initial proportions used were inefficient. Another result was that the largest impact of climate change on efficiency comes from changes in the mean river flow, not from changes in the variance. Furthermore, in an analysis of US inter-state water allocation agreements, Bennett and Howe (1998) found that agreement compliance is higher for proportional than for fixed flow allocations.

Apart from being efficient, water allocation agreements need to be stable in order to be effective instruments to increase the efficiency of water use. Efficiency and stability of agreements are not necessarily linked. Climate change, for instance, may increase the benefits of cooperation to one country while decreasing those to the other, leaving overall efficiency equal, but possibly giving the country with decreased benefits an incentive to leave the agreement. Because agreements are signed between sovereign nations, there is usually no higher level authority that can enforce compliance. The stability of agreements therefore depends on the distribution of the benefits of cooperation to the countries involved, which can be analysed using game theory. Recent studies (Ambec and Sprumont, 2002; Heintzelman, 2004; Kucukmehmetoglu and Guldmann, 2004; Wu and Whittington, 2006; Wang et al., 2008; Dinar, 2009) showed that water allocation agreements can improve the efficiency of water use and that—when benefits of cooperation are distributed properly—they can be attractive to all countries involved. This game-theoretic literature, however, does not explicitly consider the effects of climate change on river flow and agreement stability.

The objective of this chapter is to assess the stability of water allocation agreements when climate change affects river flow. This is done by constructing a game-theoretic model of water allocation that analyses stability of three sharing rules for water allocation. Our results show that a decrease in mean river flow decreases the stability of an agreement, while an increased variance can have a positive or a negative effect on stability. An agreement where the downstream country is allocated a fixed amount of water has the lowest stability compared to other sharing rules. These results hold for both constant and flexible non-water transfers. This chapter adds to the existing literature on flexibility of water allocation agreements by studying the stability of different agreement designs (cf. McCaffrey, 2003; Fischhendler, 2004; Drieschova et al., 2008; Kistin et al., 2008).

The remainder of this chapter is organised as follows. In section 2.2 we present background information for our model assumptions. In sections 2.3 and 2.4 we present our model and assess stability of cooperation. In section 2.5 we assess stability effects of asymmetric countries. In section 2.6 we illustrate the effects of climate change on the stability of cooperation for different sharing rules, using a numerical example. In section 2.7 we discuss the results, and we conclude in section 2.8.

2.2 Setting the stage

There is no standard water allocation agreement that can serve as a basis for our model assumptions. Because of historical, hydro-geographical, economic, and political reasons, the institutional setting of agreements shows a large variety. In this section we provide some evidence for this variety. We focus on three institutional aspects of water allocation agreements that are important for our model assumptions: sharing rules, non-water transfers, and reactions to noncompliance.

Sharing rules The vast majority of international agreements on water allocation are bilateral. In fact, less than ten multilateral agreements on water allocation are listed in the International Freshwater Treaties Database (e.g. the 1955 Jordan agreement based on the Johnston negotiations, that was signed by Israel, Jordan, Lebanon, and Syria) (Beach et al., 2000). Because of this limited number of countries in a typical agreement, sharing rules are usually not complex. Generally, they are based on a combination of historical rights, economic efficiency and the principle of "reasonable and equitable sharing", as defined in the 1966 Helsinki Rules.

Two basic types of sharing rules are dominant. The first type, which is most common, applies a percentage rule. An example is the 1975 Euphrates Agreement (Iran, Iraq) in which the flows of the Bnava Suta, Qurahtu, and Gangir rivers were divided equally (Beach et al., 2000). The second type guarantees a fixed amount of water to one or both of the countries. An example is the 1959 Agreement between Nepal and India on the Gandak irrigation and power project, in which irrigation water was allocated for 40,000 acres in Nepal and 103,500 acres in India (Beach et al., 2000). Combinations of these sharing rules are common too. An example is the Nile Waters Agreement (Egypt, Sudan) that allocates 48,000 MCM/yr to

Egypt and 4,000 MCM/yr to Sudan, based on acquired rights. Of the remaining flow, 34% is allocated to Egypt and 66% to Sudan (NWA, 1959).

Non-water transfers In basins where water is scarce, water use by upstream countries goes at the expense of downstream water use. A downstream country can acquire additional water from the upstream country, using non-water transfers. These transfers can be lump-sum payments, as in the 1960 Indus Waters Treaty (India, Pakistan). This treaty—allocating the east tributaries of the river to India and the west tributaries to Pakistan—included a one-time £ 62 million lump-sum payment by India (Beach et al., 2000). These transfers can also be annual payments, as in the treaty between Lesotho and South Africa called the Lesotho Highlands Water Project. Under this treaty, South Africa pays non-water transfers to Lesotho, increasing from € 14 million in 1998, when actual water deliveries started, to € 24 million in 2004 (LHDA, 2005). This example is exceptional because in most cases non-water transfers are constant over time.

Another possibility is the use of transfers in-kind. Monetary payments may be difficult from a political point of view or because the benefits from water are hard to monetise. In-kind transfers can be achieved by linking water transfers to other issues, that provide a benefit to the upstream country. For example, the Netherlands linked the issue of water allocation in the Meuse river to the issue of navigation on the Scheldt river. The Netherlands would gain from the water allocation treaty, while Belgium would gain from the improved access to the Antwerp harbour. Eventually, the agreement on water allocation in the Meuse was linked to the routing of an international railway track (Mostert, 2003).

There exist many water allocation agreements where non-water transfers are not part of the agreement, for various reasons. In the Nile basin, for instance, the military threat posed by Egypt plays an important role for the absence of non-water transfers. This threat can, nevertheless, be considered as equivalent to a non-water transfer (cf. Janmaat and Ruijs, 2006). Another possible reason is that the countries involved recognise historical water use or the equitable use of a shared resource.

Reactions to noncompliance In principle, an upstream country can use any available water whenever it wants, without considering downstream water needs. History has shown that indeed upstream countries may do this. A famous example relates to India's construction of the Farakka barrage in the Ganges basin. After the construction, India extended its trial operation of the barrage throughout the 1975–1976 dry season, diverting water away from the Ganges and through the new canal at full capacity. This operation led to severe water shortages in Bangladesh (Beach et al., 2000). A second example relates to the partitioning of the Indian subcontinent in 1947. A dispute on water rights led India to divert all water supply away from Pakistan's irrigation canals in 1948 (Barrett, 1994a). A third example is Turkey diverting all the water from the Euphrates for a month to create a reservoir behind the newly constructed Atatürk Dam in 1990, depriving Syria and Iraq of water.

These examples show that ultimately the upstream country has the power over shared water resources. Water rights that are specified in a water allocation agreement cannot be enforced by a downstream country.[1] Especially so, because there is no higher authority that can enforce compliance. In half of the current water allocation agreements disputes are handled by advisory councils, governments' conflict-addressing bodies, the United Nations, or other third parties (Wolf, 1998). The other half of the agreements does not refer to any form of dispute resolution. The absence of a higher authority that can issue penalties is clear. As a result, the only reasonable reaction to upstream noncompliance is to stop or reduce any non-water transfers. This strategy can be most effective when the issue of water allocation is linked to another transboundary issue between the two countries (Folmer et al., 1993).

In addition to a possible reduction of non-water transfers, noncompliance is likely to lead to a temporary pause of the agreement and requests for international mediation. Examples of this situation have occurred for instance in the Indus and Euphrates basins. After India diverted water away from Pakistan's irrigation canals in 1948, breaking the 1947 "Standstill Agreement", four years passed before renegotiations began. Another eight years later and with considerable support from the World Bank, disagreement was settled and the 1960 Indus Waters Treaty was signed (Beach et al., 2000). In the Euphrates basin, the 1987 security protocol between Turkey and Syria guaranteed Syria an annual average minimum flow of 500 cubic meters per second. In return, Syria would cooperate in security matters, related to its support to the Kurdish Workers' Party in Turkey. The agreement did not last long as Turkey continued the construction of a large-scale irrigation

[1] For an alternative perspective on this issue, see chapter 3.

project, and Syria did not keep to its promise. Follow-up agreements in 1992 and 1993 failed for the same reason.

2.3 A model of cooperation

Based on the examples presented in section 2.2, we construct a two-country model of cooperation. A river is shared by two countries $i \in \{u, d\}$, having its source in the upstream country u and subsequently flowing through the downstream country d. Q_t denotes the volume of river flow in year t that is available for use; it excludes the river flow necessary to sustain the environmental functioning of the river system and other vital services such as navigation. Q_t is defined by probability density function $f(Q)$ (cf. Krzysztofowicz, 2001). Contributions to river flow in d are negligible as are return flows. Climate change effects on river flow are included in the model by adapting the probability density function from $f(Q)$ to $f'(Q)$.

In year t, country i uses $q_{i,t}$ units of water. Because of the unidirectional flow of water, u has the first option to use water, which may limit water use by d. All water that was not used by u, is available for use by d:

$$0 \le q_{u,t} \le Q_t, \tag{2.1}$$

$$0 \le q_{d,t} \le Q_t - q_{u,t}. \tag{2.2}$$

Benefits $B_{i,t}(q_{i,t})$ from water use are increasing and concave with a maximum at $\bar{q}_{i,t}$. Clearly, if u maximises benefits of water use, it does not have an incentive to pass water with a positive marginal value to d. Yet, if the benefit to d of using more water outweighs the decrease in benefits to u, there is scope for cooperation, with u passing on water to d, in exchange for non-water transfers. Because we are interested in such situations, we assume water scarcity such that $\bar{q}_{u,t} + \bar{q}_{d,t} \ge E[Q_t]$. When the possible gains from cooperation are fully captured, the water allocation is Pareto-efficient. More specifically, a water allocation plan $\left(q^{\star}_{u,t}, q^{\star}_{d,t}\right)$ is Pareto-efficient for Q_t, when $B_{u,t}\left(q^{\star}_{u,t}\right) + B_{d,t}\left(q^{\star}_{d,t}\right) \ge B_{u,t}\left(q_{u,t}\right) + B_{d,t}\left(q_{d,t}\right) \ \forall \ (q_{u,t}, q_{d,t})$. An efficient agreement, however, is not necessarily stable, as will be illustrated in section 2.6.

We analyse three common sharing rules:

Proportional allocation (PA): u receives αQ_t and d receives $(1-\alpha)Q_t$, with $0 < \alpha < 1$;

Fixed upstream allocation (FU): u receives $\min\{\beta, Q_t\}$ and d receives $\max\{Q_t - \beta, 0\}$, with $0 < \beta < E[Q_t]$;

Fixed downstream allocation (FD): u receives $\max\{Q_t - \gamma, 0\}$ and d receives $\min\{\gamma, Q_t\}$, with $0 < \gamma < E[Q_t]$.

Because of water scarcity and increasing and concave benefit functions, and because for each of these sharing rules we have that $q'_{i,t} \geq q_{i,t}$ if $Q'_t > Q_t$, we know that cooperation increases total benefits of water use:

$$B^c_{u,t} + B^c_{d,t} \geq B^n_{u,t} + B^n_{d,t} \;\forall\; Q_t. \tag{2.3}$$

where superscript c denotes cooperation, n denotes non-cooperation, and water use—and therefore benefits—depends on the sharing rule agreed upon. Note that we use $B^c_{i,t}$ and $B^n_{i,t}$ as shorthand notation for $B_{i,t}(q^c_{i,t})$ and $B_{i,t}(q^n_{i,t})$. Cooperative benefits $B^c_{i,t}$ are determined by the use of one of the three sharing rules. Non-cooperative benefits $B^n_{i,t}$ are determined by unilateral benefit maximisation. That is, country i uses $q^n_{i,t}$ units of water such that $B^n_{i,t}$ is maximised, subject to constraints (2.1) and (2.2).

For cooperation to be attractive to u, we need to include non-water transfers m^c_t paid by d to u. These non-water transfers can be monetary (lump-sum or annual side payments), in-kind, or based on issue linking, as discussed in section 2.2. Because of this diversity in possible non-water transfers, we distinguish two general types of non-water transfers. Type I—denoted by m^I—has a constant value over time, representing non-water transfers that cannot be easily adjusted over time, such as issue linking. Type II—denoted by m^{II}_t—has a value that depends on Q_t, representing non-water transfers that can be easily adjusted to river flow in year t, such as monetary transfers. We assume that non-water transfers are equal to the value of compensation of u for benefits foregone and a share ϵ of the additional benefits from cooperation. The two types of non-water transfers, paid by d to u, are calculated as:

$$m^I = E\left[B^n_{u,t} - B^c_{u,t} + \epsilon\left(\left(B^c_{d,t} + B^c_{u,t}\right) - \left(B^n_{d,t} + B^n_{u,t}\right)\right)\right], \tag{2.4}$$

$$m^{II}_t = B^n_{u,t} - B^c_{u,t} + \epsilon\left(\left(B^c_{d,t} + B^c_{u,t}\right) - \left(B^n_{d,t} + B^n_{u,t}\right)\right). \tag{2.5}$$

with $0 \leq \epsilon \leq 1$ and $E[m^I] = E[m_t^{II}]$. As can be seen from equations (2.4) and (2.5), the only difference between m^I and m_t^{II} is that m^I is calculated based on expected water use instead of current water use. Therefore, m^I is constant while m_t^{II} adjusts to river flow in year t.

This method to calculate non-water transfers is commonly used in the literature on international environmental agreements. Chander and Tulkens (1997), for instance, show that correctly designed side payments—resembling those in equations (2.4) and (2.5)—can stabilise international environmental agreements in a setting of uniformly mixing pollutants. This method is also related to the Nash bargaining solution; a common solution concept from non-cooperative game theory. The Nash bargaining solution of a game maximises $(x_u - z_u)(x_d - z_d)$, subject to $(x_u, x_d) \in F$, where F is the feasible set of payoff vectors and (z_u, z_d) are non-cooperative payoffs (cf. Osborne and Rubinstein, 1994). Here, the non-water transfers are calculated according to the asymmetric Nash bargaining solution.

We analyse the stability of cooperation using an infinitely repeated game—a common approach in the analysis of international environmental agreements (cf. Finus, 2002)—because water allocation agreements typically do not have a specified termination date. The stage game in year t is played as follows. First, a value of Q_t is realised from its probability distribution and observed by the countries. Second, u chooses $q_{u,t}$. If complying with the agreement, u plays $q_{u,t} = q_{u,t}^c$ according to the selected sharing rule. If not complying, u plays $q_{u,t} = q_{u,t}^n = \min\{\bar{q}_{u,t}, Q_t\}$. Third, d observes u's action and chooses m_t. If complying with the agreement, d plays $m_t = m_t^c$ (which equals m^I or m_t^{II}, as specified in the agreement). If not complying, d plays $m_t = m_t^n = 0$. Fourth, u observes d's action and both countries receive their payoff.

The decision to comply or not comply in year t is based on the expected payoff stream: $E[\Pi_{i,t}] = \max\left(E\left[\Pi_{i,t}^c\right], E\left[\Pi_{i,t}^n\right]\right)$. We re-interpret the common reactions to noncompliance discussed in section 2.2 to punishment strategies. We assume that both countries use a trigger strategy: when a country is not complying, it is punished by the other country in the form of p years non-cooperative play of the stage game, after which countries expect to return to cooperative play (i.e. agreement strategies). The type of punishment used here differs from Bennett and Howe (1998), who used monetary penalties in their analysis of cooperation between US states. Based on the examples presented in section 2.2, we assume here that there is no authority that can issue such penalties in case of noncompliance. The expected payoff streams to u and d for compliance in year t equal:

$$E\left[\Pi^{c}_{u,t}\right] = B^{c}_{u,t} + m^{c} + \sum_{\tau=t+1}^{\infty}\left(\delta^{\tau-t}E\left[B^{c}_{u,\tau} + m^{c}_{\tau}\right]\right), \tag{2.6}$$

$$E\left[\Pi^{c}_{d,t}\right] = B^{c}_{d,t} - m^{c} + \sum_{\tau=t+1}^{\infty}\left(\delta^{\tau-t}E\left[B^{c}_{d,\tau} - m^{c}_{\tau}\right]\right). \tag{2.7}$$

where δ is the discount factor. The expected payoff streams to u and d for noncompliance in year t equal:

$$E\left[\Pi^{n}_{u,t}\right] = B^{n}_{u,t} + \sum_{\tau=t+1}^{t+p}\left(\delta^{\tau-t}E\left[B^{n}_{u,\tau}\right]\right) + \sum_{\tau=t+p+1}^{\infty}\left(\delta^{\tau-t}E\left[B^{c}_{u,\tau} + m^{c}_{\tau}\right]\right), \tag{2.8}$$

$$E\left[\Pi^{n}_{d,t}\right] = B^{c}_{d,t} + \sum_{\tau=t+1}^{t+p}\left(\delta^{\tau-t}E\left[B^{n}_{d,\tau}\right]\right) + \sum_{\tau=t+p+1}^{\infty}\left(\delta^{\tau-t}E\left[B^{c}_{d,\tau} - m^{c}_{\tau}\right]\right). \tag{2.9}$$

The differences, D_u and D_d, equal the increase in expected payoffs due to noncompliance by u or d:[2]

$$D_u = B^{n}_{u,t} - B^{c}_{u,t} - m^{c} + \sum_{\tau=t+1}^{t+p}\left(\delta^{\tau-t}E\left[B^{n}_{u,\tau} - B^{c}_{u,\tau} - m^{c}_{\tau}\right]\right), \tag{2.10}$$

$$D_d = m^{c} + \sum_{\tau=t+1}^{t+p}\left(\delta^{\tau-t}E\left[B^{n}_{d,\tau} - B^{c}_{d,\tau} + m^{c}_{\tau}\right]\right). \tag{2.11}$$

Positive values of D_i imply that country i has an incentive to deviate from the agreement. Substituting equations (2.4) and (2.5) into equations (2.10) and (2.11), we can derive D_u and D_d for the two types of transfers, see the Appendix. For type I transfers, D_d is independent from the level of Q_t and therefore constant for a given probability distribution of Q. Because an agreement would not be signed if $D_d \geq 0$ at the expected value of river flow, we consider only those situations where D_d is negative for any Q_t. Therefore, d will never have an incentive to deviate from the agreement.

[2]Note that we calculate D_d assuming that u complies with the agreement. Because we are primarily interested in the stability of the agreement—and not payoffs or efficiency—it is irrelevant which of the two countries deviates in a certain year. Any anticipated noncompliance by u (because it expects d to not comply in that year) does therefore not affect the results.

For type *II* transfers, D_u depends on a share of non-cooperative benefits minus cooperative benefits at current river flow plus the negative punishment term. Because cooperation is attractive—see equation (2.3)—we know that $D_u < 0$, which implies that u will never have an incentive to deviate from the agreement.

Concluding this section, the type of transfers that is used has implications for countries' incentives to comply with the agreement. With type *I* (constant) transfers, d never has an incentive to deviate from the agreement, but u may deviate if gains from non-cooperation outweigh the fixed transfer. With type *II* (flexible) transfers, u never has an incentive to deviate from the agreement, but d may deviate if the transfer outweighs its foregone benefits in the punishment period. In the next section, we will assess the stability of cooperation with climate change effects and different sharing rules.

2.4 Analysing stability

The folk theorem tells us that cooperation can be sustained in equilibrium as long as punishments are severe enough. When discounted payoffs of cooperation outweigh the sum of discounted payoffs of noncompliance in one year and Nash-payoffs during the subsequent punishment phase, an agreement is stable in that particular year.

Because of the uncertainty of payoffs in our model, through the stochastic variable Q, it is not possible to assess whether cooperation is stable or not. It is, however, possible to assess the probability of stability. To do this, we need to determine values of Q_t for which the agreement is not stable in year t; i.e. where either $D_u \geq 0$ or $D_d \geq 0$. Let the set $\hat{Q} \subset Q$ contain these values. We know that $\hat{Q}$ is a proper subset of Q, because an agreement would not be signed if $D_u \geq 0$ or $D_d \geq 0$ at the expected value of river flow. Therefore $E[Q_t] \notin \hat{Q}$. Because benefit functions $B_{i,t}(q_{i,t})$ are increasing and concave (see section 2.3), we can derive some properties of D_u and D_d that help to specify $\hat{Q}$ further, using equations (2.10) and (2.11) and the fact that $q^n_{u,t} \geq q^c_{u,t}$. In case of type *I* transfers, D_u is a single-peaked function of Q_t, and D_d has a constant negative value. In case of type *II* transfers, D_d is a single-peaked function of Q_t, and D_u is always negative. This implies that, for both type *I* and *II* transfers, $\hat{Q}$ is a continuous set. Because $\hat{Q}$ is a continuous set, and because we focus on water scarcity, we assume that $Q_t < E[Q_t] \; \forall \; Q_t \in \hat{Q}$. This assumption is based on the idea that scarcity is the cause of instability of water allocation agreements, as discussed in section 2.2.

Having specified $\hat{Q}$, we can express the probability of stability as $\Pr[Q_t \notin \hat{Q}]$. Given that $f(Q)$ is the probability density function of Q, we can calculate $\Pr\left[Q_t \notin \hat{Q}\right]$ as the area under $f(Q)$ where $Q_t \notin \hat{Q}$. Denote lower and upper bounds of $\hat{Q}$ by $\hat{Q}^-$ and $\hat{Q}^+$, then the probability of stability of an agreement equals:

$$\Pr\left[Q_t \notin \hat{Q}\right] = 1 - \int_{\hat{Q}^-}^{\hat{Q}^+} f(Q)dQ. \tag{2.12}$$

Equation (2.12) is illustrated in figure 2.1. In the remainder of this chapter we will use this expression as our stability indicator and refer to it simply as "stability".

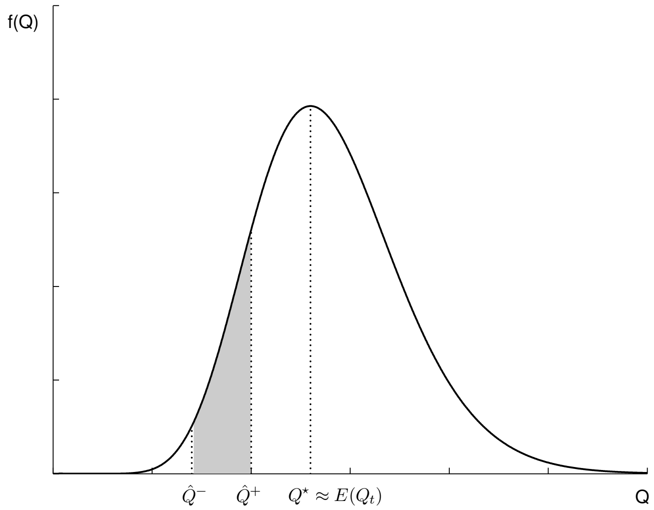

Figure 2.1: An example of a (gamma) probability density function for Q_t. Stability is calculated according to equation (2.12); it equals the area under $f(Q)$ excluding the shaded area.

We are interested in probability density functions of Q without and with climate change. A comparison of the stability in each situation shows how climate change affects the stability of cooperation. Because $\hat{Q}^-$ and $\hat{Q}^+$ are constant (i.e. independent from Q_t), we can compare stability of an agreement for $f(Q)$ (no climate change) and $f'(Q)$ (climate change). Stability in a situation with climate change is lower when it decreases $\Pr\left[Q_t \notin \hat{Q}\right]$, increasing the size of the shaded area in figure 2.1. Climate change is expected to affect river flow through the combined effects of changes in temperature, evaporation, soil moisture, and precipitation. Two general results of climate simulation models are (i) increased runoff variability, both within seasons and within years, and (ii) an increase of river flow in cold river basins and a decrease in warmer regions (cf. Arnell, 1999b; Räisänen et al., 2004; IPCC, 2007a). For the probability distribution of Q this implies a change in the mean river flow and an increased variance of river flow.

Note that climate change effects do not affect stability if $\hat{Q} = \emptyset$. If an agreement is stable for $f(Q)$, it is stable for any $f'(Q) \neq f(Q)$. If $\hat{Q} \neq \emptyset$, climate change effects on stability depend on whether they affect the size of the shaded area in figure 2.1. Note that the exact location and size of this shaded area depend on whether type I or type II transfers are used.

Recall that we assume $Q_t < E[Q_t]\ \forall\ Q_t \in \hat{Q}$. Clearly, the functional form of $f(Q)$ has implications for climate change effects on stability. Commonly applied distributions in the literature on probabilistic hydrological forecasting include the gamma and (log-) normal distributions (cf. Bobee and Ashkar, 1991). In a survey of close to 1000 sites worldwide, Finlayson and McMahon (1992) found that the annual streamflow of about 60% of these sites can be approximated by the normal distribution. This implies that $f(Q)$ is continuous, increasing up to $E[Q_t]$, and symmetric by approximation (figure 2.1 depicts a gamma distribution that is approximately symmetric).

An increased variance of river flow implies that more weight is given to the tails of the probability density function. The effect of increased variance therefore depends on the size and location of $\hat{Q}$. The only information on the lower and upper bounds of $\hat{Q}$ we have is that $\hat{Q}^- \leq \hat{Q}^+ < E[Q_t]$. The size and location of $\hat{Q}$ are bounded only by the lowest value of Q and $E[Q_t]$. Therefore, the effect of increased variance of river flow on stability can be positive or negative. If $\hat{Q}^-$ is located close to the lowest value of Q, an increased variance is likely to increase the size of the shaded area and decrease stability. If $\hat{Q}^+$ is located close to $E[Q_t]$, an increased variance is likely to decrease the size of the shaded area and increase stability.

Consider a decreasing mean river flow. Because of the properties of $f(Q)$, established above, a decreasing mean river flow will decreases stability as long as $f\left(\hat{Q}^-\right) \leq f\left(\hat{Q}^+\right)$, see figures 2.2–2.3. The reverse holds for increasing mean river flow. Because of symmetry of $f(Q)$, we know that $E[Q_t] \approx Q^\star$, where $Q^\star$ equals Q for which $f(Q)$ is maximised, see figure 2.1. Therefore, we can generalise that $f\left(\hat{Q}^-\right) \leq f\left(\hat{Q}^+\right)\ \forall\ \hat{Q}$. Consequently, a decrease (increase) in mean river flow decreases (increases) stability. More formally, given the above observations we have:

$$1 - \int_{\hat{Q}^-}^{\hat{Q}^+} f(Q)dQ \ > \ 1 - \int_{\hat{Q}^-}^{\hat{Q}^+} f'(Q)dQ \quad \text{if} \quad E[Q_t]|f(Q) \ > \ E[Q_t]|f'(Q). \tag{2.13}$$

This proofs the following proposition.

Proposition 2.1. *Stability of a water allocation agreement depends on the probability density function of river flow. Stability decreases if mean river flow decreases. An increased variance can have a positive or a negative effect on stability.*

Note that this proposition holds for both types of transfers, although the size of the effect may be different.

We expect the stability of cooperation to be different for different sharing rules. To verify this expectation, we compare $\hat{Q}$ for the three sharing rules. In the comparison, we set $\alpha E[Q_t] = \beta = E[Q_t] - \gamma$, such that at $Q_t = E[Q_t]$ the allocation of water is similar for each sharing rule. In calculating $\hat{Q}$ from equations (2.10) and (2.11) we can ignore all constant elements, such as the punishment terms, because they are equal for all three sharing rules. Because we assume that all elements in $\hat{Q}$ lie below $E[Q_t]$, we only look at the situation where $Q_t < E[Q_t]$. Note that if $Q_t < E[Q_t]$, we have $Q_t - \gamma < \alpha Q_t < \beta$.

In case of type I transfers, we use equation (2.10), from which we cancel all constant terms, which leaves the term $-B^c_{u,t}$ to be compared for the three sharing rules. For type I transfers, this comparison gives $D^{FD}_u > D^{PA}_u > D^{FU}_u\ \forall\ Q_t < E[Q_t]$. In case of type II transfers, we use equation (2.11), from which we cancel all constant terms, which leaves the term $\epsilon(B^c_{u,t} + B^c_{d,t}) - B^c_{u,t}$ to be compared for the three sharing rules. For type II transfers, this comparison gives $D^{FD}_d > D^{PA}_d > D^{FU}_d\ \forall\ Q_t < E[Q_t]$. Because both D_u and D_d are single-peaked, we have for both types of transfers:

$$\hat{Q}^{FU} \subset \hat{Q}^{PA} \subset \hat{Q}^{FD}. \tag{2.14}$$

Because stability is defined according to equation (2.12), stability is highest for FU and lowest for FD. Formally, from equations (2.12) and (2.14) we can construct:

$$1 - \int_{\hat{Q}_{FU}^{-}}^{\hat{Q}_{FU}^{+}} f(Q)dQ \; > \; 1 - \int_{\hat{Q}_{PA}^{-}}^{\hat{Q}_{PA}^{+}} f(Q)dQ \; > \; 1 - \int_{\hat{Q}_{FD}^{-}}^{\hat{Q}_{FD}^{+}} f(Q)dQ. \tag{2.15}$$

This proofs the following proposition.

Proposition 2.2. *Stability of a water allocation agreement depends on the sharing rule. It is higher for fixed upstream allocation than for proportional allocation and lowest for fixed downstream allocation.*

For type *I* transfers, this proposition is a direct consequence of the amount of risk connected to low flows that is allocated to u. For FU, this risk is minimised as u receives a fixed amount of water, constrained only by the amount of river flow available. For FD, this risk is maximised because if river flow decreases by one unit, the allocation to u may also decrease by one unit. For PA, this risk lies somewhere between those of FU and FD.

For type *II* transfers, the intuition behind this proposition is that the transfer includes a compensation for benefits foregone to u. For $Q_t < E[Q_t]$, this compensation is higher for FD than for PA and lowest for FU. Because of the sequential setting of the stage game, d first receives water and then decides whether or not to pay the transfer. The size of the transfer relative to the punishment term determines whether d complies with the agreement. Clearly, incentives for non-compliance are higher for FD than for PA and lowest for FU.

Taking a closer look at FU with type *I* transfers, we find that u can never have an incentive to deviate from the agreement. To prove this result, we show that D_u for type *I* transfers—see equation (2.10)—is always negative for FU. First we find the value of $q_{u,t}$ for which D_u is maximised. Note that we can ignore the punishment term and non-water transfers because they are constant, so we consider the maximisation problem $\max_{q_{u,t}} B_{u,t}^n - B_{u,t}^c$. There are three possibilities:

1. if $Q_t < \beta < \bar{q}_{u,t}$ then $q_{u,t}^n = Q_t$ and $q_{u,t}^c = Q_t$;
2. if $\beta < Q_t < \bar{q}_{u,t}$ then $q_{u,t}^n = Q_t$ and $q_{u,t}^c = \beta$;
3. if $\bar{q}_{u,t} \leq Q_t$ then $q_{u,t}^n = \bar{q}_{u,t}$ and $q_{u,t}^c = \beta$.

Clearly, in the last situation, $B_{u,t}^n - B_{u,t}^c$ is maximised. We argue that the last situation includes $Q_t = E[Q_t]$, because we assume that $\bar{q}_{u,t} \leq E[Q_t]$. This assumption is based on the idea that in the short term, u's economy and infrastructure are not designed to abstract and use (much) more water than is expected in a given year.[3] Because we may assume that $D_u < 0$ and that D_u is maximised for $Q_t = E[Q_t]$, we know that $D_u < 0$ for any level of Q_t. It follows that $\hat{Q} = \emptyset$ for FU with type I transfers. Hence $\Pr[Q_t \notin \hat{Q}] = 1$; FU with type I transfers is stable. This proofs the following proposition.

Proposition 2.3. *Water allocation agreements with fixed upstream allocation and constant transfers are stable for any level of river flow.*

2.5 Asymmetry

In this section, we assess the effects on stability of asymmetry in political power and benefit functions. For both factors we assess how they affect stability before and after an agreement has been signed.

As described by LeMarquand (1977), the distribution of political power has implications for the incentives for cooperation. In our model we can incorporate this aspect through the level of ϵ, which we define here to be a measure of political power for the upstream country. When benefit functions are symmetric, Kilgour and Dinar (2001) have shown that in an efficient situation, the surplus benefit is equally shared between the two countries; in our model this implies that $\epsilon = 0.5$. Examples analysed by Zeitoun and Warner (2006), however, show that power symmetry may be an exception.

When $\epsilon < 0.5$, d has more political power than u and therefore a stronger bargaining position. As a result, the non-water transfer from d to u is lower than in a situation with equally distributed political power. To assess the effect of political power on stability, we take the derivative of equation (2.10) for type I transfers and (2.11) for type II transfers, with respect to ϵ:

$$\frac{\partial D_u}{\partial \epsilon} = \sum_{\tau=t}^{t+p} \left(\delta^{\tau-t} E\left[\left(B^n_{d,\tau} + B^n_{u,\tau} \right) - \left(B^c_{d,\tau} + B^c_{u,\tau} \right) \right] \right) < 0, \tag{2.16}$$

$$\frac{\partial D_d}{\partial \epsilon} = \left(B^c_{d,t} + B^c_{u,t} \right) - \left(B^n_{d,t} + B^n_{u,t} \right) + \sum_{\tau=t+1}^{t+p} \left(\delta^{\tau-t} E\left[\left(B^c_{d,\tau} + B^c_{u,\tau} \right) - \left(B^n_{d,\tau} + B^n_{u,\tau} \right) \right] \right) > 0. \tag{2.17}$$

[3] If $\bar{q}_{u,t} \gg E[Q_t]$, FU is unstable for Q_t large enough.

Because of equation (2.3), equation (2.16) yields a negative and (2.17) yields a positive value. For type *I* transfers, an increase of ϵ leads to a decrease of D_u, increasing the stability for each level of river flow. For type *II* transfers, an increase of ϵ leads to an increase of D_d, decreasing the stability for each level of river flow. This result holds for each sharing rule. The intuition behind this result is that when ϵ is high, the non-water transfer is high relative to benefits foregone to u, making cooperation more attractive to u and less attractive to d.

For type *I* transfers, changes in the distribution of political power after an agreement has been signed have no effect on stability because the effect of ϵ on D_u works via m^I, which has been fixed. Of course, it is well possible that a change in political power leads to renegotiations of the terms of the agreement, with a more favourable outcome for the more powerful country. If the upstream country is the winner of these renegotiations, ϵ will increase, D_u will decrease and the agreement will be more stable. If the downstream country is the winner of these renegotiations, ϵ will decrease, D_u will increase and the agreement will be less stable.

Asymmetry in benefit functions between countries is assessed by scaling u's benefit function by a factor η: $B_{u,t} = \eta h(q_{u,t})$ and $B_{d,t} = h(q_{d,t})$. To assess the effect on stability for both types of transfers, we analyse how η affects D_u and D_d by taking the derivatives of equation (2.10) for type *I* transfers and (2.11) for type *II* transfers, with respect to η:

$$\frac{\partial D_u}{\partial \eta} = h\left(q^n_{u,t}\right) - h\left(q^c_{u,t}\right) + \epsilon \sum_{\tau=t+1}^{t+p} \left(\delta^{\tau-t} E\left[h\left(q^n_{u,\tau}\right) - h\left(q^c_{u,\tau}\right)\right]\right) > 0, \tag{2.18}$$

$$\frac{\partial D_d}{\partial \eta} = (1-\epsilon)\left[h\left(q^n_{u,t}\right) - h\left(q^c_{u,t}\right)\right] + (1-\epsilon) \sum_{\tau=t+1}^{t+p} \left(\delta^{\tau-t} E\left[h\left(q^n_{u,\tau}\right) - h\left(q^c_{u,\tau}\right)\right]\right) > 0. \tag{2.19}$$

Equations (2.18) and (2.19) both yield positive values, because the non-cooperative benefits to u outweigh the cooperative benefits, both at current and expected levels of river flow. An increase of η leads to an increase of D_u with type *I* transfers and D_d with type *II* transfers, decreasing the stability for each level of river flow. This result holds for each sharing rule. For any agreement, the higher the marginal benefits of water use to u compared with those to d, the lower the stability of cooperation. The intuition behind this result is as follows.

For type I transfers, higher marginal benefits to u increase its expected payoffs of noncompliance more than the transfer it receives from d. For type II transfers, higher marginal benefits to u increase the transfer that d has to pay to u, giving d a higher incentive to deviate.

For type I transfers, changes in η after an agreement has been signed can also be calculated. Such a change may occur because of demographic or economic developments. This effect does not influence m^I, because m^I has been fixed in the agreement. Therefore, to assess the effect on stability, we analyse how η affects D_u by taking the derivative of equation (2.10) with respect to η, similar to equation (2.18), but assuming that m^I is fixed:

$$\frac{\partial m^I}{\partial \eta} = 0. \tag{2.20}$$

Combining equations (2.18) and (2.20) gives:

$$\frac{\partial D_u}{\partial \eta} = h\left(q^n_{u,t}\right) - h\left(q^c_{u,t}\right) + \sum_{\tau=t+1}^{t+p} \left(\delta^{\tau-t} E\left[h\left(q^n_{u,\tau}\right) - h\left(q^c_{u,\tau}\right)\right]\right) > 0. \tag{2.21}$$

Equation (2.21) yields a positive value. For type I transfers, an increase of η after an agreement has been signed leads to an increase of D_u, decreasing the stability for each level of river flow. This result holds for each sharing rule. For any agreement, if marginal benefits to u increase after the agreement has been signed, the stability of cooperation decreases.

The results of this section are summarised in proposition 2.4. Given derivatives (2.16)–(2.19) and (2.21), a positive sign of the derivative indicates an upward shift of the D_u or D_d curve, see equations (2.10) and (2.11). Because these curves are single-peaked, an upward shift of the D_u or D_d curve decreases $\hat{Q}^-$ and increases $\hat{Q}+$, which decreases the stability indicator $1 - \int_{\hat{Q}^-}^{\hat{Q}^+} f(Q)dQ$. This proofs the following proposition.

Proposition 2.4. *Stability of a water allocation agreement depends on the level of symmetry of the countries. For type I (type II) transfers, stability is higher (lower) when the upstream county has more political power. For both types of transfers, stability is higher when the upstream country has lower benefits of water use than the downstream country.*

2.6 Numerical example

To illustrate propositions 2.1–2.3, we use the following numerical example:

$$B_{i,t} = 75q_{i,t} - 1.5q_{i,t}^2 \qquad E[Q_t] = 40$$
$$\delta = 0.95 \qquad \alpha = 0.5$$
$$p = 5 \qquad \beta = 20$$
$$\epsilon = 0.5 \qquad \gamma = 20$$

The values for α, β, and γ are chosen such that at $Q_t = E[Q_t]$ the allocation of water is similar for each sharing rule. Because the countries have identical benefit functions, the allocation is optimal when $Q_t = E[Q_t]$.[4] Furthermore, for each sharing rule, cooperation is attractive to both countries for $Q_t = E[Q_t]$, because countries would never agree to cooperate if there was no expected gain from cooperation.

Figures 2.2 and 2.3 plot D_u and D_d for different levels of Q_t, for the three sharing rules. In both figures we observe that the size of $\hat{Q}$ for the three sharing rules is according to equation (2.14). Corresponding to results 2 and 3, the incentive to deviate is highest for FD and lowest for FU. Figures 2.2 and 2.3 show that efficiency does not guarantee stability. Because the countries have identical benefit functions, PA provides a Pareto-efficient water allocation for each level of Q_t. Nevertheless, figures 2.2 and 2.3 show that this efficient allocation is not always stable. The reason for the decrease in D_u and D_d for Q_t less than ± 20 is the decreasing gain of noncompliance relative to the punishment.

The stability of cooperation depends on the probability distribution of Q. In this example we use an (approximately symmetric) gamma distribution to describe $f(Q)$ and $f'(Q)$. The effect of a change in the mean or variance of river flow on the stability of cooperation is shown in figures 2.4 and 2.5, for PA and both types of transfers. The mean river flow refers to the mean of $f'(Q)$, the probability density function of Q_t when climate change effects occur.[5]

[4]Because the countries have identical benefit functions in this example, PA will provide a more efficient allocation than FU or FD when climate change effects occur: the total benefits of water use are maximised. This property of the model is similar to results from efficiency studies that were surveyed in section 2.1 (cf. Bennett et al., 2000).

[5]The calculation of expected benefits is still based on $E[Q] = 40$—the mean of the original probability density function $f(Q)$—because the agreement will not be immediately adapted at the first signs of climate change effects on river flow. Governments need reliable information before they are

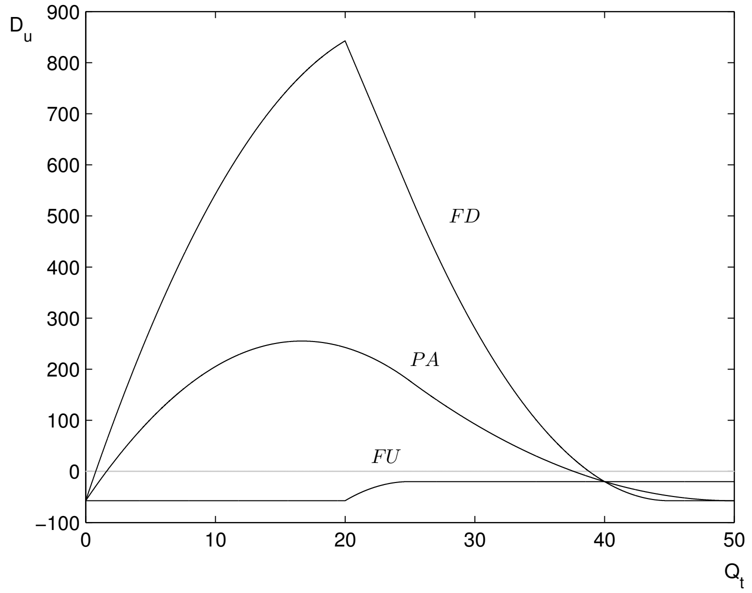

Figure 2.2: The increase in expected payoffs due to noncompliance to u (for type I transfers), for different levels of Q_t and different sharing rules.

Figures 2.4 and 2.5 illustrate proposition 2.1: a decrease in mean river flow decreases stability. When mean river flow decreases beyond $\hat{Q}^+$, the effect of changes in variance switches sign, illustrating that an increase in variance can have positive or negative effects on stability. Note that the fact that type I transfers are more stable than type II transfers is due to this specific numerical example.

2.7 Discussion

The analysis presented here shows that climate change affects the stability of water allocation agreements. The precise effect on stability depends on (i) the characteristics of the river basin: its hydrological regime and the effects of climate change on river flow, and (ii) the characteristics of the agreement: in particular

willing to change conditions of this type of agreements; long-term observations are needed before a change in the probability distribution of river flow can be assessed. Note that a change in river flow that results in a mean below 20 is not included in figures 2.4 and 2.5. For this type of extreme changes in mean river flow it would not be realistic to assume that the expected level of river flow remains $E[Q_t] = 40$.

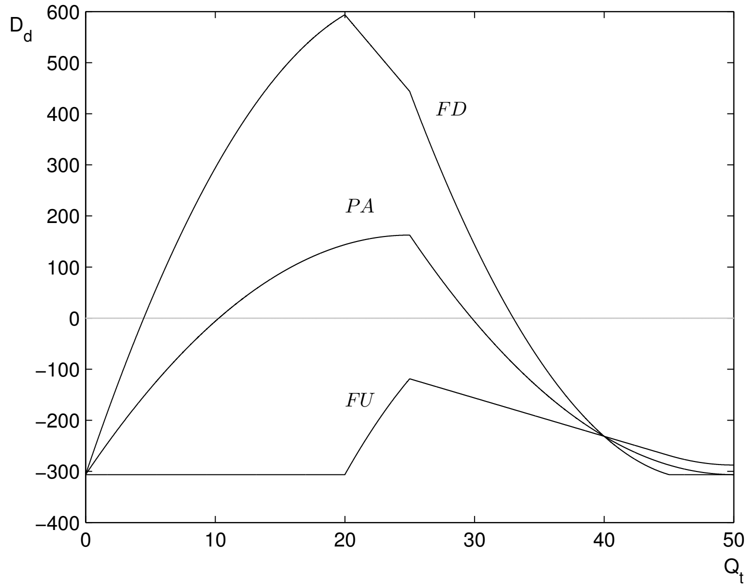

Figure 2.3: The increase in expected payoffs due to noncompliance to d (for type II transfers), for different levels of Q_t and different sharing rules.

the sharing rule, the type of non-water transfers, the countries' benefit functions, and the distribution of political power. Because the results show that stability decreases when water becomes more scarce, this result is relevant for river basins in both arid regions and in regions where impact studies project large effects of climate change on river flow.

Mendelsohn and Bennett (1997) find that the impact of climate change on the mean river flow is a far more important determinant for efficiency than its impact on the variance of river flow. Our model suggests that this conclusion may not hold for the stability of cooperation. Stability is affected by changes in both mean and variance of river flow, so both have to be taken into account when negotiating agreements on water allocation.

Besides economic gain, there are other issues that affect the allocation of water to riparian countries and the stability of cooperation. First, as the example of the Nile river basin points out, acquired water rights can be an important determinant in the allocation of river water. A sharing rule based on acquired rights is not expected to be optimal from the points of view of efficiency and stability. Second,

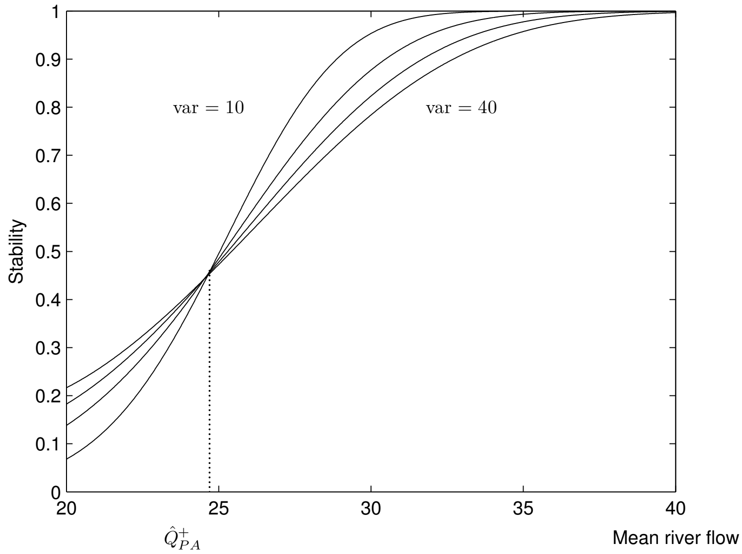

Figure 2.4: Stability—Pr[$Q_t \notin \hat{Q}$]—of an agreement with a PA sharing rule when climate change affects the mean river flow or the variance of river flow, for type I transfers, u might deviate. Mean and variance are based on $f'(Q)$, the probability density function of Q_t when climate change effects occur. Similar graphs can be derived for FU and FD, the only difference being a horizontal shift of the curves.

risk aversion might play a role. A country receiving a fixed allocation faces a lower risk of flow variability than a country that receives a non-fixed allocation or a proportional allocation (cf. Bennett et al., 2000). More risk-averse countries will prefer fixed allocations over proportional allocations. We expect stability to be positively affected by risk aversion as risk averse countries would appraise the certitude of cooperative benefits above non-cooperative benefits more than risk neutral countries.

Two approaches could be used to decrease the risk associated with low flows and generate more stable agreements. First, both upstream and downstream countries could decide to invest in reservoir capacity. When managed properly, reservoirs can provide a buffer in water supply, decreasing the dependency on river water in low flow years (Janmaat and Ruijs, 2007). Second, a water allocation agreement can be extended with water trading, which could increase stability (cf. Booker and Young, 1994). Water markets can improve the efficiency of existing water allocations such that both countries benefit. There are, however,

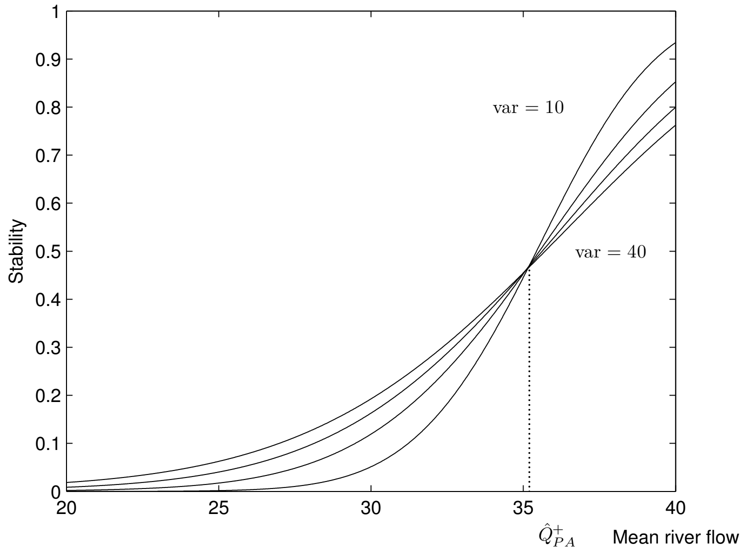

Figure 2.5: Similar to figure 2.4, for type *II* transfers, *d* might deviate.

some institutional impediments to transboundary water trading, as discussed in chapter 1. Both approaches, though, may reduce the incentive to break an existing agreement.

In theory, the use of punishment strategies enhances cooperation in a repeated game. In our model, however, punishment decreases payoffs of both the punished and the punishing country, because the non-cooperative outcome gives the punishing country lower payoffs than the cooperative outcome. Shortening the punishment period is therefore always beneficial to the punishing country. This undermines its credibility of actually going to punish in case of noncompliance. A lack of credibility of punishment strategies can obstruct the effective use of punishment strategies in international agreements on water allocation (Carraro et al., 2005). Ansink (2009a, see chapter 3) assesses self-enforcing water allocation agreements that solve this credibility problem. The examples in section 2.2, however, show that this type of behaviour is not common. Moreover, the punishment period can be used by the harmed country to gain international support in the dispute over water, which can strengthen its bargaining position in renegotiations. Ideally, punishment is implemented in a linked game, which does not affect the benefits of the punishing country.

2.8 Conclusions

The objective of this chapter is to assess the stability of water allocation agreements when climate change affects river flow. A game-theoretic model is constructed that analyses the stability of cooperation in water allocation between two countries for three sharing rules. The stability of cooperation is expressed in terms of the probability that one of the two countries does not comply with the specified agreement actions, given that the countries maximise their expected payoff stream (consisting of benefits of water use and non-water transfers).

For each sharing rule, deviation from agreement actions is found unattractive to the downstream country (d) with constant transfers and unattractive to the upstream country (u) with flexible transfers. The stability of agreements depends on the probability distribution of Q. Our results show that a decrease in mean river flow decreases the stability of cooperation. An increased variance can have a positive or a negative effect on stability. Of the three sharing rules that were analysed, agreements with FU are more stable than those with PA and FD, for both constant and flexible transfers. With constant transfers, FU was found stable for any level of river flow.

In addition to the probability distribution of river flow and the sharing rule, three other factors are identified to affect stability of cooperation. The stability of cooperation is higher if the absolute value of the punishment term is higher, and if u's benefits of water use are low relative to d's benefits. If u's political power is large relative to d's political power, stability is higher for constant transfers, but lower for flexible transfers.

This chapter shows that the stability of water allocation agreements can be affected by climate change. This chapter adds to the analysis of water allocation agreements by focusing on stability aspects, where others have focused on efficiency aspects. Where Bennett et al. (2000) found that proportional allocations are more efficient in many situations, we find that proportional allocations are less stable than fixed upstream allocations. Where Mendelsohn and Bennett (1997) found that the largest impact of climate change on efficiency comes from changes in the mean river flow, we find that both changes in mean and variance affect stability. Because water allocation agreements need to be stable in order to increase the efficiency of water use, the results of this chapter are important for the design of water allocation agreements and especially the selection of a sharing rule.

Appendix: Derivations

Substituting equation (2.4) into equation (2.10) for type I transfers yields:

$$
\begin{aligned}
D_u = {} & \underbrace{B^n_{u,t} - B^c_{u,t}}_{\geq 0} \underbrace{- E\left[B^n_{u,t}\right] + E\left[B^c_{u,t}\right]}_{\leq 0} \\
& \underbrace{-\epsilon \sum_{\tau=t}^{t+p} \left(\delta^{\tau-t} E\left[B^c_{d,\tau} + B^c_{u,\tau} - B^n_{d,\tau} - B^n_{u,\tau}\right]\right)}_{\leq 0}, \\
D_d = {} & \underbrace{E\left[B^n_{u,t}\right] - E\left[B^c_{u,t}\right]}_{\geq 0} \\
& \underbrace{+ E\left[B^c_{d,t} + B^c_{u,t} - B^n_{d,t} - B^n_{u,t}\right]}_{\geq 0} \underbrace{\left(\epsilon + (\epsilon - 1) \sum_{\tau=t+1}^{t+p} \left(\delta^{\tau-t}\right)\right)}_{\gtreqless 0},
\end{aligned}
$$

with ϵ and p such that $D_d < 0$ at $E[Q_t]$.
Substituting equation (2.5) into equation (2.11) for type II transfers yields:

$$
\begin{aligned}
D_u = {} & \underbrace{\epsilon\left[\left(B^n_{d,t} + B^n_{u,t}\right) - \left(B^c_{d,t} + B^c_{u,t}\right)\right]}_{\leq 0} \\
& \underbrace{+(1-\epsilon) \sum_{\tau=t+1}^{t+p} \left(\delta^{\tau-t} E\left[B^n_{u,\tau} + B^n_{d,\tau} - B^c_{u,\tau} - B^c_{d,\tau}\right]\right)}_{\leq 0}, \\
D_d = {} & \underbrace{B^n_{u,t} - B^c_{u,t}}_{\geq 0} \underbrace{+\epsilon\left[B^c_{u,t} + B^c_{d,t} - B^n_{u,t} - B^n_{d,t}\right]}_{\geq 0} \\
& \underbrace{+(1-\epsilon) \sum_{\tau=t+1}^{t+p} \left(\delta^{\tau-t} E\left[B^n_{u,\tau} + B^n_{d,\tau} - B^c_{u,\tau} - B^c_{d,\tau}\right]\right)}_{\leq 0}.
\end{aligned}
$$

Chapter 3

Self-enforcing agreements on water allocation*

Many water allocation agreements in transboundary river basins are inherently unstable. Due to stochastic river flow, agreements may be broken in case of drought. The objective of this chapter is to analyse whether water allocation agreements can be self-enforcing. An agreement is modelled as the outcome of bargaining game on river water allocation. Given this agreement, the bargaining game is followed by a repeated extensive-form game in which countries decide whether or not to comply with the agreement. I assess under what conditions such agreements are self-enforcing, given stochastic river flow. The results show that, for sufficiently low discounting, every efficient agreement can be sustained in subgame perfect equilibrium. Requiring renegotiation-proofness may shrink the set of possible agreements to approach a unique self-enforcing agreement. The solution induced by this particular agreement implements the "downstream incremental distribution", an axiomatic solution to water allocation that assigns all gains from cooperation to downstream countries.

*This chapter is based on Ansink (2009a). Self-enforcing agreements on water allocation. Wageningen University, mimeo.

3.1 Introduction

In this chapter I analyse an agreement that is based on the outcome of a bargaining game. This game is followed by a repeated extensive-form game in which countries decide whether or not to comply with the agreement. The motivating example for this particular setup are agreements on river water allocation.

In an international river basin, when water is scarce, countries may exchange water for side payments (Carraro et al., 2007). This type of exchange is generally formalised in a water allocation agreement. The aim of water allocation agreements is to increase the overall efficiency of water use. This increase in efficiency can be obstructed by the stochastic nature of river flow, because countries may find it profitable to break the agreement in case of drought. A recent example is Mexico's failure to meet its required average water deliveries under the 1944 US-Mexico Water Treaty in the years 1992–1997 (Gastélum et al., 2009). Additional case study evidence on agreement breakdowns because of droughts can be found in Barrett (1994a), Beach et al. (2000), Bernauer (2002), and Siegfried and Bernauer (2007). Only a minority of current international agreements take into account the variability of river flow (Giordano and Wolf, 2003; Fischhendler, 2004, 2008). Most agreements do not; they either allocate fixed or proportional shares, or they are ambiguous in their schedule for water allocation. Both the efficiency (Bennett et al., 2000) and stability (Ansink and Ruijs, 2008, see chapter 2) of such agreements may be hampered. These effects could be worsened by the impacts of climate change on river flow (McCaffrey, 2003; Drieschova et al., 2008).

In order to accommodate for stochastic river flow, Kilgour and Dinar (2001) developed a flexible water allocation agreement that provides an efficient allocation for every possible level of river flow. This agreement maximises the overall benefits of water use, after which side payments are made such that each country benefits from cooperation. This flexible agreement assures efficiency, but not stability because it ignores the repeated interaction of countries over time. Countries have an incentive to defect from the agreement when the benefits of defecting outweigh the benefits of compliance. Note that there is no supra-national authority that can enforce this type of international agreements. This implies that a stable agreement has to be self-enforcing in the sense that both countries should find it in their interest to comply with the agreement (Barrett, 1994b).[1] In

[1]Often, the term self-enforcing agreement refers to agreements that satisfy *internal* and *external*

such a setting, renegotiation-proofness of the agreement is a natural requirement (Bergin and MacLeod, 1993; Barrett, 2003).

The objective of this chapter is to analyse self-enforcing water allocation agreements. Each year, countries decide whether or not to comply with specified agreement actions. I assess under what conditions such agreements are self-enforcing, given stochastic river flow.[2] To do so, I construct a two-country repeated extensive-form game of river water allocation with stochastic river flow. Before the start of the first stage game, the outcome of a bargaining game determines the agreement specifications: water allocation and side payments. In each stage game, as water flows from one country to the other, the countries act sequentially in using water and making side payments. In doing so, they decide to cooperate or defect; that is to comply with specified agreement actions or not.

Using the theory of repeated extensive-form games (Rubinstein and Wolinsky, 1995; Wen, 2002), I show that this game setting implies that any efficient agreement can be sustained in a subgame perfect equilibrium. When renegotiation-proofness is required, every subgame perfect equilibrium is renegotiation-proof, provided that side payments are sufficiently small. For sufficiently high discounting, however, the set of possible agreements converges to approach a unique self-enforcing agreement. This particular agreement implements the "downstream incremental distribution", an axiomatic solution to water allocation constructed by Ambec and Sprumont (2002). The solution induced by this agreement is efficient and assigns all gains from cooperation to the downstream country, as discussed in section 3.4. This distribution of the gains from cooperation contrasts with the assumption in much of the river sharing literature that being upstream increases a country's power in the basin (cf. LeMarquand, 1977; Wolf, 1998; Barrett, 2003; Zeitoun and Warner, 2006; Carraro et al., 2007).

The results of this chapter are driven by the combination of the sequential structure of the game with the requirement of renegotiation-proofness. The sequential structure of the game leads to asymmetry in punishment options to deter defection. The bargaining outcome is sensitive to assumptions on this

stability (Barrett, 1994b). I follow McEvoy and Stranlund (2009) by using the term to refer to the enforcement of compliance with agreements once they are in place.

[2]This chapter is therefore a contribution to the challenge raised by Carraro et al. (2007): "Water resources are intrinsically unpredictable, and the wide fluctuations in water availability are likely to become more severe over the years. Formally addressing the stochasticity of the resource, as well as the political, social, and strategic feasibility of any allocation scheme, would significantly contribute to decreasing conflicts over water."

sequential structure. This clarifies that the distribution of bargaining power over the riparian countries depends heavily on the design of the agreement.

This chapter makes three novel contributions. First, I provide a self-enforcing agreement for river water allocation, that is generally applicable to agreements in repeated extensive-form games. Second, I assess how the bargaining outcome on agreement specifications can be affected by the prospect of playing a repeated extensive-form game in which countries decide to comply or defect from the agreement. Third, I analyse renegotiation-proofness in repeated games with an extensive-form stochastic stage game.

The remainder of this chapter is organised as follows. In section 3.2, the setting of the game is presented. In section 3.3, I show that every efficient agreement can be sustained in a subgame perfect equilibrium, but that requiring renegotiation-proofness may shrink the set of possible agreements to a unique self-enforcing agreement. In section 3.4, I describe that this particular agreement implements the downstream incremental distribution. In section 3.5, I conclude.

3.2 Game setting

In this section I describe the setting of the game, including the bargaining game and the subsequent repeated extensive-form game.

3.2.1 Model

Consider two countries $i = 1, 2$, that share a river and consider cooperation in water allocation. The countries are ordered along a river with country 1 upstream of country 2. This setting is relevant for situations where two countries share a river or where two adjacent countries share river water, without the participation of other riparians. An example of the latter situation is the Nile basin where the Nile Waters Agreement implements water sharing between Egypt and Sudan, without participation of Ethiopia and the other Nile countries.

Total river flow Q_t in year t is drawn from probability distribution $f(Q_t)$. The share of river flow that is added to the river in country i equals $Q_{i,t} = \gamma_i Q_t$, with $\gamma_i \geq 0$ and $\gamma_1 + \gamma_2 = 1$. Water use $x_{i,t}$ is constrained by both availability and unidirectionality of river flow, and by upstream water use:[3]

$$0 \leq x_{1,t} \leq Q_{1,t}, \tag{3.1}$$

$$0 \leq x_{2,t} \leq Q_{1,t} + Q_{2,t} - x_{1,t}. \tag{3.2}$$

Under a water allocation agreement, countries trade water for side payments, making both countries better off. Side payments $s_{i,t}$ may be monetary or in-kind, with:

$$s_{1,t} = -s_{2,t}. \tag{3.3}$$

Countries receive payoffs $\pi_{i,t}$, defined as the sum of benefits of water use and side payments:

$$\pi_{i,t}(x_{i,t}, s_{i,t}) = b_i(x_{i,t}) + s_{i,t}. \tag{3.4}$$

Benefit functions $b_i(x_{i,t})$ are increasing and concave with a maximum at $\bar{x}_i$.

An allocation plan for a given year t is a triple $\omega_t = (Q_t, x_t, s_t)$ with river flow vector $Q_t = (Q_{1,t}, Q_{2,t})$, water allocation vector $x_t = (x_{1,t}, x_{2,t})$, and side payment vector $s_t = (s_{1,t}, s_{2,t})$. An allocation plan ω_t, subject to (3.1), (3.2), and (3.3), is defined by the actions of the countries. Countries' have two possible actions: cooperate (C) or defect (D). When cooperating, countries choose their water use or side payment based on the specified agreement actions. When defecting, countries choose their water use or side payments non-cooperatively. In this case, no side payments are made, $s_t^D = (0, 0)$, and the unidirectionality of river flow implies that country 1, being upstream of country 2, uses any water it needs: $x_{1,t}^D = \min \{Q_{1,t}, \bar{x}_1\}$. Given Q_t, four allocation plans are possible: the cooperative allocation plan $\omega_t = \left(Q_t, x_t^C, s_t^C\right)$, the defection allocation plan $\omega_t = \left(Q_t, x_t^D, s_t^D\right)$, and two allocation plans where one country cooperates and the other defects.

For the game to be interesting, I assume super-additivity:

$$b_1\left(x_{1,t}^C\right) + b_2\left(x_{2,t}^C\right) \geq b_1\left(x_{1,t}^D\right) + b_2\left(x_{2,t}^D\right). \tag{3.5}$$

Without this assumption, there would be no need for cooperation between the two countries. Note that unidirectionality of river flow implies that country 1 can deliver water to country 2, but not vice versa. Combined, super-additivity

[3] Q_t is the river flow that is available for use; it does not include the minimum instream flow that is necessary to sustain the ecological functions of the river. Furthermore, note that $x_{i,t}$ denotes water use, not water diversion (that may re-enter the water system as return flows).

and unidirectionality imply that $x^C_{1,t} \leq x^D_{1,t}$ and that water is scarce in the sense that:

$$Q_{1,t} + Q_{2,t} \leq \bar{x}_1 + \bar{x}_2. \tag{3.6}$$

3.2.2 Bargaining game

The outcome of the bargaining game determines the cooperative allocation plan for each level of river flow. This allocation plan specifies the actions chosen by countries when they cooperate as discussed in section 3.2.1.

In order to determine the cooperative allocation plan, I use the Nash bargaining solution. This solution coincides with the limit case of a non-cooperative alternating-offers bargaining game which gives strong foundations to its application (Binmore et al., 1986). Given benefit functions and a disagreement point, the Nash bargaining solution provides the cooperative allocation of water and side payments. Here, the disagreement point equals the payoffs when both countries defect. The allocation of water and side payments in year t is such that it maximises the Nash product given Q_t:

$$\begin{aligned} \arg\max_{x^C_t, s^C_t} \ & \left[b_1\left(x^C_{1,t}\right) + s^C_{1,t} - b_1\left(x^D_{1,t}\right)\right]^{\alpha} \left[b_2\left(x^C_{2,t}\right) + s^C_{2,t} - b_2\left(x^D_{2,t}\right)\right]^{1-\alpha}, \qquad (3.7)\\ & \text{s.t.} \\ (3.1) \quad & 0 \leq \ x_{1,t} \leq Q_{1,t} \\ (3.2) \quad & 0 \leq \ x_{2,t} \leq Q_{1,t} + Q_{2,t} - x_{1,t} \\ & b_i\left(x^C_{i,t}\right) + s^C_{i,t} - b_i\left(x^D_{i,t}\right) \geq 0\ , \ i = 1,2, \end{aligned}$$

where α reflects the countries' bargaining power and the constraints are feasibility constraints (3.1) and (3.2) and individual rationality constraints.[4] In absence of exogenous differences in bargaining power, α may be endogenously determined by the game structure in section 3.3. The Nash bargaining solution provides the cooperative allocation plan $\omega_t = \left(Q_t, x^C_t, s^C_t\right)$ for each level of Q_t, used in the water allocation agreement.

The model setup assures that, given Q_t, the Nash bargaining solution maximises the joint benefits of water use. Hence, the cooperative water allocation

[4]See Houba (2008) for a convex program to implement this type of bargaining solutions for water allocation problems.

vector x_t^C, induced by the solution, is efficient. Side payments are used to distribute the gains from cooperation according to the countries' bargaining power. Note that for a given level of Q_t, there is a unique x_t^C that maximises joint benefits of water use. There are many efficient allocation plans, though, distinguished by their level of side payments. The Nash bargaining solution selects one of these efficient allocation plans, depending on the level of α. In section 3.3, we will see that the prospect of playing the repeated game described in the next subsection may affect the level of α and hence the side payments specified in the agreement.

This completes the description of the bargaining game.

3.2.3 Repeated game

In a repeated game, the stability aspects of a water allocation agreement can be analysed. In the repeated extensive-form game that follows the bargaining game, country 1 is the leader and country 2 the follower, according to the direction of river flow.[5] Given an agreement, the stage game in year t is played as follows:

1. A value for Q_t, which defines the values for $Q_{i,t}$, is drawn from probability distribution $f(Q_t)$ and observed by both countries.

2. Country 1 chooses its water use from the binary strategy set $\left\{x_{1,t}^C, x_{1,t}^D\right\}$. If it complies with the agreement, country 1 plays $x_{1,t} = x_{1,t}^C$. If it defects, country 1 plays $x_{1,t} = x_{1,t}^D$.

3. Country 2 observes the action played by country 1, which determines the maximum value of x_2, according to (3.2). Subsequently, country 2 chooses its side payment from the binary strategy set $\left\{s_{2,t}^C, s_{2,t}^D\right\}$.

Note that because of super-additivity and the possibility of making side payments, the stage game is a two-country prisoner's dilemma in extensive form, see figure 3.1. Because $s_{2,t}^C = -s_{1,t}^C < 0$, country 2 has a dominant strategy in the stage game: defect.

Consequently, in a one-shot game when binding contracts are not feasible, the game has one subgame perfect equilibrium that yields the defection allocation plan. When binding contracts are feasible, the analysis of Kilgour and Dinar

[5]This sequence of moves according to the countries' geographical location seems most natural. It follows from the fact that side payments can be "delayed" while water delivery cannot. The alternative sequence of moves is briefly discussed in section 3.3.2.

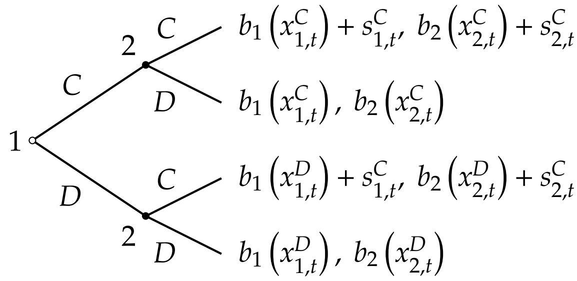

Figure 3.1: The stage game.

(2001) applies: a bargaining game contingent on Q_t yields a Pareto-efficient water allocation vector, with side payments such that the gains from cooperation are equally shared. When the stage game is repeated and binding contracts are feasible, Busch and Wen (1995) have shown that inefficient situations may arise, including delay of the signing of an agreement.

The situation analysed in this chapter is different. I analyse a non-binding water allocation agreement that is based on the outcome of a bargaining game, and subsequent interaction of the countries in a repeated game.

This completes the description of the repeated extensive-form game.

3.3 Self-enforcing agreements

A self-enforcing water allocation agreement for the repeated extensive-form game, described in section 3.2, is a pair of strategies that provides a subgame perfect and renegotiation-proof equilibrium, as discussed in section 3.1. In this section, using the two games described in section 3.2, I first show that every efficient water allocation agreement can be sustained in a subgame perfect equilibrium for sufficiently low discounting. Subsequently, I show how requiring renegotiation-proofness affects this result.

3.3.1 Subgame perfect equilibria

Given a water allocation agreement that is based on the outcome of a bargaining game, countries decide whether or not to comply with specified agreement actions in each stage game of the repeated extensive-form game. In the repeated game, countries can be punished in case of defection. A standard strategy to punish defection is to play a minimax strategy for a number of years. If the threat of punishment is credible and sufficiently severe, no country has an incentive to defect from agreement actions and cooperation can be sustained in equilibrium. This property is generally known as the folk theorem (Fudenberg and Maskin, 1986). The theorem says that, given any feasible and individually rational payoff vector $\pi^\star$ of the stage game, there exists $\underline{\delta} < 1$, such that the repeated game has a subgame perfect equilibrium with average payoff vector $\pi^\star$ for all $\delta \in \left(\underline{\delta}, 1\right)$ (Theorem 1 in Fudenberg and Maskin, 1986). This theorem holds generally for the case of two players. The game in this chapter differs from the standard repeated game in two respects; it features an extensive-form stage game and stochastic river flow. Appropriate modifications of the folk theorem have been constructed for both of these cases, and I briefly discuss these now.

The first modification concerns repeated games with an extensive-form stage game. For this type of games, Sorin (1995) shows that the Fudenberg and Maskin (1986) folk theorem generalises to extensive-form repeated games (see also Rubinstein and Wolinsky, 1995). Wen (2002) explains that the only condition for this generalisation is that the stage game satisfies *full dimensionality*. Full dimensionality requires that the dimension of the set of feasible and individually rational payoff vectors equals the number of players (two in this game). This condition is satisfied through the prisoner's dilemma payoff structure of the game. Hence, the extensive-form stage game does not require modification of the Fudenberg and Maskin (1986) folk theorem.

The second modification concerns stochastic games. A stochastic game has a (finite) collection of states, in each of which a particular stage game is played. Dutta (1995) has shown that the folk theorem generalises to stochastic games when two conditions are satisfied. The first necessary condition is that the individually rational set of payoffs should not vary across histories. This condition is satisfied because the states of the game are determined by Q_t and thereby i.i.d. given the exogenous distribution $f(Q)$ (cf. Krzysztofowicz, 2001). Hence, Q_t is independent from Q_{t-1} and from countries' previous actions. The second necessary condition is full dimensionality, discussed above. Because both conditions are satisfied, this folk theorem can be applied here. The theorem says that given a certain payoff vector $\pi^\star$ that dominates the long-run average minimax payoffs, there exists a $\delta^\star < 1$, such that the stochastic game has a subgame perfect equilibrium that approximates the payoff vector $\pi^\star$ for all $\delta \in (\delta^\star, 1)$ (Theorem 9 in Dutta, 1995). Note that because Q_t is determined exogenously, the set of payoff vectors that dominate the long-run average minimax payoffs equals the set of feasible and individually rational payoff vectors.[6] This equality implies that for the game in this chapter, we have $\underline{\delta} = \delta^\star$. Hence, stochastic river flow does not require modification of the Fudenberg and Maskin (1986) folk theorem.

The fact that the game of this chapter features an extensive-form stage game and stochasticity simultaneously is not problematic, because extensive-form games may be regarded as a special form of stochastic games (Yoon, 2001). Therefore, the extensive-form stage game and stochastic river flow do not prevent application of the Fudenberg and Maskin (1986) folk theorem. Consequently, any agreement that improves upon minimax payoffs can be sustained in a subgame perfect equilibrium for $\delta \in \left(\underline{\delta}, 1\right)$. The rationality constraints in the Nash product—see (3.7)—imply that the agreement is individually rational. More precisely, the Nash bargaining solution makes the countries coordinate on efficient equilibria, so we know that the agreement is efficient. The above discussion is summarised in the following proposition.

Proposition 3.1. *Any efficient water allocation agreement can be sustained in a subgame perfect equilibrium for* $\delta \in \left(\underline{\delta}, 1\right)$.

Consequently, the prospect of playing the repeated game cannot affect the outcome of the bargaining game for this interval of the discount factor. For lower values of the discount factor, the agreement cannot be sustained, so countries may defect in equilibrium. In the next subsection we assess how the requirement of renegotiation-proofness affects these results.

3.3.2 Adding renegotiation-proofness

A subgame perfect agreement may only be self-enforcing *ex ante*, because punishments may not be credible *ex post* once a value for Q_t is drawn from probability distribution $f(Q_t)$. Punishments are not credible when the punishment equilibrium is inefficient. Then, it is in both countries' interest to renegotiate out of the Pareto-dominated equilibrium. Hence, a self-enforcing agreement has to satisfy

[6] This equality does not hold when the transition rule between states depends on countries' actions or the previous state. This is relevant, for instance, when countries invest in reservoir capacity to create a buffer for drought years.

renegotiation-proofness. This requirement rules out equilibria where both countries are hurt by punishment (Bergin and MacLeod, 1993; Barrett, 2003). Formally, I use the concept of a "weakly renegotiation-proof equilibrium", which says that if countries agreed ex ante to play strategy σ, and if the history of the game implies that continuation equilibrium σ^e conditional on σ is to be played, they do not have a joint incentive to switch instead to another continuation equilibrium $\sigma^{e'}$ of σ (Farrell and Maskin, 1989). In other words, payoffs at any subgame must not be dominated by payoffs at any other subgame. This concept of renegotiation-proofness is equal to "internal consistency", used by Bernheim and Ray (1989).

I adapt a punishment strategy suggested by Van Damme (1989) for the normal-form repeated prisoner's dilemma. He showed that for this game there exists a punishment strategy, such that any subgame perfect equilibrium of the repeated prisoner's dilemma is renegotiation-proof, for sufficiently low discounting. This particular punishment strategy is the "penance" strategy: Each country starts with C and plays cooperatively as long as the other country does so. If country i plays D in year t, then country j plays D until country i plays C. As soon as country i has done so, its initial defection is "forgiven" by country j, and j also returns to playing C (Van Damme, 1989). In the subgame perfect and renegotiation-proof equilibrium, if a country defects, it is punished for one period and then the countries revert to the cooperative phase. This punishment phase is renegotiation-proof because of the particular payoff structure of the prisoner's dilemma. Equilibria where one country plays C, while the other plays D are never Pareto-dominated.

This penance strategy can be adapted to the setting of an extensive-form prisoner's dilemma with stochastic river flow. In the extensive-form game of this chapter, countries have different means of punishing the other country. Country 1 is in control of water delivery to country 2, while country 2 is in control of the side payment. If country 2 defects, the penance strategy prescribes that (D, C) is played in the next stage game. If country 1 defects, however, it can be punished within the same stage game by country 2 (by playing D), in addition to the penance strategy of playing (C, D) in the next stage game. Therefore, under the penance strategy, country 2 has an additional punishment option compared with country 1. Note that in the extensive-form game, stage game payoffs occur at the end of the stage game. This leads to an additional advantage for country 2: its additional punishment option is not discounted by country 1.

The implication of this asymmetry in punishment options is that for sufficiently low values of δ, when renegotiation-proofness is required, country 1 cannot punish country 2 upon defection, while country 2 can punish country 1. This is formally stated in the following lemma.

Lemma 3.1. *Given Q_t, there exists $\overline{\delta} > 0$, such that:*

(a) *for $\delta \in (0, 1)$, there is a renegotiation-proof punishment to deter defection by country 1;*

(b) *for $\delta \in \left(0, \overline{\delta}\right)$, there is no renegotiation-proof punishment to deter defection by country 2;*

(c) *for $\delta \in \left(\overline{\delta}, 1\right)$, there is a renegotiation-proof punishment to deter defection by country 2 provided that side payments are sufficiently small.*

Proof. The proof is by construction. Consider the penance strategy described above.

Given Q_t, the immediate gain in payoffs of defection in year t to country 1 equals $b_1\left(x_{1,t}^D\right) - b_1\left(x_{1,t}^C\right)$. The total value of the punishment, both in the same stage game and in the next stage game is $s_{1,t}^C + \delta E\left[s_{1,t+1}^C\right]$. Defection by country 1 is deterred when:

$$b_1\left(x_{1,t}^D\right) - b_1\left(x_{1,t}^C\right) - s_{1,t}^C \leq \delta E\left[s_{1,t+1}^C\right]. \tag{3.8}$$

Given the individual rationality constraint in (3.7), the LHS is non-positive while the RHS of this inequality is non-negative for admissible values of δ. Hence, defection by country 1 is deterred for any value of δ.

Given Q_t, the immediate gain in payoffs of defection in year t to country 2 equals $-s_{2,t}^C$. The total value of the punishment in the next stage game is $\delta E\left[b_2\left(x_{2,t+1}^C\right) - b_2\left(x_{2,t+1}^D\right)\right]$. Defection by country 2 is deterred when:

$$-s_{2,t}^C \leq \delta E\left[b_2\left(x_{2,t+1}^C\right) - b_2\left(x_{2,t+1}^D\right)\right]. \tag{3.9}$$

Given super-additivity and the concavity of the benefit function, both the LHS and the RHS of this inequality are non-negative. It is easy to verify that there exist parameter combinations for which the inequality is violated. For $\delta = \overline{\delta}$, (3.9) holds with equality. □

For $\delta \in \left(0, \overline{\delta}\right)$, lemma 3.1 implies that country 2 can defect in every single year, without being punished. This asymmetry in punishment options affects the outcome of the bargaining game such that country 2 has all bargaining power (in terms of the Nash bargaining solution in (3.7), $\alpha = 0$). The resulting agreement assigns all the gains from cooperation to country 2. Country 1 receives its minimax payoff; it is exactly compensated for sustaining the efficient water allocation vector and is therefore indifferent between C and D. Any other (efficient) agreement would be susceptible to defection by country 2. This particular agreement, however, violates full dimensionality, which is a requirement for proposition 3.1. Hence, an agreement where country 1 receives its minimax payoff cannot be a subgame perfect equilibrium. Therefore we have:

$$\overline{\delta} \leq \underline{\delta}. \tag{3.10}$$

For $\delta \in \left(\overline{\delta}, 1\right)$, lemma 3.1 implies that defection by both countries is deterred with renegotiation-proof punishment strategies. By proposition 3.1, any efficient agreement that uses these punishment strategies is also subgame perfect, because full dimensionality is satisfied. Therefore we have:

$$\overline{\delta} \geq \underline{\delta}. \tag{3.11}$$

Combining (3.10) and (3.11), we have $\overline{\delta} = \underline{\delta}$. Together with lemma 3.1, this implies that any water allocation agreement that can be sustained in subgame perfect equilibrium is renegotiation-proof, provided that side payments are sufficiently small, see (3.9). Recall that a self-enforcing water allocation agreements is a pair of strategies that provides a subgame perfect and renegotiation-proof equilibrium. Hence, the requirement of renegotiation-proofness shrinks the set of possible self-enforcing agreements.

To be precise, for values of δ close to $\overline{\delta}$ some agreements that are subgame perfect are not renegotiation-proof. As δ approaches $\overline{\delta}$, the asymmetry in renegotiation-proof punishment options increases, see (3.9). This asymmetry leads to an (asymptotic) convergence of the set of self-enforcing agreements to approach a unique self-enforcing agreement that assigns all the gains from cooperation to country 2, as discussed above. Note though, that this particular agreement itself is never reached, because it is not subgame perfect. The above discussion is summarised in the following proposition that forms the main result of this chapter.

Proposition 3.2. *For $\delta \in \left(\overline{\delta}, 1\right)$, any subgame perfect water allocation agreement is self-enforcing, provided that side payments are sufficiently small. As δ approaches $\overline{\delta}$, the set of possible agreements converges to approach a unique self-enforcing agreement that assigns all the gains from cooperation to the downstream country.*

The payoff distribution for this unique self-enforcing agreement is indicated by S in the stylised payoff space presented in figure 3.2. In this figure, the solution found by Kilgour and Dinar (2001) is indicated by *KD*; this solution assumes $\alpha = \frac{1}{2}$ which yields the "midpoint of the contract-curve".

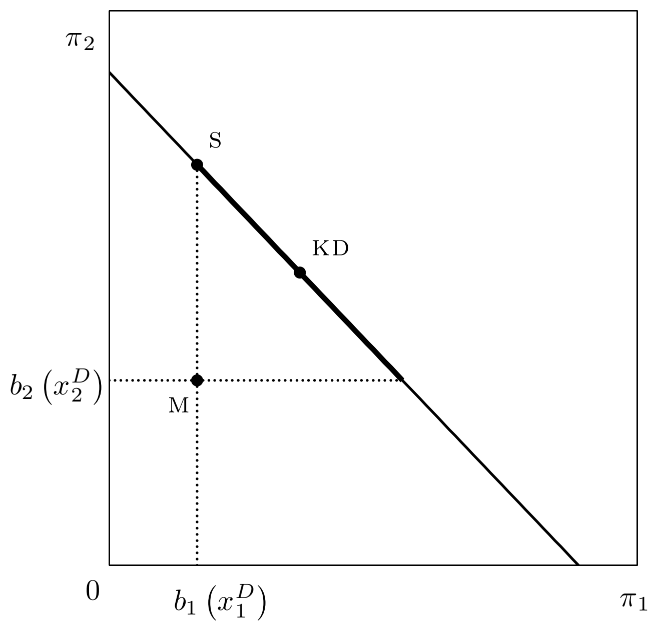

Figure 3.2: A stylised payoff space; the thick line denotes the set of possible payoffs for efficient agreements that can be sustained in a subgame perfect equilibrium; *M* denotes minimax payoffs (i.e. payoffs under the defection allocation plan); *S* denotes the payoffs for the unique self-enforcing agreement when $\delta \in \left(0, \overline{\delta}\right)$; *KD* denotes the payoffs for the Kilgour and Dinar (2001) solution.

The asymmetry in punishment options is a constraint on the allocation of payoffs for a self-enforcing agreement when δ approaches $\overline{\delta}$.This asymmetry is a result of the specific sequential structure of the stage game in which it is assumed that side payments are made after water is delivered. Given the unidirectional flow of water, this seems the most natural structure of the stage game. This structure can, however, be modified in the following two ways. First, water deliveries and payments could be made in shorter intervals (e.g. monthly instead of yearly), while retaining the same sequential structure of the stage game. This change would increase the values of $\underline{\delta}$ and $\overline{\delta}$, but it would not affect the qualitative outcome of proposition 3.2. Second, the sequential structure could be reversed such that first the side payment is made and only then water is delivered. This change would completely reverse the asymmetry in punishment options, such that any subgame perfect agreement is self-enforcing provided that side payments are sufficiently *large*.

Clearly, the solution induced by a self-enforcing agreement is very sensitive to both the sequence of water deliveries and side payments (as specified in the water allocation agreement), and the level of discounting. Using the sequence of the stage game described in section 3.2 yields a set of self-enforcing agreements that tends to favour the downstream country. This outcome is in contrast with much of the river sharing literature in which it is assumed that being upstream increases a country's power in the basin. Nevertheless, it is in line with recent literature that suggests that factors other than geography play a key role in determining bargaining power and water allocation patterns in a river basin (Dinar, 2006; Zeitoun and Warner, 2006; Zawahri, 2008b; Ansink and Weikard, 2009a).

3.4 The downstream incremental distribution

Ambec and Sprumont (2002) developed an axiomatic solution to water sharing, which assures that each country receives a welfare level between a lower and an upper bound. The lower bound is the welfare a country could achieve if all countries make unilateral, non-cooperative, decisions on water use. This bound is based on the principle of "absolute territorial sovereignty" and is similar to the defection allocation plan of this chapter. The upper bound is the welfare a country could achieve if upstream countries refrain from using water. This bound is based on the principle of "absolute territorial integrity". A compromise of these two conflicting principles, where each country is guaranteed its lower bound and aspires its upper bound, yields a unique solution. This solution allocates water such that each country's welfare equals its marginal contribution to a coalition composed of its upstream neighbours. Ambec and Sprumont (2002) call this solution the "downstream incremental distribution".

For the case of two countries, the water allocation vector induced by the downstream incremental distribution is such that it assigns all the gains from cooperation to the downstream country (Houba, 2008). Given proposition 3.2, this distribution is implemented in the limit by the self-enforcing agreement as δ approaches $\overline{\delta}$. The distribution of payoffs induced by the self-enforcing agreement corresponds to the two-country case of the downstream incremental distribution.

An alternative implementation of the downstream incremental distribution is provided by Ambec and Ehlers (2008). They propose negotiation rules to implement this distribution in a static setting, in which priority is given "lexicographically to the most downstream user". Given a set of players $\{1, 2, \ldots, k\}$, player k proposes an allocation plan to the other players. If all accept, this allocation plan is implemented. If any player declines the proposed allocation plan, player k receives $x^D_{k,t} = Q_{k,t}$ and $s^D_{k,t} = 0$, and player $k - 1$ proposes an allocation plan, etc. Ambec and Ehlers (2008) show that the unique subgame perfect equilibrium of this game implements the downstream incremental distribution.

The Ambec and Ehlers (2008) game, however, assigns all bargaining power exogenously to player k by giving him the advantage of making the first proposal. No explanation is provided as to why this is a correct approach. This weakness has been noticed by Van den Brink et al. (2007) and Houba (2008) who, based on this assumption that downstream countries have all bargaining power, found the downstream incremental distribution unconvincing (see also Khmelnitskaya, 2009). In the game described in sections 3.2 and 3.3 of this chapter, the distribution of bargaining power follows endogenously from the repeated game setting of the model and the sequential structure of the stage game. This dynamic setting provides a more realistic approach for non-cooperative bargaining on water allocation than those provided by static models. Clearly, implementation of the downstream incremental distribution is more convincing when the dynamic setting is considered in which water allocation agreements are situated. This implementation adds significant credibility to the axiomatic solution developed by Ambec and Sprumont (2002).

3.5 Conclusion

In the setting of this chapter, any efficient agreement can be sustained in a subgame perfect equilibrium for sufficiently low discounting. Requiring renegotiation-proofness may shrink the set of possible agreements to approach a unique self-enforcing agreement. This is the agreement that assigns all bargaining power and all gains from cooperation to the downstream country, and thereby implements the downstream incremental distribution.

I have used a non-cooperative approach to analyse the allocation of water in international river basins. Related approaches have been applied to open-access fisheries (Polasky et al., 2006), transboundary wildlife management (Bhat and Huffaker, 2007), and international pollution (Germain et al., 2009). Analysis of this topic using cooperative game theory is the subject of Dinar et al. (2006) and Beard and MacDonald (2007). The non-cooperative approach comes closest to actual negotiations on river water allocation. In many current agreements, the allocation of water is—at least to some extent—based on average river flow. This is an important reason for the instability of such agreements (cf. Drieschova et al., 2008).

Kilgour and Dinar (2001) argued for a flexible agreement that adapts to available river flow. I have developed their approach one step further by accounting for countries' incentives to break the agreement. This chapter shows that any efficient water allocation agreement is self-enforcing, provided that side payments are sufficiently small. In other words, these agreements are stable. This result supports the approach by Kilgour and Dinar (2001), because given that flexible agreements are efficient, they are stable too. This type of agreement is therefore preferable over conventional agreements such as proportional allocations and fixed flow allocations, which are generally inefficient and less stable (Ansink and Ruijs, 2008). A related advantage of the self-enforcing agreement is that by offering stability, it can withstand de-stabilising effects of, for instance, climate change. A possible impact of climate change is an increased frequency of years with low river flow. Because the self-enforcing agreement has water allocation and side payments contingent on river flow, the agreement does not need to be reconsidered when these impacts occur.

Based on the results of this chapter, a recommendation for countries that meet to negotiate the allocation of river water is to explicitly account for stability issues in their negotiations. Ideally, a water allocation agreement specifies (i) the sequence of water deliveries and side payments, taking into account renegotiation-proofness, (ii) the water allocation vector and side payments contingent on river flow, and (iii) an appropriate punishment strategy based on the penance strategy outlined in section 3.3.2. Such an agreement is self-enforcing, and always more stable than any alternative agreement.

Although most water allocation agreements are bilateral, it seems straightforward to extend the analysis of this chapter to cover multilateral agreements. Intuitively, the main results of this chapter would not be affected by adding more countries. Difficulties may arise, however, when the distribution of river flow (i.e. the parameters γ_i) is such that a certain country cannot be minimaxed. As a result, full dimensionality may not hold, so that the folk theorem does not carry over to the multilateral case. Such an extension is, however, left for future research.

Chapter 4

Contested water rights*

In many international river basins disputes over property rights to water lead to inefficient water allocation and a waste of resources. In this chapter, we examine how contested water rights impede water trade. To show this, we use a model in which property rights to water are contested because countries have overlapping claims to water. In the model, countries decide whether to bargain over the allocation of contested river water or not. If not, they engage in conflict. In the conflict, countries spend their resources on production, which also requires water, or on fighting to secure part of the contested water. The resulting equilibrium is inefficient as both countries spend a positive amount of resources on fighting which is not productive. However, a third party may be requested to intervene in the looming conflict and allocate the water in an equitable way. The results show that for certain model parameters countries prefer not to bargain an efficient allocation, but to engage in conflict, hoping for third party intervention. The mere possibility of third party intervention may give rise to an inefficient equilibrium. Two new features of this chapter are the application of a conflict model to the issue of water rights and the introduction of (overlapping) claims to non-cooperative bargaining problems.

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*This chapter is based on Ansink and Weikard (2009a). Contested water rights. *European Journal of Political Economy 25*(2), 247–260.

4.1 Introduction

With growing population and increasing water demand, competition for water in international river basins gets fiercer. In many cases, water rights are contested and a source of conflict (Gleick, 1993; Wolf, 2007).[1] In this chapter we want to shed light on the question under which conditions countries will jointly define property rights to contested water in transboundary river basins. Our motivation for this analysis is the general absence of international trade in river water.

The economics discipline advocates water trade in order to maximise the basin-wide benefits of this scarce resource (Easter et al., 1998). Even in situations without a social planner who can allocate water to maximise benefits, efficient outcomes are expected to prevail through bargaining. When water is scarce and when property rights are well defined, a difference in the marginal value of water between two users—greater than the costs of transferring the water—is expected to lead to a trade in water (Rosegrant and Binswanger, 1994; Holden and Thobani, 1996). Nevertheless, the International Freshwater Treaties Database (Wolf, 1998) contains only nine (out of 49) water allocation agreements where payments are explicitly coupled to water delivery, see table 4.1.[2] This is a surprisingly low fraction of transboundary river basins where contractual agreements on water are established. Especially so given the existence of over 250 transboundary rivers world-wide, many of which face water scarcity.

The presence of contested water rights is, in our view, a major cause for missing international water trade. We argue in this chapter that if water rights are contested, this may obstruct water trade. To show this, we use a conflict model in which water rights are contested. Conflict models have been introduced by Bush and Mayer (1974). For an overview of the economics of conflict see Garfinkel and Skaperdas (2007); recent applications of conflict models to contests over natural resources include Wick and Bulte (2006) and Schollaert and Van de Gaer (2009).

The core idea is as follows. Two countries share a river and each claims a portion of river water. Water is scarce and claims are overlapping, making water a contested resource. Countries bargain over the allocation of contested river

[1]Some argue that conflict over water is a misconception, disqualifying water wars as a "myth" (Barnaby, 2009). See chapter 1 for comments on this line of reasoning.

[2]We use a broad definition of water trade in this chapter. It includes the signing of water allocation agreements, when these agreements explicitly couple water allocation to side payments. Such agreements can be interpreted as water trade contracts, whose specifications are determined in a bargaining process.

Table 4.1: Agreements on water allocation with payment details.

Basin (year) and agreement name	Side payment details
Indus (1892): Amended terms of agreement between the British Government and the State of Jind, for regulating the supply of water for irrigation from the Western Jumana Canal.	Jind (India) made a fixed annual payment to Great Britain for the delivery of water for the irrigation of 50,000 acres through newly constructed distribution works.
Gulf of Aden drainage basin (1910): Convention regarding the water supply of Aden between Great Britain and the Sultan of Abdali.	Great Britain agreed to make monthly payments to the Sultan of Lahej for extracting groundwater.
Gash (1925): Exchange of notes between the United Kingdom and Italy respecting the regulation of the utilisation of the waters of the River Gash.	Sudan (the United Kingdom) agreed to pay a share of its income from irrigated agriculture to Eritrea (Italy) for passing through the necessary water.
Näätämo (1951): Agreement between the Government of Finland and Norway on the transfer from the course of the Näätämo (Neiden) river to the course of the Gandvik river.	Norway receives water from the Näätämo basin to be used for power generation and compensates Finland for lost water power through a lump-sum payment of NKR 15,000.
Isonzo (1957): Agreement between the government of the Italian Republic and the government of the Federal People's Republic of Yugoslavia concerning the water supply of the town of Gorizia.	Italy pays 58 million lira annually to Yugoslavia for receiving 4.5 million MCM/year, which equals 85% of the total river flow in the Isonzo.
Colorado (1966): Exchange of notes constituting an agreement concerning the loan of waters of the Colorado river for irrigation of lands in the Mexicali valley.	Mexico reimburses losses in power generation to the USA for releasing 50 MCM in the fall of 1966 for irrigation purposes (on top of its allocation according to the 1944 Water Treaty).
Roya (1967): Franco-Italian convention concerning the supply of water to the Commune of Menton.	France made a one-time ITL 10 million payment for diverting water from the Roya to supply the village of Menton, while agreeing to pass through a fixed share of its diversion to the Italian village of Ventimiglia.
Helmand (1973): Helmand River Water Treaty.	On top of its original allocation of 22 cubic metres per second, Iran was to purchase an additional four cubic metres per second from Afghanistan.
Orange (1986): Treaty on the Lesotho Highlands Water Project between the Government of the Republic of South Africa and the Government of the Kingdom of Lesotho.	South Africa agreed to make annual payments to Lesotho for water transfers, increasing from EUR 14 million in 1998, when actual water deliveries started, to EUR 24 million in 2004.

Sources: Compiled from Beach et al. (2000); Wolf (1999); Dinar (2006) and the International Freshwater Treaties Database, available at `http://www.transboundarywaters.orst.edu/`.

Note: The table lists only those agreements where payments are explicitly coupled to water delivery.

water. If the bargaining succeeds, property rights to water are defined, based on which countries may trade water. If not, they engage in conflict. In the conflict, countries spend their resources on production, which also requires water, or on fighting to secure part of the contested water. The resulting equilibrium—the "natural distribution" (Buchanan, 1975)—is inefficient as both countries spend a positive amount of resources on fighting which is not productive. The natural distribution serves as the disagreement point of the bargaining game. During the bargaining each country may use its outside option and request intervention by a third party.[3] This third party would settle the conflict and allocate the water in an equitable way. Successful intervention, however, cannot be expected with certainty, so that conflict may still emerge. Hence, the mere possibility of third party intervention may give rise to an inefficient equilibrium.

Our contribution to the literature is twofold. First, we apply a conflict model to the issue of water rights. Although the lack of property rights has been recognised as a problem in the water literature (Richards and Singh, 2001), no supporting theory has been constructed yet.[4] Conventional explanations for missing international water trade in this strand of literature are mostly based on empirical studies of the economic and demographic characteristics of riparian countries. A key finding in this literature is that power distribution, governance, scarcity, and trade relations are important determinants for riparians to either have negotiated water allocation agreements or engage in international water trade (Song and Whittington, 2004; Dinar et al., 2007; Dinar, 2007). In this chapter we aim to shed light on these findings from a theoretical angle. A study close to ours is Janmaat and Ruijs (2006), although they are more interested in the probability of conflict over river water, while our focus is on the role of contested water rights in explaining the general absence of water trade.

Second, we introduce the concept of (overlapping) claims in non-cooperative

[3]In the setting of international river basins interventions can be expected from international organisations, such as the World Bank or the United Nations. These third parties are expected to allocate the water in an equitable way, based on, for instance, the 1966 "Helsinki Rules" proposed by the International Law Association. Note that the model developed in this chapter is applicable to intranational water allocation too. In this case, a national government may act as the intervening third party.

[4]Various reasons for poorly defined property rights have been proposed in the literature, most of them related to hydrological characteristics. For example, Brennan and Scoccimarro (1999) discuss difficulties of defining property rights to water, given the spatial and temporal setting of the resource; see also Randall (1981) and Ward (2007). Return flows and conveyance losses are two important characteristics that may hamper the determination of property rights too (Griffin and Hsu, 1993; Chakravorty and Umetsu, 2003; Chakravorty et al., 1995).

bargaining problems. These claims can be based on, for instance, historic water use or a perceived "equitable" use of available river water (Daoudy, 2008). The concept of claims has been introduced in the axiomatic approach to bargaining, starting with O'Neill (1982) and Chun and Thomson (1992). The focus of this literature is the characterisation of solutions with certain attractive properties for the division of contested resources. Our focus is on the strategic role that claims can play in non-cooperative bargaining. Note that Grossman (2001) also constructs a conflict model with claims; these claims are, however, not overlapping.

Our results show that, for certain model parameters, countries prefer not to bargain an efficient allocation. Instead, they may prefer to stick to their claims, hoping for a favourable settlement of the bargain by a third party. As intervention might not occur or fail, conflict may emerge. Thus, the prospect of third party intervention can cause persisting conflict and thereby obstruct water trade.

We analyse a bargaining game with probabilistic outside options. If an agreement is reached, water rights are allocated according to the agreement, production takes place and payoffs are realised. If either country opts out, a third party is asked to intervene. Whether or not intervention will settle the conflict is uncertain. If intervention is successful, water is allocated by the third party, production takes place and payoffs are realised. If intervention does not occur or is unsuccessful, or if bargaining breaks down for any other reason, conflict results. Both countries invest in fighting to secure part of the contested water, production takes place and payoffs are realised. We analyse the game backwards. Therefore the remainder of this chapter is organised as follows. In section 4.2 we present the conflict model and derive the natural distribution of water that determines the disagreement point of the bargaining game. In section 4.3 we analyse countries' incentives to bargain over the property rights to water or to take up their outside option. In section 4.4 we illustrate the results using a numerical example. In section 4.5 we discuss the results and conclude.

4.2 A conflict model for transboundary rivers

4.2.1 Model structure

In this section we construct a conflict model inspired by Grossman and Kim (1995). Our conflict model is built on two assumptions that are relevant for water allocation, thereby setting this model apart from conventional conflict models. First, we assume that only water is fought over, instead of produce or endowments. In general, property rights to goods and production factors have been defined and are respected. Countries may, however, contest water resources of a shared river, even when they respect property rights to all other goods. This is caused by water being a flowing resource; any claimed property rights to water are easily contested.

Second, we explore the role of claims to water that make (part of the) river water a contested resource. There is ample evidence for the existence of claims (Dellapenna, 2007), for instance in Asian river basins; see Wirsing and Jasparro (2007). Clearly, these claims can be overlapping as is demonstrated by the vast amount of conflicts over river water (Wolf, 1998). We assume that claims are exogenous, they can be based on for instance historical use or irrigation needs (Wolf, 1999). Claims are the main drivers of the results in this chapter. They are both the cause of river water being contested and they form the basis for a possible settlement.

The setting of the conflict model is as follows. A river flows from country 1 to country 2. River water W is normalised to unity, so water use w_i can be seen as the share of water used by country i ($i = 1, 2$), such that $W = w_1 + w_2 = 1$. Each of the two countries has an initial endowment of resources e_i that can be used as production input x_i or fighting input g_i:

$$e_i = x_i + g_i. \tag{4.1}$$

Water is an input in the production function $y_i(w_i, x_i)$ with production increasing in w_i and in x_i (hence decreasing in g_i). Note that this production function requires both water and non-water input. Irrigation is the obvious example of a production function with water being one of the production factors (in addition to, for instance, fertiliser). We use a simplified Cobb-Douglas production function, where non-water input can be used to increase productivity, for instance through irrigation efficiency:

$$y_i(x_i, w_i) = (x_i w_i)^{\alpha_i} \quad \text{with } 0 < \alpha_i \leq \frac{1}{2}, \tag{4.2}$$

where α_i are parameters that capture asymmetry between the countries in terms of agricultural productivity. Note that this production function reflects non-increasing returns to scale. The differences between α_1 and α_2 on the one hand and x_1 and x_2 on the other hand create opportunities for water trade as they define the marginal productivity of water in each country.

In terms of fighting, a higher level of g_i increases country i's fighting capacity. Note that "fighting" does not necessarily refer to military efforts. It may also refer to lobbying or diplomatic activity. Moreover, even if it refers to military efforts, open conflict need not occur (Skaperdas, 1992).

Because property rights to water are not established, water use depends on countries' water claims $c_i \in [0, 1]$ and their inputs to fighting (g_i) to secure these claims. As long as $c_1 + c_2 \leq 1$, no water is contested. The interesting case is, of course, where $c_1 + c_2 > 1$. The target of fighting is the portion of water that is contested: $c_1 + c_2 - 1 > 0$. The portion of contested water that is secured by country i is determined by a contest success function (CSF) $p_i(g_1, g_2)$, with $p_i \in [0, 1]$. We have p_1 increasing in g_1 and decreasing in g_2. Similarly, p_2 is decreasing in g_1 and increasing in g_2. The interpretation of p_i is country i's spending on fighting relative to the other country, which gives country i the possibility to secure water.

Hirshleifer (1989, 2000) and Garfinkel and Skaperdas (2007) discuss two common functional forms for a CSF. When the *difference* in inputs to fighting is considered important for the portion captured, a logistic form of the CSF is appropriate. We will use the alternative and more common form where the *ratio* of inputs to fighting is considered important for the portion captured:

$$p_1 = \frac{g_1}{g_1 + g_2}, \tag{4.3}$$

$$p_2 = \frac{g_2}{g_1 + g_2}. \tag{4.4}$$

The cost of fighting is production foregone. An equilibrium is obtained when, for each country, its marginal costs of fighting equal its marginal benefits of fighting, given the other country's distribution of resources over production and fighting.[5] Note that the marginal benefits of fighting reflect the marginal benefits of water use according to (4.2). There are three steps to determine the equilibrium of the contest game. First, countries independently and simultaneously choose

[5]See Hirshleifer (1995) for further comments on the costs of fighting.

levels of g_i (which determines x_i). Second, countries fight over the contested water, securing $p_i(c_1 + c_2 - 1)$, based on the chosen levels of g_1 and g_2. This determines water use w_i:

$$w_1 = 1 - c_2 + p_1(c_1 + c_2 - 1), \tag{4.5}$$

$$w_2 = 1 - c_1 + p_2(c_1 + c_2 - 1). \tag{4.6}$$

The first terms in equations (4.5) and (4.6), $1 - c_j$, represent the amount of water that is not contested by the other country (country j) and is therefore secure to country i. The second terms represent the portion of contested water that is secured through conflict. Third, countries receive payoffs π_i, where payoffs are due to production only. Using (4.1) and (4.2) we have

$$\pi_1 = y_1(x_1, w_1) = \left((e_1 - g_1)\left(1 - c_2 + \frac{g_1(c_1 + c_2 - 1)}{g_1 + g_2}\right)\right)^{\alpha_1}, \tag{4.7}$$

$$\pi_2 = y_2(x_2, w_2) = \left((e_2 - g_2)\left(1 - c_1 + \frac{g_2(c_1 + c_2 - 1)}{g_1 + g_2}\right)\right)^{\alpha_2}. \tag{4.8}$$

This completes the description of our conflict model; the equilibrium is determined in the following subsection.

4.2.2 The natural distribution of water

An equilibrium—the natural distribution—of the conflict model presented in section 4.2.1 can be found by combining the countries' best response functions. Country 1's best response is to choose g_1 to maximise π_1 given g_2 and vice versa. Solving the first order conditions of the maximisation problem with respect to g_i gives the following best response functions:[6]

$$g_1 = \frac{\sqrt{c_1(c_1 + c_2 - 1)g_2(e_1 + g_2)}}{c_1} - g_2, \tag{4.9}$$

$$g_2 = \frac{\sqrt{c_2(c_1 + c_2 - 1)g_1(e_2 + g_1)}}{c_2} - g_1. \tag{4.10}$$

[6] A logarithmic production function of the form $y(x_i, w_i) = \ln \alpha_i(x_i w_i + 1)$ yields similar best response functions.

Note that α_1 and α_2 do not appear in the best response functions.[7] Differences in productivity do not affect equilibrium levels of fighting. Also note that the best responses do not depend on the other country's resource endowment, only on the portion of this endowment that is used for fighting.

Symmetric countries In the special case where the countries have equal claims and resource endowments (i.e. $c_1 = c_2 = c > \frac{1}{2}$ and $e_1 = e_2 = e$), countries have equal fighting inputs $g_1 = g_2 = g$. To determine the natural distribution, the system of two equations (4.9)–(4.10) can be easily solved for g:

$$g^\star = \left(\frac{2c-1}{2c+1}\right)e. \tag{4.11}$$

Equilibrium levels of fighting (denoted by *) are increasing and linear in resource endowments and increasing and concave in claims. Because of symmetry, water is divided equally in the natural distribution: $w^\star = \frac{1}{2}$. Payoffs can be determined by combining (4.7) with (4.11):

$$\pi^\star = \left(\frac{e}{2c+1}\right)^\alpha. \tag{4.12}$$

Equilibrium payoffs are increasing and concave in resource endowments and decreasing and convex in claims.

When resource endowments increase, there is more fighting. Although increasing inputs to fighting are costly, payoffs increase with resource endowments. When claims increase, there is also more fighting. Given constant resource endowments, this increase in fighting reduces the countries' payoffs. Clearly, the larger the share of contested water, the less efficient is the natural distribution. These results are consistent with the standard comparative-static results for two-player contest games (Malueg and Yates, 2005).

Asymmetric countries In the general case, without assuming symmetry, calculation of the equilibrium is more complex. Solving the system of two equations (4.9)–(4.10) for g_1 and g_2 gives polynomials of degree three. Using Cardano's formula, equilibrium values of $g_i^\star$ can be expressed as a function of c_1, c_2, e_1, and

[7] This is due to the simplified form of the Cobb-Douglas production function (4.2). It allows for an analytical solution in the case of symmetric countries as shown below.

e_2.[8] This function is analytically not tractable and, therefore, we resort to numerical simulations over a wide range of parameter values. Our results show that equilibrium fighting efforts, water allocation, and payoffs are well-behaved (see figures 4.7–4.8 in the Appendix) and that the qualitative results of the symmetric outcome also hold for asymmetric countries, as is demonstrated in section 4.4. Again, increasing resource endowments causes an increase in fighting and payoffs. Increasing claims causes an increase in fighting but a decrease in payoffs.

It is possible to determine the ratio of both fighting inputs and water use in the natural distribution. Rearranging the response functions (4.9)–(4.10) gives

$$(g_1 + g_2)^2 = \frac{(c_1 + c_2 - 1)g_2(e_1 + g_2)}{c_1}, \tag{4.13}$$

$$(g_1 + g_2)^2 = \frac{(c_1 + c_2 - 1)g_1(e_2 + g_1)}{c_2}. \tag{4.14}$$

By substitution and rearranging, the ratio of g_1 to g_2 in equilibrium is

$$\frac{g_1^\star}{g_2^\star} = \frac{c_2(e_1 + g_2^\star)}{c_1(e_2 + g_1^\star)}. \tag{4.15}$$

Hence, $g_1^\star > g_2^\star$ if and only if $c_2(e_1 + g_2^\star) > c_1(e_2 + g_1^\star)$. In equilibrium, the ratio of inputs to fighting between country 1 and country 2 is a function of their claims and endowments. A larger endowment gives a higher ratio of inputs to fighting. A larger claim, however, gives a lower ratio of inputs to fighting, because having a larger claim corresponds to the other country having a smaller uncontested water claim, which will increase its inputs to fighting. These results are illustrated in section 4.4.

With equilibrium levels of fighting determined, we can turn our attention to water use in the natural distribution. Substituting and rearranging (4.5) and (4.6) gives us the ratio of p_1 to p_2:

$$\frac{p_1}{p_2} = \frac{w_1 + c_2 - 1}{w_2 + c_1 - 1}. \tag{4.16}$$

Because (4.3) and (4.4) imply that $g_1/g_2 = p_1/p_2$, the right hand sides of (4.15)

[8] This function is available upon request. See e.g. Sydsaeter et al. (2000) for Cardano's formula, who advise against its use. The polynomials have at least one real root in the relevant range. It can be shown that there is a unique interior solution such that $0 < g_i^\star < e_i$. This proof is also available upon request. I thank Rudi Weikard for mathematical advice.

and (4.16) are equal. The relation between w_1 and w_2 in the natural distribution is

$$\frac{w_1^\star + c_2 - 1}{w_2^\star + c_1 - 1} = \frac{c_2(e_1 + g_2^\star)}{c_1(e_2 + g_1^\star)}. \tag{4.17}$$

Because we normalise river water W to unity, we have $w_1 + w_2 = 1$. By substitution and rearranging we obtain the natural distribution of water:

$$w_1^\star = \frac{c_1[c_2(e_1 + g_2^\star) + (1 - c_2)(e_2 + g_1^\star)]}{c_1(e_2 + g_1^\star) + c_2(e_1 + g_2^\star)}, \tag{4.18}$$

$$w_2^\star = \frac{c_2[c_1(e_2 + g_1^\star) + (1 - c_1)(e_1 + g_2^\star)]}{c_1(e_2 + g_1^\star) + c_2(e_1 + g_2^\star)}. \tag{4.19}$$

In the natural distribution, water use is a function of the countries' claims, endowments and inputs to fighting. Note that equilibrium water use depends on equilibrium values of fighting, of which we only know the ratio in equilibrium, see (4.15). Hence, this system cannot be solved analytically, but results are easy to compute for any specification of parameters.

Because resources are spent on fighting, the natural distribution is not efficient. Total payoffs will increase if countries are able to prevent conflict. As explained in section 4.1, we analyse this possibility in a bargaining game where the natural distribution serves as the disagreement point. The interesting issue is how countries' incentives to bargain depend on the possibility of third party intervention. This is the topic of the following section.

4.3 Bargaining or intervention?

In this section we analyse whether countries are successful in bargaining over the property rights to water. Instead of bargaining, they may leave the bargaining table and ask for third party intervention. We include this possibility as an "outside option", as discussed below. Countries bargain over the allocation of contested river water. If bargaining succeeds, the Nash bargaining solution is used to determine the allocation of water, and the game is finished. If one of the countries leaves the bargaining table and opts out, third party intervention will be successful with probability q, which settles the conflict. With probability

$(1-q)$ conflict results and the natural distribution emerges.[9]

First, we discuss bargaining in more depth. Countries can prevent the inefficient conflict equilibrium by defining property rights to water in a bargaining game.[10] This game can be modelled as a non-cooperative alternating-offers bargaining game in the spirit of Rubinstein (1982). An obvious solution concept for this bargaining game is the limit case, where the non-cooperative bargaining solution approaches the axiomatic Nash bargaining solution (Binmore et al., 1986). In the Nash bargaining solution, the choice of the disagreement point drives the outcome. The natural distribution is used as the disagreement point (D in figure 4.1), as it is the outcome under conflict when bargaining would break down (cf. Muthoo, 1999, chapter 4). The Nash bargaining solution, denoted by $\left(\pi_1^N, \pi_2^N\right)$ is obtained by maximising the product of the countries' gains in payoff compared with their payoffs at the disagreement point (denoted by $\star$):

$$\left(\pi_1^N, \pi_2^N\right) = \max_{(w_1, w_2)} \left[\left(e_1 w_1\right)^{\alpha_1} - \left((e_1 - g_1^\star) w_1^\star\right)^{\alpha_1}\right]\left[\left(e_2 w_2\right)^{\alpha_2} - \left((e_2 - g_2^\star) w_2^\star\right)^{\alpha_2}\right], \quad (4.20)$$

subject to rationality constraints. The payoff frontier f is concave, see figure 4.1:

$$f = \left(\frac{e_1\left(e_2 - \pi_2^{1/\alpha_2}\right)}{e_2}\right)^{\alpha_1}. \quad (4.21)$$

The Nash water allocation (w_1^N, w_2^N) can be computed by solving the following system of equations (Muthoo, 1999):

$$\frac{\pi_1^N(0, w_1^N) - \pi_1(g_1^\star, w_1^\star)}{\pi_2^N(0, w_2^N) - \pi_2(g_2^\star, w_2^\star)} = -f'(\pi_2) = \frac{\alpha_1 \pi_2^{1/\alpha_2 - 1}\left(e_1\left(e_2 - \pi_2^{1/\alpha_2}\right)/e_2\right)^{\alpha_1}}{\alpha_2\left(e_2 - \pi_2^{1/\alpha_2}\right)}, \quad (4.22)$$

$$w_1^N = 1 - w_2^N. \quad (4.23)$$

Note that for the case of symmetric countries, discussed in section 4.2.2, $w^N = \frac{1}{2}$, and $\pi^N = \left(\frac{1}{2}e\right)^\alpha$.

This establishes the outcome of the Nash bargaining solution, denoted by N

[9]Later in this section we will use subjective probabilities q_i.

[10]Buchanan (1975) argues that the resource allocation when moving away from (or, in our case, preventing) conflict, is equal to the allocation in the natural distribution. The only difference is that countries disarm (or do not arm), which increases total payoffs. We do not see why countries would choose this specific allocation of water as a basis for the definition of property rights (cf. Houba and Weikard, 1995).

in figure 4.1. This outcome is self-enforcing as any deviation (i.e. investing in g to secure more water) would imply a shift to the natural distribution, which is worse for both countries in terms of payoff. In this respect, our model is different from conventional conflict models where enforcement of a negotiated outcome is necessary to prevent open conflict (see Anbarci et al., 2002 and Skaperdas, 2006 for discussions on how enforcement costs depend on the bargaining solution used).

Alternatively, instead of bargaining over the property rights to water, a country can decide to leave the bargaining table and engage in conflict, anticipating an intervention by a third party. Such an intervention may be requested by any of the two countries, for instance by submitting a case to the International Court of Justice. Three examples illustrate the effectiveness of third party intervention.

The first example is the 1953 US intervention on water allocation in the Jordan river basin. This intervention occurred after a period in which the dispute on Jordan river water became more and more tense. The following Johnston negotiations resulted in an allocation of water that was originally based on the area of irrigated land in each country. Although the Johnston Accord was never ratified, its allocation has been used in agreements between Israel and Jordan (1994) and Israel and the Palestinian authorities (1995), in which property rights to water were finally established (Wolf, 1999). The second example is the 1951 intervention by the World Bank in the dispute between India and Pakistan on the Indus river basin. In 1948, India diverted water away from Pakistan's irrigation canals, breaking the 1947 Standstill Agreement. The World Bank successfully allocated the contested water by assigning the three eastern rivers of the basin to India and the three western rivers to Pakistan, which formed the basis of the 1960 Indus Waters Treaty (Alam, 2002). The third example concerns the Euphrates basin, where Iraq called for intervention by the Arab League in 1974 after it claimed that Syria diverted too much water at the Tabqa dam. Although this intervention failed and military threats increased, mediation by Saudi Arabia in 1975 was successful. Beach et al. (2000) report that ultimately 40% of the Euphrates water was allocated to Syria and 60% to Iraq.

Note that (successful) intervention cannot be expected with certainty. The examples above illustrate that interventions in water negotiations usually concern the proposal of an allocation of water that is beneficial to all parties involved, and includes some notion of "equity". Equitable water allocation may be based on pragmatic principles such as population, irrigation needs, catchment size, or historic use (Wolf, 1999; Van der Zaag et al., 2002). Alternatively, principles of international water law such as "reasonable and equitable use" and "no significant harm" can be applied, as summarised in the Helsinki Rules, the UN Watercourses Convention, and the Berlin Rules (Salman, 2007). We assume that the third party proposes an allocation of water, based on any of these principles, that satisfies two requirements. First, the equitable allocation yields higher payoffs to both countries compared to the natural distribution. Second, the equitable allocation is efficient. Denote this equitable allocation by w_i^E. An appealing example is an allocation of water that is proportional to the countries' (exogenous) water claims:

$$w_1^E = \frac{c_1}{c_1 + c_2}, \tag{4.24}$$

$$w_2^E = \frac{c_2}{c_1 + c_2}. \tag{4.25}$$

In the remainder of this chapter, we use this functional form for w_i^E. Furthermore, we assume that the equitable allocation is enforced by the third party.

In choosing between bargaining property rights and opting out, hoping for a possible settlement of claims through third party intervention, countries will compare the associated payoffs. Stylised payoffs for the disagreement point (the natural distribution) D, the Nash bargaining solution N, and the equitable allocation E are shown in figure 4.1. Note that N is located on h, the highest rectangular hyperbola relative to axes through D that has a point in common with f. Because f is continuously decreasing, and both N and E are on f (no resources are spent on fighting), if N is preferred by one country, then E is preferred by the other.

When defining property rights using the Nash bargaining solution, country i's payoff is according to (4.20). When opting out, hoping for intervention, country i's payoff depends on the subjective probability $q_i \in (0, 1)$ that third party intervention occurs.[11] Its payoff is the probability weighted sum of the payoffs at the equitable allocation $\pi_i^E(0, w_i^E)$ and the natural distribution $\pi_i(g_i^\star, w_i^\star)$. Con-

[11]Perceptions of the likelihood of third party intervention and the probability of its success may differ across countries. Note that we do not explicitly model the third party's decision to intervene as is done, for instance, by Chang et al. (2007). The parameters q_i therefore capture all relevant information on the expectation and success of intervention by a third party.

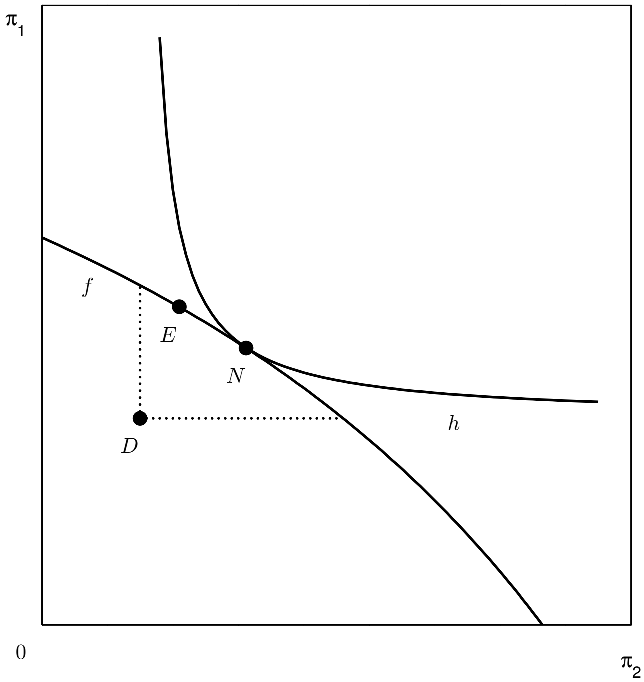

Figure 4.1: A stylised payoff space for countries 1 and 2. D denotes the disagreement point (the natural distribution), N denotes the Nash bargaining solution, E denotes the equitable allocation, f is the payoff frontier, and h is a rectangular hyperbola relative to axes through D.

sequently, country i will prefer to define property rights in a bargaining game rather than call for intervention, and vice versa, if

$$\pi_i^N(0, w_i^N) \geq q_i \pi_i^E(0, w_i^E) + (1 - q_i)\pi_i(g_i^\star, w_i^\star). \tag{4.26}$$

The presence of possible third party intervention can be interpreted as an "outside option" (Muthoo, 1999).[12] If (4.26) is violated for country i, waiting for third party intervention is a credible outside option. In figure 4.1, this may be an attractive possibility for country 1. The outside option payoffs are on a straight line connecting D and E (using probabilities q_i and $1 - q_i$), as reflected by (4.26). In figure 4.1, country 2 will always prefer a bargain. However, for a

[12]Conventionally, outside options have a time constraint. In this model, there is no time constraint, but a probability constraint, see Muthoo (1999).

sufficiently large q_1, the outside option is attractive enough for country 1 to leave the bargaining table; country 1 will not agree on the Nash bargaining solution N, but hope for a third party intervention to obtain E.

The presence of an outside option as such does not obstruct an efficient and immediate bargaining outcome. The country with an outside option has a strategic advantage in the bargaining procedure. Consequently, its payoff in a bargaining solution must be at least as high as its outside option payoff (Muthoo, 1999).

Without loss of generality, let country 1 have an outside option, as in figure 4.1. Furthermore, let $\tilde{q}_1$ denote the level of q_1 for which (4.26) holds with equality. When $q_1 < \tilde{q}_1$, the outside option is not credible and countries will bargain to reach N. When $q_1 \geq \tilde{q}_1$, the outside option is credible, leading to one of two outcomes. Either $q_2 \geq q_1$, then countries will bargain and country 1 receives its outside option payoff as explained above. Or $q_2 < q_1$, then country 2 is not willing to give in to country 1's outside option—as it considers country 1 to overstate its subjective probability of third party intervention—leading to emerging conflict with possibly third party intervention. Clearly then, what can obstruct a bargaining outcome is a difference in the countries' perceptions of the probability of third party intervention.[13]

As shown, the bargaining solution depends on the perceived probability of third party intervention in two ways. First, the probability of third party intervention may influence the payoffs of the countries in the bargaining outcome, as discussed above. Second, when the probability of third party intervention is sufficiently large, it may cause a country to use its outside option.

4.4 Numerical example

For asymmetric countries, payoffs and water use in both the natural distribution and the Nash bargaining solution cannot be determined analytically. Therefore, and to provide further insights and illustrations we present a numerical example.

[13] Note that, alternatively we could model different perceptions of the location of E, possibly determined as the expected values of two different probability density functions. Such differences in the perception of the location of E may be attributed, for instance, to a "self-serving bias" (cf. Babcock and Loewenstein, 1997). An alternative reason why countries would not bargain an efficient outcome is a "long shadow of the future". In a dynamic setting, initial conflict may permanently increase future payoffs, for instance by eliminating the adversary (Garfinkel and Skaperdas, 2000). In the context of this chapter, however, this does not seem to be a plausible argument.

Throughout this example we keep the parameters of country 2 constant at $c_2 = 0.7$ and $e_2 = 1.5$, while varying the parameters of country 1. Also, productivity parameters are constant at $\alpha_1 = \alpha_2 = \frac{1}{4}$.

Figure 4.2 shows the best response functions (4.9)–(4.10) for the symmetric case where $c_1 = c_2 = 0.7$ and $e_1 = e_2 = 1.5$. Equilibrium values for the natural distribution are $g_1^\star = g_2^\star = 0.25$ and $w_1^\star = w_2^\star = 0.5$. A second equilibrium where both countries do not fight at all ($g_1 = g_2 = 0$) is not stable because a very small increase in fighting by one of the countries would cause a shift to the other equilibrium. This instability can also be derived from the specification of the contest success function in (4.3) and (4.4), given that resource endowments e_i are not too asymmetric. The figure shows that inputs to fighting are concave in inputs to fighting by the other country.[14]

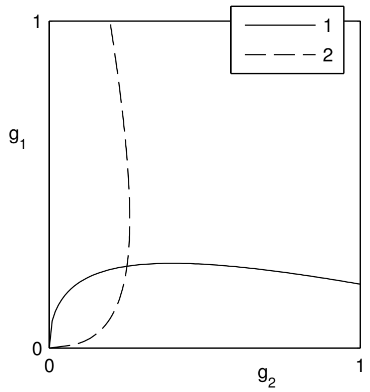

Figure 4.2: Best response functions of countries 1 and 2 for the symmetric case where $c_1 = c_2 = 0.7$ and $e_1 = e_2 = 1.5$.

Figure 4.3 shows the equilibrium values for $g_i^\star$, $w_i^\star$, and $\pi_i^\star$ in the natural distribution as a function of c_1. Clearly, increasing claims lead to higher inputs to fighting by both countries. Having a higher claim increases a country's water use and payoffs. Due to the production foregone because of fighting, total payoffs decrease with increasing claims.

Figure 4.4 shows the equilibrium values for $g_i^\star$, $w_i^\star$, and $\pi_i^\star$ in the natural distribution as a function of e_1. Increasing resource endowments leads to higher inputs to fighting by the country with the higher endowment (not necessarily by

[14]Figure 4.6 in the Appendix provides a more general picture and shows the best response functions for nine different combinations of c_1 and e_1.

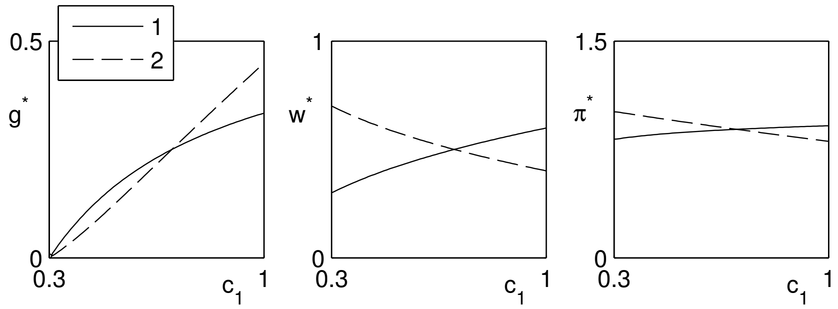

Figure 4.3: Natural distribution equilibrium values for $g_i^\star$, $w_i^\star$, and $\pi_i^\star$ as a function of c_1 with $e_1 = 1.5$ and $c_2 = 0.7$.

both countries as can be seen in figure 4.8 in the Appendix). Having a higher resource endowment increases a country's water use and payoffs. Notwithstanding the production foregone because of fighting, total payoffs increase with increasing resource endowments.

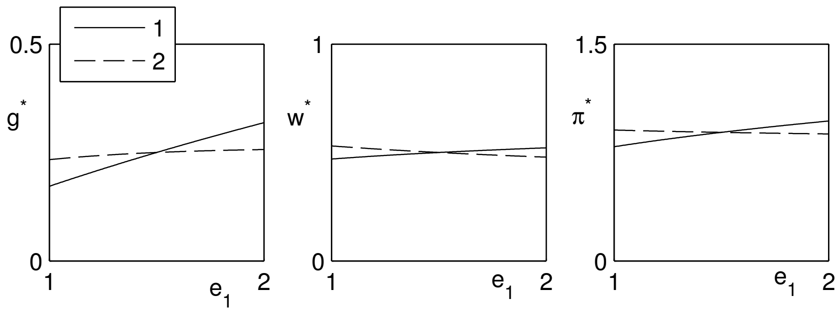

Figure 4.4: Equilibrium values for $g_i^\star$, $w_i^\star$, and $\pi_i^\star$ as a function of e_1 with $c_1 = c_2 = 0.7$ and $e_2 = 1.5$.

Three additional model features for the natural distribution are obtained using a range of simulations (see figures 4.7–4.8 in the Appendix); they are partly illustrated by figures 4.3 and 4.4. First, inputs to fighting, water use, and payoffs are increasing at a decreasing rate in a country's own claim, see figure 4.3. Second, despite the opportunity costs of fighting, a country's payoff increases with both its claims and its endowments, irrespective of the other country's claims or endowments, see figures 4.7 and 4.8 in the Appendix. Third, just having a high claim, or just having high endowments does not necessarily make a country better off than its opponent in terms of payoffs. Claims and endowments appear to be substitutes. This can be seen in the bottom-left panels of figures 4.7 and 4.8 in the Appendix, where country 1's payoff curves are below country 2's payoff curves.

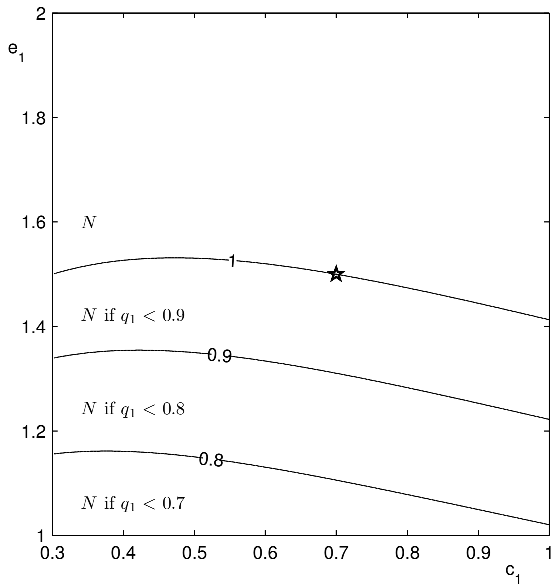

Figure 4.5: Preference of country 1 for N (bargaining) or E (waiting), as a function of c_1 and e_1. Isolines indicate threshold values of q_1 for which country 1 is indifferent between N and E. Note that $c_2 = 0.7$ and $e_2 = 1.5$.

Parameter combinations of c_1 and e_1 determine the locations of the Nash bargaining solution N and the equitable allocation E on the payoff frontier as illustrated in figure 4.1. A comparison of payoffs in choosing between bargaining and leaving the bargaining table hoping for third party intervention, is shown for country 1 in figure 4.5. The figure shows isolines for threshold values of q_1 such that (4.26) holds with equality as a function of parameter combinations of c_1 and e_1. Recall that when (4.26) holds with equality, country 1 is indifferent between bargaining property rights and opting out. As explained in section 4.3, when N is preferred by one country, then E is preferred by the other. This implies that the $q_1 = 1$ isoline, where country 1 is indifferent between bargaining and opting out, coincides with the $q_2 = 1$ isoline. This is the case, for instance, at the symmetric point where countries have equal claims and endowments, indicated by $\star$ in figure 4.5. In the upper part of the figure where country 1 prefers to bargain to reach N, country 2 will—for certain levels of q_2—prefer to opt out and hope for third party intervention. This implies that, given q_1 and q_2, bargaining is more likely for parameter combinations of c_1 and e_1 close to the $q_1 = q_2 = 1$ isoline.

In this numerical example claims have almost no impact on the country's preference for bargaining. Note that even with a tiny overlapping claim (c_1 close to 0.3), there is a possibility that only one country prefers to bargain, leading eventually to conflict. Endowments, however, have a high impact. The more equal the distribution of resources endowments, the more likely it is that countries bargain property rights to reach N.

The impact of claims on the preference for bargaining seems counter-intuitive: starting in the symmetric point, when c_1 increases, country 1 prefers to bargain. One would expect that when c_1 increases, E moves in a north-western direction along the payoff frontier because water allocation in E is determined proportional to claims, see (4.24). This would make E more attractive relative to N, as illustrated in figure 4.1. A shift in relative claims, however, also affects the position of D and thereby the position of N. When c_1 increases, the position of D changes such that N moves even further than E in the same direction along the payoff frontier. Country 1's payoff at N increases more than its payoff at E. Hence we find the preference of country 1 for bargaining to reach N instead of hoping for third party intervention E.

Note that for symmetric countries, N and E coincide and countries will always bargain property rights. In figure 4.5, the difference between payoffs for N and E are smaller the closer we get to the centre of the figure (where countries are symmetric). This implies that for more symmetric countries, the threshold level of q_i to not bargain property rights becomes higher. In other words, conflict between countries is more likely the larger the differences between them.

4.5 Discussion and conclusion

This chapter develops a theory of how conflict over river water may emerge through contested water rights. Formal property rights to water are not necessarily established; one country may prefer not to bargain an efficient allocation. Instead, it may prefer to engage in conflict, hoping for a third party intervention.

This result is illustrated using a numerical example in which, for certain parameter combinations, conflict in the natural distribution is an equilibrium outcome. Apparently, the resolution of water disputes and resulting trade in water is not necessarily an attractive option, even though trade is beneficial to both countries. Hence, we provide a theory for the lack of property rights over water in transboundary river basins.

The Coase theorem applied to water resources implies that the efficient use of water does not depend on the distribution of water rights. Transaction costs, arising from uncertainty and contract enforcement, can obviously obstruct the bargaining process over water (Richards and Singh, 2001). This chapter shows that there is another potentially important obstruction to Coasean bargaining: the presence of overlapping claims to water, making water a contested resource for which property rights are disputed. The presence of claims has severe implications for the efficiency of water use, because claims determine both the equilibrium water use in the natural distribution, and consequently, the possibilities to bargain a more efficient allocation of water. Clearly, claims combined with subjective probabilities of third party intervention render the Coase theorem inapplicable in the case of river water resources. Conflict is possible, with countries hoping for a third party to intervene. This obstructs water trade because property rights to water fail to emerge.

Intervention by a third party in a conflict is not always desirable (cf. Chang et al., 2007). Our model shows that the mere possibility of third party intervention may cause an inefficient equilibrium of water use through investments in fighting. This illustrates the problematic position of organisations whose aim is to mediate or resolve international conflicts, such as the World Bank or the United Nations. The existence of organisations that facilitate conflict resolution may actually generate conflict. In other words, the prospect of conflict mediation may crowd out the capacity of conflicting parties to resolve the conflict themselves. Our results also highlight the problem created by conflicting principles of international law in water allocation (Salman, 2007). Conflicting principles may cause countries to have different perceptions of what is an equitable allocation which, in turn, may obstruct a bargaining solution; see footnote 13.

The model developed in this chapter describes a situation in which countries may end up in an inefficient equilibrium, instead of bargaining an efficient outcome. Overlapping claims to productive resources and the presence of an information asymmetry cause this inefficiency. The model results depend on parameter combinations of countries' resource endowments and claims, which are presumed to be exogenous. It seems attractive to endogenise the claims. Given the best response functions (4.9) and (4.10), and because claims have no cost, this implies that in the natural distribution both countries would claim 100% of the water. These extremely high claims would cause high inputs to fighting (see figure 4.3) and consequently, low payoffs. In practice, however, claims are never this high; countries generally do not invoke 100% claims (Wolf, 1999).[15] Instead, they base their claims on an observable criterion, such as irrigation needs or historic use. In addition, 100% claims would not be credible to a third party that would have to settle claims. Hence, endogenous claims are not a logical feature of this model.

In this chapter, we have studied the case of two countries sharing a river. Although our model is general enough for other applications, it can capture the upstream-downstream character of a shared river. The geographical advantage of the upstream country can be reflected by assigning it a higher claim. A model of this type is relevant for other bargaining situations too, where claims are overlapping and with the possibility of third party intervention. Possible applications are: (i) countries' claims to the control of a fishing area or a shared aquifer; (ii) disputed territory; and (iii) partners' claims to common property in a divorce, where a court may settle the division of the property.

We see two logical extensions to the model described in this chapter. First, instead of modelling the outcome of third party intervention proportional to the countries' water claims, it could be impacted by lobbying at the third party. Second, repeated interaction between the countries may increase cooperation (cf. Wolf, 1998) or induce conflict (cf. Garfinkel and Skaperdas, 2000). A dynamic version of the model presented in this chapter may treat x_i and g_i as flows of input to stocks of goods and weapons. These extensions, however, are left for future work.

[15] A 100% claim by an upstream country reflects the principle of absolute territorial sovereignty, a 100% claim by a downstream country reflects the principle of absolute territorial integrity.

Appendix: Three figures

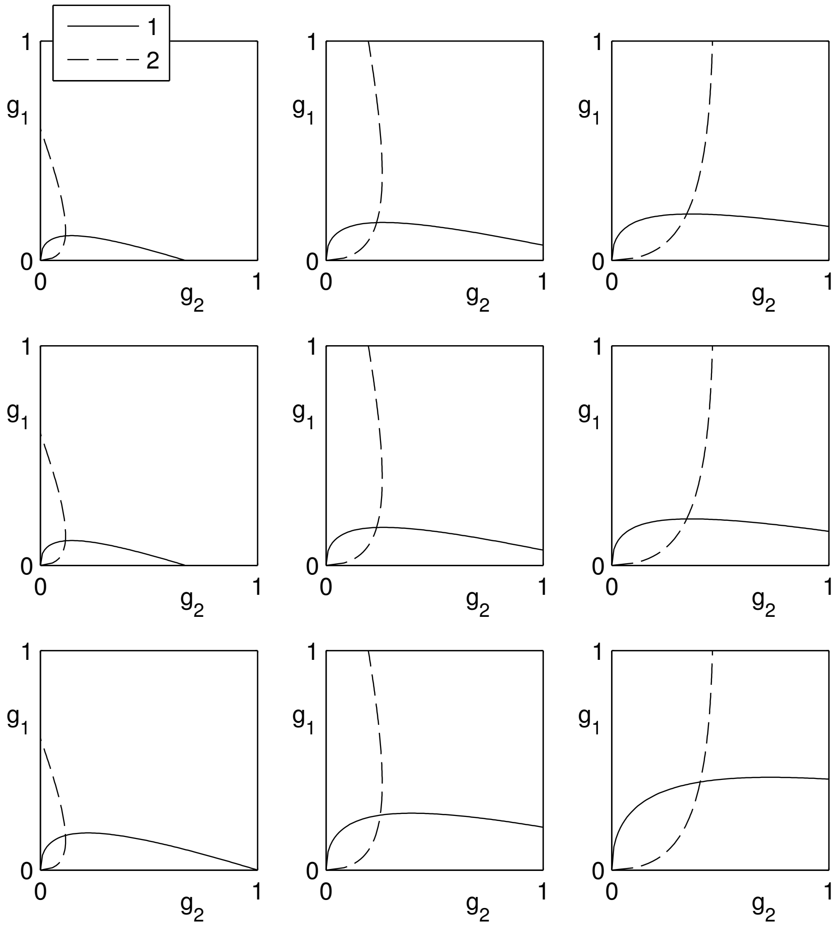

Figure 4.6: Best response functions of countries 1 and 2, with c_1 increasing in the columns (0.5, 0.7, and 0.9), and e_1 increasing in the rows (1, 1.5, and 2). Parameter values of country 2 are constant at $c_2 = 0.7$ and $e_2 = 1.5$.

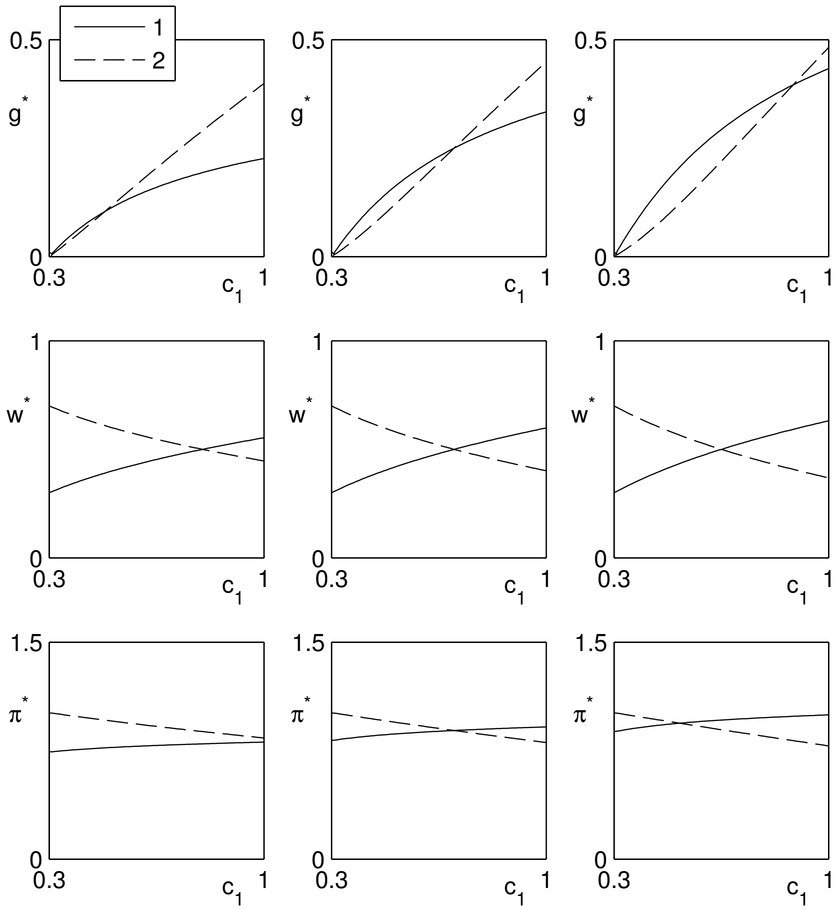

Figure 4.7: Natural distribution equilibrium values for $g_i^\star$, $w_i^\star$, and $\pi_i^\star$ as a function of c_1, with e_1 increasing in the columns (1, 1.5, and 2). Parameter values of country 2 are constant at $c_2 = 0.7$ and $e_2 = 1.5$.

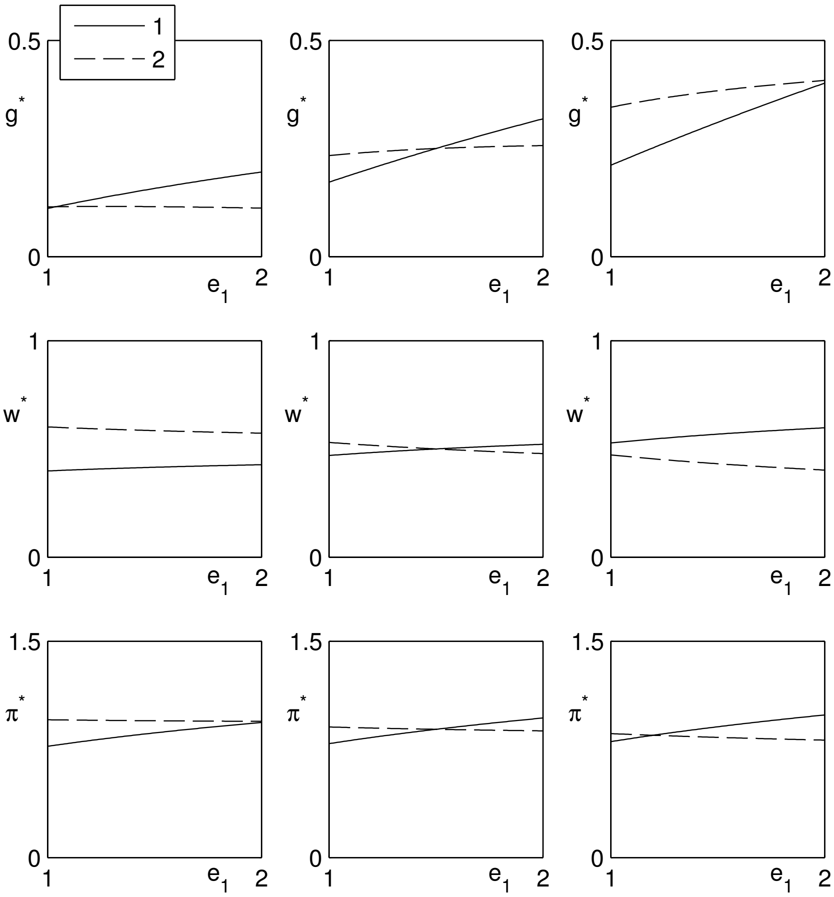

Figure 4.8: Natural distribution equilibrium values for $g_i^\star$, $w_i^\star$, and $\pi_i^\star$ as a function of e_1, with c_1 increasing in the columns (0.5, 0.7, and 0.9). Parameter values of country 2 are constant at $c_2 = 0.7$ and $e_2 = 1.5$.

Chapter 5

Sequential sharing rules for river sharing problems*

We analyse the redistribution of a resource among agents who have claims to the resource and who are ordered linearly. A well known example of this particular situation is the river sharing problem. We exploit the linear order of agents to transform the river sharing problem to a sequence of two-agent river sharing problems. These reduced problems are mathematically equivalent to bankruptcy problems and can therefore be solved using any bankruptcy rule. Our proposed class of solutions, that we call sequential sharing rules, solves the river sharing problem. Our approach extends the bankruptcy literature to settings with a sequential structure of both the agents and the resource to be shared. In this chapter, we first characterise a class of sequential sharing rules. Subsequently, we apply sequential sharing rules based on four classical bankruptcy rules, assess their properties, and compare them to four alternative solutions to the river sharing problem.

*This chapter is based on Ansink and Weikard (2009b). Sequential sharing rules for river sharing problems. Paper presented at the 17th Annual Conference of the European Association of Environmental and Resource Economists, Amsterdam, the Netherlands.

5.1 Introduction

In this chapter we analyse the redistribution of a resource among agents who have claims to the resource and who are ordered linearly. Our choice for this particular situation is motivated by the following two examples.

The first example is the distribution of intergenerational welfare (Arrow et al., 2004). The agents are the generations, ordered linearly in time. Each generation is endowed with certain resources, but also has a claim to inherit part of the resources of the previous generation. A specific problem of this kind is the climate change problem, where each generation adds to the stock of greenhouse gasses, but also makes a claim to previous generations' mitigation efforts (Dasgupta et al., 1999; Weikard, 2004b; Davidson, 2008).

The second example is the river sharing problem (Ambec and Sprumont, 2002; Parrachino et al., 2006; Carraro et al., 2007). This is the topic of this chapter. In the river sharing problem, the agents are countries (or water users in general), ordered linearly along a river. On the territory of each agent tributaries and rainfall add water to the river. This constitutes the agent's endowment of river flow. Each country also has a claim to river water. These claims can be based on any of a wide range of principles for river sharing (Wolf, 1999; Daoudy, 2008). Two common principles for river sharing are absolute territorial sovereignty (ATS) and absolute territorial integrity (ATI) (Salman, 2007). ATS prescribes that each agent has the right to all water on his territory while ATI prescribes that each agent has the right to all upstream water. Though these extreme principles are not often invoked in practice, agents' claims are often larger than their endowments, as illustrated for instance by Egypt's large claim to water in the Nile river basin. Agents' overlapping claims to river water make water a contested resource (Ansink and Weikard, 2009a, see chapter 4).

In both examples, redistribution of the resource endowments may be desirable, for instance when some agents have large endowments but only small claims (cf. Bossert and Fleurbaey, 1996). We exploit the linear order of agents to determine this redistribution using an axiomatic approach. Using two very natural requirements, the order of agents allows us to transform the river sharing problem to a sequence of two-agent river sharing problems that we call reduced river sharing problems. Reduced river sharing problems are mathematically equivalent to bankruptcy problems (Aumann and Maschler, 1985; Young, 1987;

Moulin, 2002). Therefore we can use sharing rules from the bankruptcy literature to solve these reduced river sharing problems. In each of these reduced problems, water rights are allocated to an agent and the set of his downstream neighbours. As in bankruptcy problems, our proposed class of solutions—denoted sequential sharing rules—is based on the agents' claims. Sequential sharing rules are constructed by the recursive application of a bankruptcy rule to the sequence of reduced river sharing problems.

In a bankruptcy problem, a perfectly divisible resource (usually called the estate in this literature) is to be distributed over a set of agents who have overlapping claims. A solution to a bankruptcy problem is a sharing rule (or alternatively, a rationing scheme), that is based on the agents' claims to the resource. Various axiomatic approaches to the construction of such sharing rules have been analysed (cf. Herrero and Villar, 2001; Thomson, 2003).

In a river sharing problem, agents are ordered linearly, characterised by an initial resource endowment and a claim to the resource. Claims are exogenous and may be smaller or larger than an agent's endowment. As in the bankruptcy problem, we assume scarcity of the resource. River sharing problems differ from bankruptcy problems in two ways. First, there is a difference in the position of the agents. In the standard bankruptcy problem, all agents have equal positions. In a river sharing problem, agents are ordered linearly, reflecting the direction of river flow. Therefore, the agents' claims have a sequential structure, linking the river sharing problem to bankruptcy problems with a priority order (cf. Moulin, 2000). Second, there is a difference in the initial state of the resource. In a bankruptcy problem, the resource is initially completely separated from the agents. In a river sharing problem, the resource is initially endowed to the agents. This endowment of resources links our approach to reallocation problems (cf. Fleurbaey, 1994; Klaus et al., 1997). Both differences play a key role in the construction of the class of sequential sharing rules.

There are two reasons for solving river sharing problems using bankruptcy rules.[1] First, as indicated above, both types of problems have many common properties. Because the properties of bankruptcy rules are well understood, these rules are logical candidates to be applied to river sharing problems too.

[1]The standard approach to analyse river sharing problems is to apply non-cooperative game-theoretic models (cf. Carraro et al., 2007; Ansink and Ruijs, 2008, see chapter 2). The merit of the axiomatic approach employed in this chapter is to complement, support, and improve our understanding of the outcomes of these strategic models.

The second reason is based on current practices in water allocation. Many two-agent water rights disputes are solved using variants of bankruptcy rules, for instance equal sharing or sharing proportional to some objective criterion (for instance population or the amount of irrigable land, see Wolf, 1999). Often, these solutions are explicitly proposed by third parties or joint river basin committees, but they can also be the result of negotiations between the agents. This chapter shows the logical extension of such sharing rules for river sharing problems with more than two agents.

This chapter makes two novel contributions. First, our approach extends the bankruptcy literature to settings with a sequential (or spatial) structure of both the agents and the resource to be shared.[2] Second, we provide axiomatic foundations for a class of solutions to the river sharing problem that satisfy some attractive properties.

The chapter is organised as follows. In section 5.2 we introduce the setting of the river sharing problem. In section 5.3 the class of sequential sharing rules is characterised. In section 5.4 we apply four sequential sharing rules, based on four classical bankruptcy rules, to a numerical example. In section 5.5 some properties of sequential sharing rules are assessed. In section 5.6 we compare our approach to four alternative solutions to the river sharing problem. In section 5.7 we discuss the results and conclude.

5.2 The river sharing problem

Consider an ordered set N of $n \geq 2$ agents located along a river, with agent 1 the most upstream and n the most downstream. Agent i is upstream of j whenever $i < j$. Denote by $U_i = \{j \in N : j < i\}$ the set of agents upstream of i, and denote by $D_i = \{j \in N : j > i\}$ the set of agents downstream of i. On the territory of i, rainfall or inflow from tributaries increases total river flow by $e_i \geq 0$; $e = (e_1, \ldots, e_n)$. River inflow e_i can be considered the endowment of i. This does not imply that agent i has property rights to e_i. Rights are assigned as a solution to a river sharing problem, as discussed below. In addition to river inflow e_i, each agent is characterised by having a claim $c_i \geq 0$; $c = (c_1, \ldots, c_n)$ to river flow. We do not impose which portion of an agent's claim is directed to $e_1, e_2, \ldots$ etc.

[2] Branzei et al. (2008) also analyse bankruptcy rules in a flow network. In their approach, however, the flows are cost functions that are used to implement bankruptcy rules in a network approach.

This information suffices to define our river sharing problem.

Definition 5.1 (River sharing problem)**.** A river sharing problem is a triple $\omega = \langle N, e, c \rangle$, with N an ordered and finite set of agents, $e \in \mathbb{R}^n_+$ and $c \in \mathbb{R}^n_+$.

To delineate the setting of the river sharing problem, let the total available water on the territory of agent i be denoted by

$$E_i \equiv e_i + \sum_{j \in U_i} (e_j - x_j), \tag{5.1}$$

where $x = (x_1, \ldots, x_n)$ is a vector of allocated water rights. This is the sum of river inflow on the territory of i and any unallocated upstream water. For the river sharing problem to be relevant, we make the following assumption.

Assumption 5.1. Agent n claims more than what is available to him: $c_n > E_n$.

This assumption implies that $c_n > e_n$, and it assures that there is contested water throughout the river (see lemma 5.1, below). Without this assumption, agent n could satisfy his claim completely and hence there would be no problem.

Denote by Ω the set of relevant river sharing problems that satisfy assumption 5.1. A sharing rule allocates water rights to each agent.

Definition 5.2 (Sharing rule)**.** A sharing rule is a mapping $F : \Omega \to \mathbb{R}^n$ that assigns to every river sharing problem $\omega \in \Omega$ a water rights allocation vector $x = (x_1, \ldots, x_n)$, $x \in \mathbb{R}^n_+$, such that (a) $\sum_{i \in N} x_i = \sum_{i \in N} e_i$, (b) $0 \leq x \leq c$, and (c) $x_i \leq e_i + \sum_{j \in U_i} e_j \; \forall i \in N$.

The allocation of water rights to agent i is $F_i(\omega) = x_i$. Requirement (a) of the sharing rule imposes efficiency: no water rights remain unallocated. Requirement (b) says that agents receive a non-negative allocation that is bounded by their claim. Requirement (c) is a feasibility constraint. Figure 5.1 illustrates a river sharing problem for $n = 4$.

5.3 Characterisation of sequential sharing rules

Solutions from the bankruptcy literature cannot be directly applied to the river sharing problem, because the resource is distributed over the agents. The linear order of agents along the river and the unidirectionality of river flow enable us,

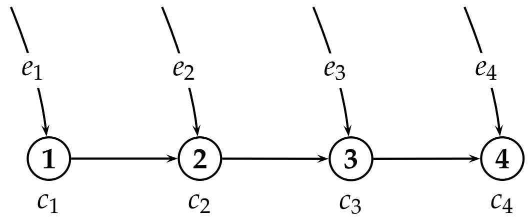

Figure 5.1: The river sharing problem for $n = 4$; nodes are agents and arrows indicate water flows.

however, to represent the river sharing problem as a sequence of reduced river sharing problems. These reduced river sharing problems are mathematically equivalent to bankruptcy problems. In this section we propose two axioms for a solution to the river sharing problem. They lead to the definition of reduced river sharing problems and they characterise the class of sequential sharing rules using this definition.

Only n's excess claim matters. For each river sharing problem $\omega = \langle N, e, c\rangle$, and each related problem $\omega' = \langle N, e', c'\rangle$ such that $e' = (e_1, \ldots, e_{n-1}, e'_n)$ and $c' = (c_1, \ldots, c_{n-1}, c'_n)$ with $e'_n = 0$ and $c'_n = c_n - e_n$, we have $F_i(\omega) = F_i(\omega')\ \forall i \in N$.

This property says that allocation of upstream contested water should not be affected by the part of the claim of agent n that can be satisfied with the endowment of agent n. In other words, only n's excess claim $c_n - e_n$ is effective (by assumption 5.1, $c_n - e_n > 0$). This is a mild requirement, because n is not confronted with any claims from downstream agents. In addition, there is no alternative use for e_n than to allocate it to n; endowment e_n is uncontested. Hence, it is very natural that e_n is used to partially satisfy c_n.

No advantageous downstream merging. For each river sharing problem $\omega = \langle N, e, c\rangle$, and each related problem $\omega' = \langle N', e', c'\rangle$ such that $N' = N \setminus \{n\}$ and $e' = (e_1, \ldots, e_{n-2}, e'_{n-1})$ and $c' = (c_1, \ldots, c_{n-2}, c'_{n-1})$, with $e'_{n-1} = e_{n-1} + e_n$ and $c'_{n-1} = c_{n-1} + c_n$, we have $F_i(\omega) = F_i(\omega')\ \forall i < n - 1$.

This property pertains to the possibility that agents $n - 1$ and n consolidate their claims and endowments and present themselves as a single claimant. The axiom prescribes that the allocation to upstream agents is not affected by such behaviour. Note that the axiom is similar in spirit to the *No Advantageous Merging or Splitting* axiom (see O'Neill, 1982; Thomson, 2003).

Together, *Only n's Excess Claim Matters* and recursive application of *No Advantageous Downstream Merging* prescribe that downstream river flow is first used to (partly) satisfy downstream claims. Only claims in excess of downstream river flow may affect upstream water allocation. Hence, to derive solutions we can use excess downstream claims, which we denote by c_{D_i}:

$$c_{D_i} \equiv \sum_{j \in D_i} (c_j - e_j). \tag{5.2}$$

Consequently, the corresponding downstream endowments are $e_{D_i} = 0$. *Only n's Excess Claim Matters* and *No Advantageous Downstream Merging* are a first step to approach the river sharing problem using bankruptcy rules by assuring that downstream agents cannot claim something that they already possess.

Using (5.2), the two axioms lead directly to the representation of a river sharing problem ω as a sequence $(\omega_1, \ldots, \omega_n)$ of reduced river sharing problems ω_i.

Definition 5.3 (Reduced river sharing problem)**.** A reduced river sharing problem is a triple $\omega_i = \langle N_i, E_i, C_i \rangle$, with two agents $N_i = \{i, D_i\}$, who have claims $C_i = \{c_i, c_{D_i}\}$, to the resource E_i.

Note that, in slight abuse of notation, we denote the second agent in the reduced river sharing problem by D_i. This set of agents is treated as a single claimant. In each reduced problem ω_i, available river flow E_i is distributed between i and D_i. By assumption 5.1, there is contested water throughout the river, as stated in the following lemma.

Lemma 5.1. *In each reduced river sharing problem the sum of claims exceeds available water: $E_i < c_i + c_{D_i}$ $\forall i \in N$.*

Proof. See Appendix.

Lemma 5.1 assures that a reduced river sharing problem is a river sharing problem according to definition 5.1, with two agents and no endowment downstream. Therefore, a sharing rule assigns to every reduced river sharing problem ω_i a water rights allocation vector $x = (x_i, x_{D_i})$, such that $x_i + x_{D_i} = E_i$.

A reduced river sharing problem is mathematically equivalent to a bankruptcy problem.[3] Hence, bankruptcy rules can be applied to any reduced river sharing problem. In order to solve a river sharing problem, a bankruptcy rule is applied to the sequence $(\omega_1, \ldots, \omega_n)$ of its reduced problems. Because of (5.1), however, the reduced problems and their solutions are dependent on each other. Because $E_1 = e_1$ by definition, ω_1 is the only reduced problem whose outcome is independent of the outcome of other reduced problems. Its solution—allocating x_1 to agent 1—determines E_2 which enables the formulation of and a solution to ω_2, etc. Hence, the sequence of reduced problems can be solved recursively in the linear order of agents along the river. This is summarised in the following proposition.

Proposition 5.1. *For each river sharing problem $\omega = \langle N, e, c \rangle$ and its corresponding sequence of reduced river sharing problems $(\omega_1, \ldots, \omega_n)$, we have $F_i(\omega) = F_i(\omega_i)\ \forall i \in N$.*

The water rights allocated to each agent are equal for the solution of the river sharing problem and for the recursive solution of its corresponding sequence of reduced problems. Given the vectors of claims and endowments, the allocation to agent i is therefore independent from the number of agents in D_i, the distribution of their claims $(c_{i+1}, \ldots, c_n)$ and the distribution of their endowments $(e_{i+1}, \ldots, e_n)$; only the aggregate claims $\sum_{j \in D_i} c_j$ and endowments $\sum_{j \in D_i} e_j$ matter.

Only n's Excess Claim Matters and *No Advantageous Downstream Merging* characterise a class of rules that we call sequential sharing rules. Sequential sharing rules are constructed by the recursive application of a bankruptcy rule to the sequence of reduced river sharing problems. In the next sections we focus on four classical bankruptcy rules and assess the properties of their corresponding sequential sharing rules.

5.4 Application

In this section we apply four sequential sharing rules, based on four classical bankruptcy rules, to an illustrative river sharing problem. The four classical rules are the proportional rule, constrained equal awards, constrained equal losses, and the Talmud rule (Herrero and Villar, 2001). In our notation for two-agent problems, the definitions of the four rules are as follows.

[3] In the concluding section we will discuss a difference in interpretation.

Proportional rule (PRO). For all $\omega_i = \langle N_i, E_i, C_i \rangle \in \Omega$, there exists $\lambda > 0$, such that $x_i^{\text{PRO}} = \lambda c_i$ and $x_{D_i}^{\text{PRO}} = \lambda c_{D_i}$.

PRO assigns each agent a share of the resource in proportion to the agents' claims.

Constrained equal awards (CEA). For all $\omega_i = \langle N_i, E_i, C_i \rangle \in \Omega$, there exists $\lambda > 0$, such that $x_i^{\text{CEA}} = \min\{c_i, \lambda\}$ and $x_{D_i}^{\text{CEA}} = \min\{c_{D_i}, \lambda\}$.

CEA assigns each agent an equal share of the resource, subject to no agent receiving more than his claim.

Constrained equal losses (CEL). For all $\omega_i = \langle N_i, E_i, C_i \rangle \in \Omega$, there exists $\lambda > 0$, such that $x_i^{\text{CEL}} = \max\{0, c_i - \lambda\}$ and $x_{D_i}^{\text{CEL}} = \max\{0, c_{D_i} - \lambda\}$.

CEL assigns each agent a share of the resource such that their losses compared to their claim are equal, subject to no agent receiving a negative share.

Talmud rule (TAL). For all $\omega_i = \langle N_i, E_i, C_i \rangle \in \Omega$, there exists $\lambda > 0$, such that

$$x_i^{\text{TAL}} = \begin{cases} \min\left\{\frac{1}{2}c_i, \lambda\right\} & \text{if } E_i \leq \frac{1}{2}\left(c_i + c_{D_i}\right), \\ c_i - \min\left\{\frac{1}{2}c_i, \lambda\right\} & \text{otherwise,} \end{cases}$$

$$x_{D_i}^{\text{TAL}} = \begin{cases} \min\left\{\frac{1}{2}c_{D_i}, \lambda\right\} & \text{if } E_i \leq \frac{1}{2}\left(c_i + c_{D_i}\right), \\ c_{D_i} - \min\left\{\frac{1}{2}c_{D_i}, \lambda\right\} & \text{otherwise.} \end{cases}$$

TAL assigns each agent his uncontested share of the resource and divides the contested part equally.

As discussed in section 5.1, many two-agent water rights disputes are solved using variants of bankruptcy rules. The practice of sharing water proportional to some objective criterion corresponds to the application of PRO in case that the agents' claims are based on the same principle for water sharing. CEA corresponds to equal sharing when claims are sufficiently high, whereas CEL corresponds to equal sharing when claims are equal. The principles of ATS and ATI are approximated in situations where the upstream agent has either a very high or very low claim compared to the downstream agent, for any of these four classical rules.

To illustrate how a solution to the river sharing problem is calculated, table 5.1 shows the steps to the solution to a river sharing problem for $n = 4$ and using

PRO. In this example, the values chosen for e and c illustrate a river sharing problem in which the major share of river flow originates on the territory of agent 1, while the largest claim is made by agent 4.

Table 5.1: Example of the calculation of x using PRO.

i	e_i	c_i	$\Rightarrow$	E_i	c_{D_i}	$\Rightarrow$	x_i^{PRO}	$x_{D_i}^{PRO}$	$\Rightarrow$	p_i^{PRO}
1	80	50		80	90		29	51		0.57
2	10	10		61	90		6	55		0.61
3	10	20		65	80		13	52		0.65
4	10	90		62	-		62	-		0.69

In table 5.1, the river sharing problem is described by the first three columns that represent the set of agents N and the vectors e and c. The first reduced river sharing problem is $\omega_1 = \langle N_1, E_1, C_1 \rangle$, with two agents $N_1 = \{1, D_1\}$, who have claims $C_1 = \{c_1, c_{D_1}\}$, to the resource E_1. $E_1 = 80$ is calculated using (5.1) and $c_{D_1} = 90$ is calculated using (5.2). The solution using PRO yields $x = (29, 51)$. This solution (i.e. $x_{D_1} = 51$) is used as input for the second reduced river sharing problem ω_2, etc. The last column of table 5.1 provides values for $p_i \equiv x_i/c_i$: the proportion of agent i's claim that is allocated to him. This column shows that the sequential sharing rule based on PRO generates a solution with different values for p_i. In a bankruptcy problem, PRO yields a constant value for p_i. This difference illustrates that taking account of the linear order of agents and their endowments indeed affects the solution to the river sharing problem.

Table 5.2 continues on the example given in table 5.1 by comparing solutions for three different combinations of claims and endowments of river flow, for the four rules described above. It illustrates how changes in claims or endowments affect the different solutions. In case 2 of table 5.2, c_2 increases from 10 to 30 compared with case 1. This increase in claims of agent 2 causes an increase in x_2, as illustrated by PRO ($6 \rightarrow 16$), CEA ($10 \rightarrow 25$), CEL ($0 \rightarrow 10$), and TAL ($5 \rightarrow 15$). This *Claims Monotonicity* property is further examined in section 5.5. In case 3 of table 5.2, e_2 increases from 10 to 30 compared with case 1. This increase in endowment of agent 2 causes an increase in x for all agents, as illustrated by PRO ($(29, 6, 13, 62) \rightarrow (33, 8, 16, 73)$), and can be verified for the other three rules too. This *Resource Monotonicity* property is also further examined in section 5.5.

Table 5.2: Comparison of solutions for three different combinations of claims and endowments of river flow.

i	e_i	c_i	$\Rightarrow$	x_i^{PRO}	p_i^{PRO}	x_i^{CEA}	p_i^{CEA}	x_i^{CEL}	p_i^{CEL}	x_i^{TAL}	p_i^{TAL}
case 1											
1	80	50		29	0.57	40	0.80	20	0.40	25	0.50
2	10	10		6	0.61	10	1.00	0	0.00	5	0.50
3	10	20		13	0.65	20	1.00	10	0.50	10	0.50
4	10	90		62	0.69	40	0.44	80	0.89	70	0.78
case 2											
1	80	50		25	0.50	40	0.80	10	0.20	25	0.50
2	10	$\boxed{30}$		16	0.54	25	0.83	10	0.33	15	0.50
3	10	20		12	0.59	18	0.88	10	0.50	10	0.50
4	10	90		57	0.63	28	0.31	80	0.89	60	0.67
case 3											
1	80	50		33	0.67	40	0.80	30	0.60	30	0.60
2	$\boxed{30}$	10		8	0.77	10	1.00	0	0.00	5	0.50
3	10	20		16	0.79	20	1.00	15	0.75	13	0.63
4	10	90		73	0.81	60	0.67	85	0.94	83	0.92

5.5 Properties

In this section we assess the properties of sequential sharing rules, focusing on the four rules introduced in the previous section. We limit ourselves to two monotonicity properties and two of the characterising properties of the class of priority rules used by Moulin (2000). When a bankruptcy rule satisfies a property, this does not necessarily imply that its corresponding sequential sharing rule also satisfies this property. For some properties, however, the implication does hold. Some of these are appealing properties for the setting of a river sharing problem, including the following two monotonicity properties.

Claims monotonicity. For each river sharing problem $\omega = \langle N, e, c\rangle$, each $i \in N$, and each related problem $\omega' = \langle N, e, (c_i', c_{-i})\rangle$ such that $c_i' > c_i$, we have $F_i(\omega') \geq F_i(\omega)$.

This property says that that any agent i should not be worse off with a larger claim.

Resource monotonicity. For each river sharing problem $\omega = \langle N, e, c\rangle$, each $i \in N$, and each related problem $\omega' = \langle N, (e'_i, e_{-i}), c\rangle$ such that $e'_i \geq e_i$, we have $F(\omega') \geq F(\omega)$.

This property says that no agent should be worse off when some agent has a larger endowment.[4] No agent looses loses regardless of his position along the river.

Moulin (2000) characterises a class of priority rules for bankruptcy problems with a priority order, which is related to our approach (see section 5.6.3). The four characterising properties that he employs are *Upper Composition*, *Lower Composition*, *Scale Invariance*, and *Consistency*. The first two of these are difficult to assess in the context of a river sharing problem. *Scale Invariance* and *Consistency* can be assessed and we will see that *Consistency* can be satisfied, while *Scale Invariance* is satisfied by sequential sharing rules that are based on any bankruptcy rule that satisfies *Scale Invariance* itself.

Scale invariance. For each river sharing problem $\omega = \langle N, e, c\rangle$, each $i \in N$, all $\lambda \geq 0$, and each related problem $\omega' = \langle N, \lambda e, \lambda c\rangle$, we have $F(\omega') = \lambda F(\omega)$.

This property says that a rescaling of endowments and claims (or a change of the unit in which they are measured) does not affect the solution to any agent.

The definition of *Consistency* requires some explanation. The property says that agents receive the same allocation whether or not a subset of N has left with their allocation. Following Moulin (2000), let this subset be a single agent $j \in N$. Denote by ω the river sharing problem including j and denote by ω' the river sharing problem where j has left. Agent j leaves by eliminating the j'th element from both the set of players and the claims vector. Because agent j leaves with his allocation $x_j = F_j(\omega)$, this amount has to be deducted from the endowments vector. In a standard bankruptcy problem, we have $E' = E - x_j$. In a river sharing problem, the problem is to find a suitable endowments vector e'. The vector difference $e - e'$ can then be regarded as the contribution of each agent's endowment to the allocation of water rights to agent j. Formally:

Consistency. For each river sharing problem $\omega = \langle N, e, c\rangle$, each $i, j \in N$, $i \neq j$, and each related problem $\omega' = \langle N', e', c'\rangle$ such that $N' = N \setminus \{j\}$, $c' = c \setminus \{c_j\}$, and

[4] This property implies that *Drop Out Monotonicity* (no agent is worse off whenever one of the agents decides to drop out), introduced by Fernández et al. (2005), is satisfied.

$e' = \left(e'_1, \ldots, e'_{j-1}, e'_{j+1}, \ldots, e'_n\right)$, with e' feasible and efficient such that $\sum_{i \leq k} \left(e'_i - e_i\right) \leq 0 \; \forall k < j$ and $\sum_{k \in N'} \left(e'_k - e_k\right) = e_j - x_j$, we have $F_i(\omega) = F_i(\omega')$

The following proposition covers the four axioms discussed in this section.

Proposition 5.2. *The following relations between the properties of bankruptcy rules and their corresponding sequential sharing rules hold:*

(a) *If a bankruptcy rule satisfies Claims Monotonicity, its corresponding sequential sharing rule satisfies Claims Monotonicity.*

(b) *If a bankruptcy rule satisfies Resource Monotonicity, its corresponding sequential sharing rule satisfies Resource Monotonicity.*

(c) *If a bankruptcy rule satisfies Scale Invariance, its corresponding sequential sharing rule satisfies Scale Invariance.*

(d) *If a bankruptcy rule satisfies Claims Monotonicity and Resource Monotonicity, there exists an endowment vector e' such that its corresponding sequential sharing rule satisfies Consistency.*

Proof. See Appendix.

Because PRO, CEA, CEL, and TAL satisfy *Claims Monotonicity*, *Resource Monotonicity*, and *Scale Invariance* (Moulin, 2002; Thomson, 2003), this proposition immediately leads to the following corollary.

Corollary 5.1. *Sequential sharing rules based on PRO, CEA, CEL, and TAL satisfy Claims Monotonicity, Resource Monotonicity, Scale Invariance, and Consistency.*

Note that proposition 5.2 implies that to satisfy *Consistency*, a sequential sharing rule need not be based on a bankruptcy rule that satisfies *Consistency*. The construction of sequential sharing rules assures that every bankruptcy rule that satisfies *Claims Monotonicity* and *Resource Monotonicity*, has a corresponding sequential sharing rule that satisfies *Consistency* for some feasible endowment vector e'.

A final property discussed in this section relates to an agent's position in the order of agents and how this affects his allocation. No general statement can be made on whether it is favourable for an agent to be located upstream or downstream in the river. An agent's allocation of water rights can be affected positively or negatively by the combination of the vectors of claims and endowments as well as the specific sequential sharing rule used, as illustrated by table 5.2. For a sequential sharing rule based on PRO though, we can infer that downstream agents are always better off in terms of the portion of their claim that they receive.

As illustrated by table 5.2, the values of p_i^{PRO} increase with i (for case 1, $p^{PRO} = (0.73, 0.76, 0.79, 0.82)$). This is not a coincidence, as proposition 5.3 shows:

Proposition 5.3. *The sequential sharing rule based on PRO satisfies the following property. For each* $i, j \in N$, $p_i^{PRO} \leq p_j^{PRO}$ *if and only if* $i < j$.

Proof. See Appendix.

This proposition says that the sequential sharing rule based on PRO always favours downstream agents. The explanation is that all water is allocated proportional to claims while endowments need not be shared with upstream agents. E_1 is allocated proportional to claims to agents 1 and D_1. E_2 is allocated proportional to claims to agents 2 and D_2, etc. If $e_2 = 0$, then $E_2 = x_{D_1} = E_1 - x_1$ and by proportionality to claims we have $p_1^{PRO} = p_2^{PRO}$. If $e_2 > 0$, then $E_2 = x_{D_1} + e_2$ and we have $p_1^{PRO} < p_2^{PRO}$; agent 2 can never be worse off than agent 1, because he also receives, proportional to his claims, part of the additional resource e_2. A special case occurs if $e_j = 0 \; \forall j > i$, then p_j^{PRO} is constant for all $j \in D_i$ (see proposition 5.4 in section 5.6).

5.6 Comparison to four alternative solutions

In this section, we compare our solution to four alternative solutions that can be applied to river sharing problems. The first of these is only relevant for the special case where all river water is endowed to agent 1, while the other agents have no endowments. Bankruptcy rules can be directly applied in this case, when ignoring the order of the agents. The second solution is a generalisation of the first one. It applies bankruptcy rules directly to the river sharing problem, while treating endowments and the linear order as a feasibility constraint. The third solution is similar in spirit to the class of priority rules constructed by Moulin (2000). The fourth solution is the one proposed by Ambec and Sprumont (2002).

Although each of these four solutions possesses some attractive features, they also have disadvantages compared to the approach presented in this chapter.

The first solution is only valid for a special class of river sharing problems. The second solution does not allow for differential treatment of agents that have equal claims but different endowments. The third solution strongly favours upstream agents, while the fourth solution strongly favours downstream agents.

5.6.1 Direct application of bankruptcy rules

If all water originates at the head of the river: $e_i = 0\ \forall i > 1$, and the ordering of the agents is not considered, then bankruptcy rules can be directly applied to this class of river sharing problems.

At first sight, this approach seems unrelated to the sequential sharing rules. There is a class of rules, however, for which this approach replicates the sequential sharing rules. This class of rules includes all bankruptcy rules that satisfy *No Advantageous Merging or Splitting* (O'Neill, 1982; Thomson, 2003). PRO is one of the bankruptcy rules in this class. Hence, the solution given by application of the sequential sharing rule based on PRO corresponds to the solution given by PRO itself applied to the river sharing problem. This is stated in the following proposition.[5]

Proposition 5.4. *The sequential sharing rule based on PRO satisfies the following property. If $e_i = 0\ \forall i > 1$, then $p_i^{PRO} = \frac{e_1}{\sum_{j \in N} c_j}\ \forall i \in N$.*

Proof. See Appendix.

This proposition says that for this class of river sharing problems, the characterising properties of PRO also hold for its corresponding sequential sharing rule. Consequently, each agent receives the same proportion of his claim. Clearly then, differences between the solutions induced by PRO and by its corresponding sequential sharing rule are completely driven by the distribution of the claims over the agents. These differences are not a result of the linear order of the agents.

This result implies that the proportional solution to a bankruptcy problem equals the proportional solution to a sequence of reduced bankruptcy problems (i.e. bankruptcy problems in which the available resource is distributed between agent i and the set of other agents D_i). Hence, this class of river sharing problems is a generalisation of the bankruptcy problem. Note, however, that from the river

[5] A proposition and proof for the full class of rules that satisfy *No Advantageous Merging or Splitting* is omitted.

sharing perspective this class of problems reflects a very special case, because of its specific assumption that all water originates at the head of the river (although some rivers come close to resembling this extreme structure).

5.6.2 Constrained direct application of bankruptcy rules

Bankruptcy rules can be applied to river sharing problems in general, if the endowments and linear order of the agents are considered as feasibility constraints. For example, a sharing rule based on CEA implements CEA, constrained by feasibility. Two agents with equal claims therefore receive the same water rights (if feasible) no matter their location in the basin. Because the endowments and order are treated as a feasibility constraint only, this approach preserves *Equal Treatment of Equals* when possible, and ignoring the differences in location of the agents.

Constrained direct application of bankruptcy rules is an attractive solution in the sense that it treats the river sharing problem as a bankruptcy problem to the largest extent possible. This approach is used by İlkiliç and Kayı (2009), who model allocation rules in a network structure, (see also Bergantiños and Sanchez, 2002).

In our solution, however, the *Equal Treatment of Equals* property is not necessarily satisfied. Two agents with equal claims and endowments may end up with different allocations, even if an equal allocation would be feasible. This difference is driven by the agents' position in the linear order of agents and depends on the sequential sharing rule that is applied. Agents' location in the order of agents and their endowment both matter for the solution, also when feasibility is not a binding constraint. Our approach allows these distinctive features of the river sharing problem to determine the solution. The position in the linear order does not just constrain the set of possible solutions, but assigns significance to an agent's endowment with a particular amount of water.

5.6.3 Priority rule in the spirit of Moulin (2000)

As discussed in section 5.5, the class of priority rules constructed by Moulin (2000), is related to our approach. In fact, the bankruptcy problem studied in Moulin (2000), including an ordered set of agents, is a special case of the river sharing problem. The ordering of agents is according to a complete, transitive, and antisymmetric binary relation, which is equivalent to the linear order in our approach. In our notation, the priority rules satisfy:

$$\forall i, j \in N \text{ with } i < j, \text{ if } x_j > 0, \text{ then } x_i = c_i.$$

In words, priority rules allocate water rights to upstream agents until their claim is met in full, before the next agent is served.

Again, as in the previous approach, we have to treat the endowments and linear order of the agents as a feasibility constraint. Hence, when $c_i > E_i$, agent $j = i + 1$ is allocated a positive amount of water rights only when e_j is positive. This approach is an extreme rule in the sense that it strongly favours upstream agents over downstream agents.

5.6.4 Sharing a river based on Ambec and Sprumont (2002)

Recently, Ambec and Sprumont (2002) proposed an axiomatic solution that is based on ATS and ATI, as discussed in section 5.1. These two principles are used as a lower bound and aspiration upper bound to the welfare of a coalition of agents, with welfare originating from water and side payments. Ambec and Sprumont (2002) show that there is a unique welfare distribution that provides a compromise between these two principles: water is allocated such that each agent's welfare equals his marginal contribution to a coalition composed of all upstream agents (see also Herings et al., 2007).

Comparison of the class of sequential sharing rules and the solution proposed by Ambec and Sprumont (2002) is not straightforward because their solution is in terms of welfare while we follow the bankruptcy literature by having a solution in terms of the resource to be distributed. Comparison is only possible if we assume that benefits are linear in water use.[6] In that case, the solution proposed by Ambec and Sprumont (2002) falls in the class of sequential sharing rules. In fact, it is an extreme case of this class of rules in which $x_i = e_i \; \forall i \in N$. The solution allocates to each agent the rights to his own endowment. Obviously, this solution is independent of the claims vector because Ambec and Sprumont (2002) do not consider claims in their model.

This approach may be an attractive compromise of ATS and ATI but we question its applicability for two reasons. First, Ambec and Sprumont (2002)

[6] Ambec and Sprumont (2002) assume strictly increasing and strictly concave benefits of water use.

find a solution to the river sharing problem using a combination of lower and upper bounds to welfare. Uniqueness of this solution follows by construction because of the implicit assumption that lower and upper bounds coincide for the most upstream agent. In other words, it is assumed that the most upstream agent does not aspire a higher welfare level than what he can secure himself. This assumption is driving the solution. Second, the solution by Ambec and Sprumont (2002) assigns all gains from cooperation to downstream agents which is not very convincing, as noted by Van den Brink et al. (2007), Houba (2008), and Khmelnitskaya (2009).

5.7 Discussion and conclusion

A remaining issue to discuss is whether a reduced river sharing problem, although mathematically equivalent to a bankruptcy problem, can indeed be interpreted as such. The answer to this question depends on the interpretation of E_i, the resource that is to be distributed between i and D_i. In a bankruptcy problem, the resource is separated from the agents. In a reduced river sharing problem, E_i is the river flow available to agent i. If we do not consider claims, this endowment could be interpreted as agent i's "property rights" (as in the Walrasian framework and as in the ATS principle, see section 5.1). The redistribution of water is then equivalent to the redistribution of the property rights to water.

In our interpretation, overlapping claims imply that endowments do not constitute property rights. Thus a sharing rule is needed to introduce such rights. E_i is not interpreted as a property right, but as a resource whose level may influence the solution to a river sharing problem, depending on the sharing rule used. In this case, E_i is separated from the agents and, hence, a reduced river sharing problem is fully equivalent to a bankruptcy problem. Although this interpretation gives additional support to the use of sequential sharing rules, we do not claim this interpretation to be more convincing than the alternative. We leave it to the reader to judge the merits of both interpretations.

In this chapter we analyse a river sharing problem with linearly ordered agents who have resource endowments and claims to this resource. We construct a class of sequential sharing rules, by transforming the river sharing problem to a sequence of reduced river sharing problems. These reduced problems are mathematically equivalent to bankruptcy problems and can therefore be solved using bankruptcy rules. This approach for solving river sharing problems contrasts with alternative approaches by allowing agents' position in the order of agents and their endowment to play an important role in the solution. A solution to a river sharing problem is determined by the combination of endowments and claims and the selected bankruptcy rule.[7]

The results of this chapter can be readily adopted for application in negotiations on national or international river sharing problems. The approach to be followed is to jointly agree on the sharing rule to allocate water rights to the most upstream agent, who then leaves the negotiation table with his allocation. The same sharing rule is then used sequentially to allocate water rights to the other agents.

A remaining question is whether this negotiation procedure has any credible non-cooperative foundations. The n-player "sequential share bargaining" procedure, proposed by Herings and Predtetchinski (2007) appears to be a promising approach. Sequential share bargaining is an n-player extension of the Rubinstein-Ståhl bargaining model, in which the players' shares are determined sequentially according to a fixed order, and require unanimous agreement. Its resemblance to sequential sharing rules is apparent. A complete analysis of this implementation, however, is left for future work.

Appendix: Proofs

Proof of lemma 5.1

Proof. The proof is by contradiction.

Suppose that the lemma does not hold, then $\exists i \in N : E_i \geq c_i + c_{D_i}$, which can be written as (i) $E_i + \sum_{j \in D_i} e_j \geq c_i + \sum_{j \in D_i} c_j$. By construction we have (ii) $E_n = E_i + \sum_{j \in D_i} e_j - x_i - \sum_{j \in D_i \setminus \{n\}} x_j$ By substitution and rearrangement of (i) and (ii) we obtain:

$$E_n - c_n \geq c_i - x_i + \sum_{j \in D_i \setminus \{n\}} (c_j - x_j).$$

[7]Two related approaches are the following. Goetz et al. (2008) apply sequential sharing rules to irrigation water allocation, based on (Barberà et al., 1997). The domain of their paper is different, however, as they focus on strategy-proof rules for situations with single-peaked preferences and, unlike Klaus et al. (1997), no initial endowments. Coram (2006) implements a sequential bidding game to allocate water. This approach also assigns an important role to agents' endowments and their location in the river, but its scope is clearly different from ours.

Because definition 5.2 requires that $x \leq c$, we know that the RHS of this weak inequality is non-negative. This implies that $E_n \geq c_n$, which violates assumption 5.1. ◻

Proof of proposition 5.2

Proof. Because a reduced river sharing problem is mathematically equivalent to a bankruptcy problem, in any reduced river sharing problem, *Claims Monotonicity*, *Resource Monotonicity*, and *Scale Invariance* are satisfied (Moulin, 2002; Thomson, 2003). The remainder of the proof is for each axiom separately.

(a) Claims Monotonicity Consider a river sharing problem $\omega = \langle N, e, c \rangle$, and a related problem $\omega' = \langle N, e, (c'_i, c_{-i}) \rangle$ such that $c'_i > c_i$. In any reduced problem ω'_j, $j < i$, *Claims Monotonicity* implies that $x'_{D_j} \geq x_{D_j}$ and therefore $x'_j \leq x_j$. By (5.1), this gives $E'_i \geq E_i$. Because *Claims Monotonicity* is satisfied in reduced river sharing problem ω_i, and because $E'_i \geq E_i$, it follows that $c'_i > c_i \Leftrightarrow F_i(\omega') \geq F_i(\omega)$.

(b) Resource Monotonicity Consider a river sharing problem $\omega = \langle N, e, c \rangle$, and a related problem $\omega' = \langle N, (e'_i, e_{-i}), c \rangle$ such that $e'_i \geq e_i$. In reduced problem ω'_1, *Resource Monotonicity* implies that $x'_1 \geq x_1$ (and $x'_{D_1} \geq x_{D_1}$). By (5.1), this gives $E'_2 \geq E_2$. This argument can be repeated to show that for ω'_2, *Resource Monotonicity* implies that $x'_2 \geq x_2$ (and $x'_{D_2} \geq x_{D_2}$), etc. It follows that $e'_i \geq e_i \Leftrightarrow F(\omega') \geq F(\omega)$.

(c) Scale Invariance Consider a river sharing problem $\omega = \langle N, e, c \rangle$, and a related problem $\omega' = \langle N, \lambda e, \lambda c \rangle$, with $\lambda > 0$. In reduced problem ω'_1, *Scale Invariance* implies that $x'_1 = \lambda x_1$ and $x'_{D_1} = \lambda x_{D_1}$. By (5.1), this gives $E'_2 = \lambda E_2$. This argument can be repeated to show that for ω'_2, *Scale Invariance* implies that $x'_2 = \lambda x_2$ (and $x'_{D_2} = \lambda x_{D_2}$), etc. It follows that $F(\omega') = \lambda F(\omega)$.

(d) Consistency Denote by $e''_i = e'_i - e_i \ \forall i \in N'$ the difference in endowments to agent i between e and e'. Feasibility requires $\sum_{i \leq k} e''_i \leq 0 \ \forall k < j$. Efficiency requires $\sum_{k \in N'} e''_k = e_j - x_j$.

To prove the proposition, we show how to construct the vector difference e'', first for the case where $j = 1$ and then for the case where $j \geq 2$. Note that excess downstream claims may be lower in ω' compared with ω. Using (5.2), we have $c'_{D_i} = c_{D_i} - c_j + e_j - \sum_{k=i+1}^{j+1} e''_k \ \forall i \leq j-1$, so that $c'_{D_i} \leq c_{D_i} \ \forall i \leq j-1$.

Suppose $j = 1$. By construction, $x_1 \leq e_1$, so we can set $e''_2 = e_1 - x_1$. This gives $E'_2 = e_2 + e_1 - x_1 = E_2$, while satisfying efficiency and feasibility, and we are done.

Suppose $j \geq 2$. Consider reduced problem ω'_1. We have $E'_1 = e_1 + e''_1 \leq E_1$. Because $c'_{D_1} \leq c_{D_1}$, by *Claims Monotonicity* and *Resource Monotonicity* there exists $e''_1 \leq 0$ such that $x'_1 = x_1$. Using this value of e''_1, we have $x'_{D_1} = x_{D_1} + e''_1$.

Now, consider reduced problem ω'_2. We have $E'_2 = e_2 + e''_2 + x'_{D_1} = e_2 + e''_2 + x_{D_1} + e''_1$, and because of feasibility $e''_2 \leq -e''_1$, such that $E'_2 \leq E_2$. Because $c'_{D_2} \leq c_{D_2}$, by *Claims Monotonicity* and *Resource Monotonicity* there exists $e''_2 \leq -e''_1$ such that $x'_2 = x_2$. Using this value of e''_2, we have $x'_{D_2} = x_{D_2} + e''_2$.

The same argument can be repeated up to and including reduced problem ω'_{j-1}.

Now, consider reduced problem ω'_{j+1}. We have:

$$\begin{aligned} E'_{j+1} &= e_{j+1} + x_{D_{j-1}} + e''_{j+1} \\ &= e_{j+1} + e''_{j+1} + \sum_{k \leq j-1} \left(e_k - x_k + e''_k \right). \end{aligned}$$

We can set $e''_{j+1} = e_j - x_j - \sum_{k \leq j-1} \left(e''_k \right)$. This gives:

$$E'_{j+1} = e_{j+1} + e_j - x_j + \sum_{k \leq j-1} (e_k - x_k) = E_{j+1}.$$

while satisfying efficiency and feasibility, and we are done. □

Proof of proposition 5.3

Proof. We first show that the proposition holds for $j = i + 1$.[8] Following from definition 5.2 and the definition of PRO, $x_i = \lambda c_i$, with $\lambda = p_i = \frac{E_i}{c_i + c_{D_i}}$. For $j = i + 1$, we should verify whether:

$$p_i = \frac{E_i}{c_i + c_{D_i}} \leq \frac{E_j}{c_j + c_{D_j}} = p_j.$$

We do so by by contradiction. Suppose that $p_i > p_j$, then:

$$\frac{E_i}{E_j} > \frac{c_i + c_{D_i}}{c_j + c_{D_j}}.$$

[8]For ease of notation, the superscript ^{PRO} is omitted.

Substituting $E_j = E_i + e_j - x_i$, and $x_i = c_i E_i/(c_i + c_{D_i})$, and re-ordering terms gives:

$$c_j + c_{D_j} > \frac{(c_i + c_{D_i})(E_i + e_j)}{E_i} - c_i.$$

Substituting $c_j + c_{D_j} = c_{D_i} + e_j$, re-ordering, and cancelling terms gives:

$$E_i > c_i + c_{D_i},$$

which contradicts lemma 5.1. By transitivity of the order of the agents, the proposition also holds for $j = i + k \ \forall k \geq 1$. □

Proof of proposition 5.4

Proof. Following from definition 5.2 and the definition of PRO, $x_i = \lambda c_i$, with $\lambda = p_i = \frac{E_i}{c_i + c_{D_i}}$.[9] Hence, we have (i) $x_{D_i} = \frac{E_i}{c_i + c_{D_i}} c_{D_i}$.

Because $e_i = 0 \ \forall i > 1$, by (5.1) we have (ii) $E_{i+1} = x_{D_i}$ and by (5.2), we have (iii) $c_{D_i} = c_{i+1} + c_{D_{i+1}}$.

Using (ii) and (iii), we have (iv) $p_{i+1} = \frac{E_{i+1}}{c_{i+1} + c_{D_{i+1}}} = \frac{x_{D_i}}{c_{D_i}}$. Combining (i) and (iv), we obtain $p_{i+1} = \frac{E_i}{c_i + c_{D_i}} = p_i$. □

[9]For ease of notation, the superscript ^{PRO} is omitted.

Chapter 6

Conclusions

The overall objective of this thesis is to analyse water allocation in transboundary river basins, with a focus on the strategic interaction between riparian countries in their decisions on water use. In chapters 2–5, I have analysed and discussed various aspects of this strategic interaction, using game-theoretic models. In this final chapter, I will first summarise the results and draw some overall conclusions in section 6.1. Then, I will discuss the results of this thesis in the context of practical water management issues in section 6.2. Finally, in section 6.3, I describe the relevance of this thesis for issues other than transboundary water allocation.

6.1 Summary of results

In short, the results of this thesis are the following.

In chapter 2, I assess the stability of various water allocation agreements under climate change impacts on river flow. The agreements differ in terms of the sharing rule that they employ and in terms of the side payments (constant or flexible). The results show that a decrease in mean river flow decreases the stability of an agreement, while an increased variance can have a positive or a negative effect on stability. The type of side payment—in the context of this chapter—does not really affect stability. What matters is the distribution of risk related to low river flows over the countries. This risk originates mainly from the sharing rule, which distributes water—and hence the shortage of water when there is less than expected—over the countries. Due to the sequential structure of water deliveries and side payments, agreements where a fixed amount of water is allocated to the upstream country, offer the largest stability. The only agreement that offers stability for any level of river flow has such a sharing rule, and has constant side payments, based on expected levels of river flow (instead of actual levels).

Chapter 2 offers the first thorough analysis of the stability of water allocation agreements in transboundary river basins. It extends the research of Bennett and Howe (1998) and Bennett et al. (2000), who studied efficiency and stability in a national context, and it enhances the literature on flexibility of water allocation agreements, initiated by Kilgour and Dinar (1995, 2001), by studying the stability of different agreement designs. In addition, chapter 2 provides an economic rationale for agreement noncompliance, as observed by for instance Barrett (1994a), Beach et al. (2000), Bernauer (2002), and Gastélum et al. (2009), which may induce water conflicts (Dinar and Dinar, 2003; Dombrowsky, 2007; Wolf, 2007). The results of this chapter are admittedly subject to the credibility of the punishment strategy employed. When punishments are not considered credible, none of the analysed agreements can offer stability for any level of river flow. This result begs the question whether any water allocation agreement can be fully stable. This topic is covered in chapter 3.

In chapter 3, I analyse self-enforcing water allocation agreements. Self-enforcement implies that the agreement is sustained in subgame perfect equilibrium and is renegotiation-proof. I model the agreement as the outcome of a bargaining game, which is followed by a repeated extensive-form game in which countries decide whether to comply with the agreement. The results show that, for sufficiently low discount rates, every efficient agreement can be sustained in subgame perfect equilibrium. Not all of these agreements, however, are renegotiation-proof. Depending on parameter combinations, the set of possible agreements may shrink to approach a unique self-enforcing agreement, which assigns all gains from cooperation to downstream countries. This solution corresponds (and so implements) the "downstream incremental distribution" (Ambec and Sprumont, 2002).

Chapter 3 offers a general framework for analysing the stability of agreements in a repeated extensive-form game. Specifically, the methodology employs the literature on folk theorems in repeated games (e.g. Yoon, 2001; Wen, 2002) to assess self-enforcement in the sequential and stochastic setting of water allocation agreements. In addition, the chapter adds to the literature on renegotiation-proof equilibria (Bergin and MacLeod, 1993; Barrett, 2003) by analysing the existence of renegotiation-proof agreements in extensive-form games, an unexplored topic as of yet. Chapter 3 shows that self-enforcing agreements exist and how they distribute the gains from cooperation. Stability, therefore, can be attained by careful design of the water allocation agreement. This result, if implemented in practice, could potentially eliminate noncompliance with water allocation agreements. This chapter is therefore a contribution to the challenge raised by Carraro et al. (2007): "Formally addressing the stochasticity of the resource, as well as the political, social, and strategic feasibility of any allocation scheme, would significantly contribute to decreasing conflicts over water". So far, however, an implicit assumption has been that contracts (i.e. agreements) over water can be easily signed. This assumption ignores that property rights to water are often ambiguous, disputed, and a source of conflict. The presence of contested water rights potentially obstructs the signing of agreements. This topic is covered in chapter 4.

In chapter 4, I use a conflict model in which countries have overlapping claims to water such that water rights are contested. Countries may end up in a costly conflict equilibrium. Before that happens, however, they bargain over the allocation of river water in order to avoid conflict. During the bargaining process, countries may request third-party intervention to settle the conflict, which succeeds with a certain probability. The results show that exactly this probabilistic outside option may prevent the countries from reaching a bargaining agreement on the property rights to water. Hence, the prospect of third party intervention may obstruct the capacity of countries to settle their conflict themselves.

Chapter 4 provides two new contributions to the literature on the economics of conflict. First, it is the first application of an economic conflict model to the issue of water rights. Although conflicts on water have been studied extensively (cf. Gleick, 1993; Wolf, 2007), no supporting economic theory for the existence of conflicts had been proposed. This chapter does so. Second, it is the first study to introduce claims in a conflict model. Although claims to water, or to a resource in general, play an important role in many conflicts (Murphy, 1990; Cressey, 2008), they have not been modelled formally as of yet. The inclusion of claims in this chapter allows a better understanding of their particular role in a conflict. Chapter 4 identifies a possible cause for the existence of persisting conflicts over river water in some river basins.[1] One of the causes of conflict over river water is that countries perceive the current allocation as unfair. The literature on fair allocations of river water does not extend far beyond "equal sharing" and the conflicting principles of international water law as discussed in chapter 1. A formal treatment using axiomatic foundations would give new perspectives on the fair sharing of river water.

In chapter 5, I construct such a formal axiomatic model, in order to derive attractive sharing rules for river water. To do so, I adapt a well-established strand of the literature that studies bankruptcy problems and apply it to the river sharing problem. The results show that by doing so, it is possible to transform each bankruptcy rule to a corresponding sequential sharing rule for river water. Many attractive properties of these bankruptcy rules are preserved in this transformation. Uncovering the relation between a sharing rule and its properties can make the fairness aspects of water allocation more transparent to the countries involved.

Chapter 5 presents a novel axiomatic approach for water allocation, tailored to the specific linear setting of a river basin. This approach combines the river sharing literature with the literature on bankruptcy problems (Moulin, 2002; Thomson, 2003). It widens the applicability of bankruptcy rules by generalising bankruptcy problems to river sharing problems that contain information on the sequential structure of the agents and the resource to be shared. In addition, the chapter provides an alternative axiomatic approach to river sharing to the one presented by Ambec and Sprumont (2002). This axiomatic analysis does not model strategic behaviour directly, but approaches it from an alternative point of view, describing the outcomes of a strategic situation in terms of its properties. Thereby, it complements the strategic models of chapters 2–4.

Three conclusions can be drawn from this thesis as a whole. First, increasing water scarcity or stochasticity does not necessarily obstruct the signing of international agreements on water allocation. It may, however, make these agreements more prone to defection. Chapters 2 and 3 demonstrate that some agreements are more stable than others and that careful design of the agreement provides stability. These results hold for any level of water scarcity. Hence, in the face of climate change and water use developments outlined in chapter 1, international agreements on water allocation, when properly designed, are sufficiently capable

[1] Admittedly, other causes are possible, some of which are mentioned in chapter 4.

to cope with water scarcity and stochasticity.

Second, the status quo situation of claims and property rights matters for both the probability of conflict over river water, and the outcome of negotiations on water allocation. Chapter 4 demonstrates how the presence of claims to water and the absence of water rights may affect the distribution of water in a conflict equilibrium. Resource-rich countries and those with larger claims receive larger allocations of water in equilibrium. This distribution of claims and resources would naturally translate into a more advantageous bargaining position in a bargaining game over water as outlined in chapter 3. Hence, these factors matter and drive the outcome of a strategic process toward cooperation.

Third, there is not a unique "fair" allocation of transboundary river water. Chapter 5 proposes a class of sharing rules and described some alternative axiomatic approaches to water allocation, in addition to the principles for water sharing listed in chapter 1. This multitude of sharing rules signals the difficulties that any neutral third party faces in a decision on how much water to allocate to each country. Factors that may be included in a water allocation decision are a country's claim, its own endowment of water, and its geographical position in the river basin. The above-mentioned sharing rules do not agree on which factors to include and how they should affect the allocation.

To conclude this section, I address an issue that is present implicitly or explicitly throughout chapters 2–5. This issue is whether, all other things being equal, an upstream country is (or should be) allocated more or less water than a downstream country? The short answer is that this question is impossible to answer. The slightly longer answer is as follows. Consider the following three approaches, based on the methodology used in chapters 3–5. Using the strategic bargaining model of chapter 3, the downstream country will be weakly better off, as its punishment options in case of noncompliance weakly dominate those of the upstream country. Using the contest model of chapter 4 would result in equal sharing, because in this chapter, any geographical advantage is reflected by the countries' claims. Using the axiomatic model of chapter 5 could result in a multitude of solutions depending on the choice for a specific sequential sharing rule. The various strategic models described in this thesis do not agree on upstream-downstream allocation, and even provide very different outcomes. Clearly then, this thesis does not solve the transboundary water allocation problem. It does, however, provide insight into the strategic aspects that play an important role in this problem and its possible solutions.

6.2 Recommendations for water management

The results of this thesis bring about a number of recommendations and suggestions for water management at the international level. These recommendations expand on the set of recommendations described briefly at the end of chapter 3.

A first recommendation is to start cooperation based on a common perception of the status quo situation. This common perception includes a mutual acceptance of aspects like the presence of claims to water, perceived property rights, and official water use data. Consequently, the negotiation process on the specifications of a water allocation agreement or on a jointly supported principle for water sharing can begin. In this process, countries have common priors and complete information, which facilitates cooperation. Chapter 4 shows that in absence of common priors (in particular on the probability of third-party intervention), the bargaining process may break down, leading to persistent conflict. Two examples illustrate this recommendation. First, in the case of the Ganges, India and Bangladesh could not agree on the accuracy of each other's hydrologic data (Beach et al., 2000), obstructing cooperation for many years. Second, only four decades after the start of their negotiations, the water dispute between Jordan and Israel on the waters of the Jordan river was solved at an official level in their 1994 bilateral agreement.[2] One of the main reasons for the break-through in this ongoing dispute was a change in the basis of negotiations. Prior to this agreement, negotiations were based on perceived property rights which the countries could not agree upon. The allocation of water in the 1994 agreement was based on objectively defined irrigation needs, which made it acceptable to both parties (Wolf, 1995, 1999; Haddadin, 2000).

A related suggestion concerns third parties such as the United Nations and the World Bank. Chapters 1 and 4 discuss the conflicting principles for water allocation in international law (cf. Salman, 2007). This situation of conflicting principles translates into uncertainty on expectations regarding third parties' opinion on water allocation. Chapter 4 shows the inefficiencies that may result. Hence, the suggestion for these parties is to be completely transparent on the

[2]Note that this agreement was never ratified and water has remained a source of dispute between Israel and its neighbours.

principle for water allocation that they use in conflict mediation or intervention in water rights disputes.

A second recommendation is to allow for flexibility in transboundary water allocation agreements. From chapters 2 and 3, it is clear that flexibility mitigates the disrupting effects of stochastic river flow. This recommendation does not only pertain to hydrological stochasticity of river flow though. It also relates to changes in the institutional setting, for instance when river flow decreases as a result of water use increase by an upstream country that is not part of an agreement. This situation is presently occurring in several river basins, including the Nile, where downstream Egypt and Sudan have an agreement in place but upstream Ethiopia is expected to increase its water abstraction in the coming years (though Egypt may use its regional power to press Ethiopia not to do so). Another example is the Ganges basin where Nepal is not part of the Ganges Treaty. Nepal does, however, offer ample opportunities to augment river flow in the dry season using reservoir storage, which would significantly reduce damage caused by water scarcity and increase the benefits of cooperation (Bhaduri and Barbier, 2008a). The strict practice of bilateral negotiations by India, has obstructed such an agreement (and its benefits) to date (Crow and Singh, 2000).

Related suggestions were made in the concluding section of chapter 3, viz. the specifications of a water allocation agreement (e.g. specification of water allocation and side payments contingent on river flow, and specification of an appropriate punishment strategy).

A third and final recommendation is to dispose of the concept of fairness in the context of international water allocation, because it allows for conflicting outcomes. There does not exist a dominant principle for water sharing that will bring about a fair allocation. Moreover, although it may be easy to reach agreement on general principles of fair water sharing, it is harder to implement these principles in a specific case (cf. Zeitoun, 2009). This is nicely illustrated by the 1997 United Nations Convention on International Watercourses, which was adopted by the General Assembly with an overwhelming majority (103 votes for and 3 against), although this convention was not particularly favourable for upstream states and its principles are a source of dispute in many conflicts (McCaffrey and Sinjela, 1998). The class of sequential sharing rules proposed in chapter 5 is just one of many possible approaches to arrive at a "fair" allocation. A more pragmatic approach would be to focus on desirable properties (see chapter 5) for the allocation of water. Properties are more tangible than the concept of fairness, which is sometimes embodied in these properties, and a small list of properties may already single out one possible sharing rule for water allocation.

6.3 Relevance

In this section I first describe the relevance of the approach used in this thesis for issues outside water allocation in transboundary river basins. Then, I will provide some comments on the general relevance of the methodology used in chapters 2–5.

Issues other than transboundary water allocation for which the approach and results of this thesis are relevant include those with a clear upstream-downstream setting. Three of these issues are (i) water quality in transboundary river basins, (ii) transboundary air pollution, and (iii) intergenerational sharing. I will discuss these now.

The first issue is water quality in transboundary river basins. This issue features the same geographical and institutional setting as transboundary water allocation, discussed in chapter 1 (cf. Sigman, 2002). Water polluted upstream with e.g. nutrients or heavy metals may create ecological damage or water treatment costs downstream. An important aspect of water quality is that pollutant concentration depends in a complex way on various processes related to dispersion and decay of pollutants. This implies that there is no direct relation between upstream pollution and downstream damage. Nevertheless, with appropriate simplifications, the issue of water quality in transboundary river basins can be approached using the same type of game-theoretic models as used in this thesis.

Alongside the game-theoretic strand of literature on water allocation, a separate game-theoretic literature on optimal levels of water quality and cost sharing of water treatment has developed. Some examples of this literature are the following. Several studies have focused on water quality in shared waters along the US-Mexico border. Fischhendler (2007) reviews cost-sharing solutions to pollution reduction in the Tijuana basin on the US-Mexico border and finds that there is a trade-off between perceived fairness and effectiveness of solutions. His results show that the polluter-pays-principle is not effective and was therefore replaced by other cost-sharing principles that better offset the asymmetric situation between the two countries. Fernandez (2009) reviews sharing rules in terms of pollution and side payments for cooperative agreements between the US and Mexico. The analysis builds on Fernandez (2002a,b) and includes asymmetries in abatement costs and pollution damage. Her results show the effect of the various rules on the size of side payments to be made. An explicit axiomatic analysis on water pollution sharing is presented by Ni and Wang (2007), based on the analysis of Ambec and Sprumont (2002). Other studies include Gengenbach (2009) who analyses the effects of coalition formation in wastewater treatment, and Van der Veeren and Tol (2001) who assess the optimal distribution of abatement measures to reduce nutrient pollution in the Rhine basin.

The second issue is transboundary air pollution by e.g. chemicals, particulates, and gaseous compounds, from both anthropogenic and natural sources. Air pollution in one country may—depending on wind speeds, humidity, and other factors—cause damage from deposition in a downwind country, including health effects, and damage to vegetation. As is the case for water pollution, dispersion and decay of air pollutants complicate the relation between pollution and damage. In addition, depending on the type of pollution, stock and flow effects can be distinguished.

Reviews of game-theoretic approaches to model air pollution games are provided by Missfeldt (1999) and Folmer and Van Mouche (2000). A large part of this literature is devoted to studying the so-called acid rain game starting with Mäler (1989), Newbery (1990), and Folmer and Van Mouche (2002). Emissions of sulphur dioxide and nitrogen oxides cause wet and dry deposition of acids downwind, with adverse effects on water, soils, and vegetation. Meteorological models are used to model the transport and transformation of the pollutants across countries. Stock effects are included by using a differential game as is done by Mäler and De Zeeuw (1998), with an application to Great Britain and Ireland (see also Kaitala et al., 1992). Our approach is better suited for air pollution with pure flow pollutants. More precisely, those pollutants with a short lifetime which can therefore be considered flow pollutants. These include the above-mentioned nitrogen oxides, but also suspended particulate matter and carbon monoxide (Liu and Lipták, 2000).

For the issues of water quality and air pollution, material from each of the chapters 2–5 seems relevant, given the almost identical setting of the problems. Chapters 2 and 3 provide insight into the design of contracts on emission prevention. Chapter 4 shows how the lack of property rights to clean water and air may lead to conflict. Chapter 5 provides an axiomatic approach to the sharing of the burden of pollution abatement.

The third and final issue is intergenerational sharing of welfare, briefly mentioned in chapter 5. The upstream-downstream element in this issue relates to time where the current generation is "upstream" of future generations. Sharing of welfare relates to pollution and the use of natural resources on the one hand, and investment in education, research, and capital accumulation on the other. The balance between these two factors, and possibilities for substitution between natural and man-made capital, determines the potential for the distribution of welfare between generations (cf. John et al., 1995; Arrow et al., 2004). The actual distribution is a trade-off between different measures of equity and time preference, to which a large literature is devoted (cf. Chichilnisky, 1996).

For intergenerational sharing of welfare, especially chapter 5 seems relevant. It may provide additional insight into the efforts that each generation should undertake to safeguard future welfare by approaching the issue as a bankruptcy problem. Each generation is then faced with the (excess) claim to welfare from the infinite stream of future generations. Desirable properties for intergenerational sharing can then be used to determine current consumption patterns, abatement levels, or conservation measures. The strategic models of chapters 2–4 are less suitable for this issue as future generations do not have the option to negotiate in the present. Negotiations between generations are only possible when one distinguishes between the "older" and "younger" generation, currently alive. Such a distinction is for instance being made in debates on pension schemes (e.g. Weikard, 2004a). In this case, chapters 2–4 may provide some insight into strategic aspects of intergenerational sharing.

Finally, some comments on the general relevance of the methodology. The approach of chapters 2 and 3 is relevant for any type of agreement in a stochastic setting. The stability of agreements has been studied in other contexts too, including open-access fisheries (Polasky et al., 2006) and transboundary wildlife management (Bhat and Huffaker, 2007). My contribution is a.o. the inclusion of sequentiality of actions provided by the upstream-downstream setting. This addition has an important effect on the desirable specifications of agreements and highlights that contract details can have important consequences on stability and hence efficiency.

Part of the methodology used in chapter 4 consisted of the inclusion of claims in a resource contest model. It allows to model a conflict where both claims and investment in arms or lobbying jointly determine the outcome of the conflict. This methodology seems promising for other types of resource contests where claims play an important role, such as contested territories (Ansink, 2009b). The methodology can be easily adapted to suit the specific conditions of a certain resource contest.

The approach taken in chapter 5 is not only suited for river sharing problems and intergenerational sharing. Other types of (re-)distribution problems seem applicable too, including those where the ordering of agents is not in space or time, but according to an exogenously given priority-ranking. An example is the (re-)distribution of water between various economic sectors. This topic is a pressing policy issue in for instance California and Australia, where continuing water scarcity and lack of options to increase water supply ask for drastic policy responses. These responses concern the re-distribution of water rights to those sectors that are deemed more important than others. The axiomatic approach that I present in this thesis may serve as a guideline to make the appropriate decisions. In general, the approach taken in chapter 5 can be applied to any distribution problem that differs in one or more aspects from the standard bankruptcy problem. Because the properties of bankruptcy rules are well understood, this approach provides immediate insight into the properties of different solutions. It is therefore an attractive approach whenever an axiomatic analysis is relevant to the problem at hand.

6.4 Final words

To conclude this thesis, recall the theme of the 2009 World Water Day stated in the opening lines of this thesis: "Shared Water—Shared Opportunities". This thesis shows that countries that share water indeed share opportunities. The challenge lies in whether and how these opportunities can be transformed into cooperation in order to reap its benefits.

Summary

Water is scarce. Globally, many river basins are faced with a decrease in water supply through the impacts of climate change. At the same time, demographic trends and economic growth contribute to increased water demand. Jointly, changes in supply and demand will cause a further increase of water scarcity.

In transboundary river basins, this development puts pressure on international relations as water is a valuable resource for a.o. households, agriculture, and industry. In some basins, countries have organised the allocation of river water resources through joint river basin committees or formal water allocation agreements. In the majority of transboundary river basins though, there is no cooperative management framework in place. Even the existence of a committee or agreement, however, may not be sufficient to prevent conflict over water. Committees may be powerless due to conflicting international principles for water allocation, and agreements may be broken when the short-term benefits of noncompliance are substantial.

Open questions are how cooperation in water allocation can be improved, and how to design international agreements such that countries will not break them. Underlying these questions are the issues of contested property rights to river water and the design of attractive sharing rules for river water. The objective of this thesis is to analyse water allocation in transboundary river basins, using game-theoretic models. This type of models is well-suited to analyse the strategic interaction between riparian countries regarding their decisions on water use.

Although existing game-theoretic models of water allocation in transboundary river basins have analysed a fair range of topics and river basins, many issues remain to be researched. To mention a few, the stability of agreements is a topic that has not been settled completely yet. Also, existing studies do not

demonstrate which factors cause actual negotiations on water allocation to be so cumbersome and lengthy. In addition, the axiomatic approach has hardly been used to design attractive sharing rules for water and makes for a wide open research area. After an introduction of the problem at hand and a concise literature review in chapter 1, these topics are covered in chapters 2–5 of this thesis.

In chapter 2, I assess the stability of various water allocation agreements under climate change impacts on river flow. The agreements differ in terms of the sharing rule that they employ and in terms of the side payments (constant or flexible). The methodology employed is a two-country game-theoretic model of water allocation. This approach continues on existing studies that focus on the efficiency of water allocation, while the focus of this chapter is stability. The results show that a decrease in mean river flow decreases the stability of an agreement, while an increased variance can have a positive or a negative effect on stability. The type of side payment—in the context of this chapter—does not really affect stability. What matters is the distribution of risk related to low river flows over the countries. This risk originates mainly from the sharing rule, which distributes water—and hence the shortage of water when there is less than expected—over the countries. Due to the sequential structure of water deliveries and side payments, agreements where a fixed amount of water is allocated to the upstream country, offer the largest stability. Clearly, this chapter provides an economic rationale for agreement noncompliance. Unstable sharing rules are expected to contribute to noncompliance and possible conflict over water.

In chapter 3, I analyse whether *ex ante* stable water allocation agreements exist at all. I do so by using the notion of self-enforcement. Self-enforcement implies that the agreement is sustained in subgame perfect equilibrium and is renegotiation-proof. The water allocation agreement is modelled as the outcome of a bargaining game, which is followed by a repeated extensive-form game in which countries decide whether to comply with the agreement. The agreement is specified by a water allocation schedule and side payments, both contingent on river flow. The results show that, for sufficiently low discount rates, every efficient agreement can be sustained in subgame perfect equilibrium. Not all of these agreements, however, are renegotiation-proof. Depending on parameter combinations, the set of possible agreements may shrink to approach a unique self-enforcing agreement, which assigns all gains from cooperation to downstream countries. This solution corresponds (and so implements) the "downstream incremental distribution", an axiomatic solution to water allocation. Stability, therefore, can be attained by careful design of the water allocation agreement. This chapter extends the repeated game literature to assess self-enforcement and renegotiation-proofness in the sequential and stochastic setting of water allocation agreements.

In chapter 4, I analyse situations where water rights are contested and a source of conflict. The methodology employed is a conflict model. More specifically, I use a conflict model in which countries have overlapping claims to water such that water rights are contested. Before moving to a costly conflict equilibrium, countries bargain over the allocation of river water in order to avoid conflict. In addition, countries may opt to request third-party intervention to settle the conflict. The results show that exactly this intervention possibility may prevent the countries from reaching a bargaining agreement on the property rights to water, leading to the conflict equilibrium. This chapter thereby identifies one possible cause for the existence of persisting conflict over river water in some river basins. It offers the first application of an economic conflict model to the issue of water rights, and is the first study to introduce claims in a conflict model, which allows a better understanding of their particular role in a conflict.

In chapter 5, I assess an axiomatic approach to the allocation of river water. This approach is tailored to the upstream-downstream setting of countries along a river basin. Methodologically, I define a river sharing problem such that it can be approached as a bankruptcy problem, an axiomatic approach to resource allocation in which resources are insufficient to meet all demands. Bankruptcy rules for bankruptcy problems are shown to have corresponding sequential sharing rules for river sharing problems. Many attractive properties of these bankruptcy rules are preserved in this transformation. Uncovering the relation between a sharing rule and its properties can make the fairness aspects of water allocation more transparent to the countries involved. This chapter widens the applicability of bankruptcy rules by generalising bankruptcy problems to river sharing problems that contain information on the sequential structure of both the agents and the resource to be shared. In addition, it provides one of the first axiomatic approaches to river sharing.

Three conclusions can be drawn from this thesis as a whole. First, increasing water scarcity or stochasticity does not necessarily obstruct the signing of international agreements on water allocation; it may, however, make these agreements more prone to defection. Second, the status quo situation of claims and (perceived) property rights matters for both the probability of conflict over river water, and the outcome of negotiations on water allocation. Third, there is not a unique "fair" allocation of transboundary river water. Overall, this thesis does not solve the transboundary water allocation problem. It does, however, provide insight into the strategic aspects that play an important role in this problem and its possible solutions.

Samenvatting

Water is schaars. Wereldwijd hebben veel rivieren te maken met een afname van watertoevoer en een toename van variantie door de effecten van klimaatverandering. Tegelijkertijd zorgen demografische ontwikkelingen en economische groei voor een toename van de vraag naar water. Gezamenlijk veroorzaken deze ontwikkelingen in aanbod en vraag een toenemende schaarste van water.

In grensoverschrijdende rivieren kan deze ontwikkeling internationale relaties onder druk zetten. Water is namelijk een kostbaar product voor o.a. huishoudens, landbouw, en industrie. In sommige rivieren hebben landen de verdeling van water uitbesteed aan internationale commissies of formeel vastgelegd in een waterverdelingsverdrag. In de meerderheid van grensoverschrijdende rivieren echter, is er geen enkele vorm van formele samenwerking. Zelfs de aanwezigheid van een internationale commissie of internationaal verdrag is soms niet toereikend om conflicten over water te voorkomen. Commissies hebben te maken met een gebrek aan machtsmiddelen en conflicterende internationale principes voor waterverdeling, terwijl verdragen kunnen worden geschonden wanneer de baten op korte termijn hoog genoeg zijn.

Open onderzoeksvragen zijn hoe samenwerking in waterverdeling kan worden verbeterd, en hoe internationale verdragen zo kunnen worden ontworpen dat ze niet worden verbroken. Onderliggende onderwerpen zijn de aanwezigheid van betwiste eigendomsrechten op water en het ontwerp van aantrekkelijke verdeelregels voor rivierwater. Het doel van dit proefschrift is het analyseren van waterverdeling in grensoverschrijdende rivieren met behulp van speltheoretische modellen. Dit type modellen is geschikt voor het analyseren van strategische interactie tussen landen die een rivier delen, in hun beslissingen omtrent watergebruik.

Ondanks het feit dat bestaande speltheoretische modellen al zijn toegepast op een aantal aspecten van internationale waterverdeling, is er een aanzienlijk aantal aspecten die tot nog toe onderbelicht zijn. Om er een paar te noemen; de stabiliteit van waterverdragen is een onderwerp waar nog geen eenduidige conclusie over bestaat. Daarnaast hebben bestaande studies nog niet kunnen aantonen welke factoren ervoor zorgen dat onderhandelingen over waterverdeling zo problematisch kunnen verlopen en lang kunnen duren. Ten slotte is de axiomatische methode nog vrijwel niet gebruikt voor het ontwerpen van aantrekkelijke verdeelregels voor water; een open onderzoeksveld. Na een introductie van het probleem en een literatuuroverzicht in hoofdstuk 1, worden deze onderwerpen behandeld in hoofdstukken 2–5 van dit proefschrift.

In hoofdstuk 2 evalueer ik de stabiliteit van verscheidene waterverdelingsverdragen onder de effecten van klimaatverandering op het debiet van rivieren. Deze verdragen verschillen in de verdeelregel voor water en in financiële compensatie (constant of flexibel). De methodologie die gebruikt wordt in dit hoofdstuk is een twee-landen speltheoretisch model voor waterverdeling. Deze methode bouwt voort op enkele bestaande studies die zich focussen op de efficiëntie van waterverdeling, terwijl dit hoofdstuk focust op stabiliteit. De resultaten tonen aan dat met een afname van het gemiddelde debiet de stabiliteit van een verdrag ook afneemt, terwijl een toename van de variantie van het debiet een positief of negatief effect kan hebben op stabiliteit. In de context van dit hoofdstuk heeft het type compensatie geen effect op stabiliteit. Wat wel van belang is, is de verdeling van risico gerelateerd aan een laag debiet over de twee landen. Deze verdeling is gebaseerd op de verdeelregel, die water—en daarmee het tekort aan water wanneer er minder is dan verwacht—verdeelt over de landen. Door de opeenvolgende structuur van waterlevering en betaling van compensatie, zijn verdragen waarbij het bovenstroomse land een vaste hoeveelheid water toebedeeld krijgt, het meest stabiel. Dit hoofdstuk presenteert een duidelijk economische oorzaak voor het schenden van waterverdelingsverdragen. Instabiele verdeelregels dragen bij aan deze mogelijkheid en de daarmee samenhangende conflicten over water.

In hoofdstuk 3 analyseer ik het bestaan van *ex ante* stabiele waterverdelingsverdragen. Dit doe ik met behulp van het concept zelf-afdwingbaarheid. Zelf-afdwingbaarheid houdt in dat een verdrag wordt ondersteund in een deelspel perfect evenwicht, en dat het verdrag bestand is tegen heronderhandelingen.

Het verdrag is in dit hoofdstuk gemodelleerd als de uitkomst van een onderhandelingsspel, en wordt gekarakteriseerd door een waterverdeling en compensatie, voor elk mogelijk debiet. Deze onderhandeling wordt gevolgd door een herhaald spel in extensieve vorm, waarin landen besluiten of ze zich al dan niet voegen naar het verdrag. De resultaten tonen aan dat, voor een voldoende lage discontovoet, elk efficiënt verdrag kan worden ondersteund in een deelspel perfect evenwicht. Echter, niet al deze verdragen zijn bestand tegen heronderhandelingen. Afhankelijk van de waarden van parameters kan de verzameling van mogelijke verdragen krimpen tot het een uniek zelf-afdwingbaar verdrag benadert, dat alle baten van samenwerking toewijst aan het benedenstroomse land. Deze uitkomst is gelijk aan (en implementeert daarmee) de "benedenstroomse toenemende verdeling", een axiomatische uitkomst voor waterverdeling. Klaarblijkelijk kan stabiliteit bereikt worden door middel van een zorgvuldig ontwerp van een waterverdelingsverdrag. Dit hoofdstuk breidt de bestaande literatuur over herhaalde spelen uit middels een analyse van zelf-afdwingbaarheid en bestandheid tegen heronderhandelen in de opeenvolgende en stochastische omstandigheden die kenmerkend zijn voor onderhandelingen over water.

In hoofdstuk 4 analyseer ik situaties waarin waterrechten worden betwist en daarmee een bron van mogelijke conflicten vormen. De methodologie die gebruikt wordt in dit hoofdstuk is een conflictmodel. Om precies te zijn gebruik ik een conflictmodel waarin landen overlappende claims op water hebben, zodat waterrechten worden betwist. Voordat zij eventueel uitkomen in een onaantrekkelijk conflict-evenwicht, onderhandelen landen over de verdeling van water om zo een conflict te voorkomen. Daarnaast hebben de landen de mogelijkheid om, tijdens de onderhandelingen, een neutrale derde partij te vragen om te interveniëren. De resultaten tonen aan dat juist deze mogelijkheid van interventie kan voorkomen dat landen een succesvol onderhandelingsresultaat bereiken over de betwiste waterrechten. In plaats daarvan wacht hen het onaantrekkelijke conflict. Dit hoofdstuk identificeert hiermee een mogelijke oorzaak voor het ontstaan en voortduren van conflicten over water. Het biedt de eerste toepassing van een economisch conflictmodel op het onderwerp waterrechten, en het is ook de eerste studie die claims introduceert in zo'n conflictmodel. Dit geeft een beter inzicht in de rol van claims in conflict-situaties.

In hoofdstuk 5 evalueer ik een axiomatische methode voor het waterverdelingsvraagstuk in rivieren. Deze methode is speciaal toepasbaar in de bovenstroom-benedenstroom situatie die typerend is voor de verdeling van rivierwater. Methodologisch gezien definiëer ik een waterverdelingsprobleem op zo'n manier dat het geanalyseerd kan worden als een faillissementsprobleem. Ik laat zien hoe verdeelregels voor faillissementsproblemen ieder een corresponderende verdeelregel voor waterverdelingsproblemen hebben. Veel aantrekkelijke eigenschappen van deze faillissementsregels blijven bewaard in deze transformatie. Deze eigenschappen zijn sterk verwant aan het aspect rechtvaardigheid dat een belangrijke rol speelt bij waterverdeling. De verzameling van verdeelregels voor waterverdelingsproblemen die in dit hoofdstuk wordt gepresenteerd heeft gemakkelijk identificeerbare eigenschappen door hun verwantschap aan faillissementsregels. Dit hoofdstuk verbreedt de toepasbaarheid van faillissementsregels door het generaliseren van faillissementsproblemen tot waterverdelingsproblemen die informatie bevatten over de lineaire structuur van zowel de agenten (bijv. landen) als het rivierwater. Daarnaast biedt dit hoofdstuk een van de eerste axiomatische benaderingen voor de verdeling van rivierwater.

Dit proefschrift bevat drie algemene conclusies. Ten eerste: toenemende schaarste en stochasticiteit van het debiet in rivieren verhindert niet noodzakelijkerwijs het opstellen van internationale waterverdelingsverdragen; het kan deze verdragen echter minder stabiel maken. Ten tweede: de aanwezigheid van claims en eigendomsrechten—al dan niet terecht—zijn van belang voor zowel de kans op conflict over water als de uitkomst van onderhandelingen over waterverdeling. Ten derde: er bestaat geen unieke "rechtvaardige" verdeling van grensoverschrijdend rivierwater. In zijn algemeenheid geeft dit proefschrift daarmee geen oplossing voor het probleem van waterverdeling in grensoverschrijdende rivieren. Het geeft echter wel inzicht in de strategische aspecten die een belangrijke rol spelen in dit probleem en zijn mogelijke oplossingen.

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Erik Ansink was born on 9 December 1979 in Doetinchem, the Netherlands. In 2002 he finished an MSc in Environmental Economics at Wageningen University. During his studies, he has spent six months as an exchange student at the Swedish Agricultural University in Uppsala. Between 2002 and 2004, he first worked at Dutch Sustainability Research and then as a researcher at Wageningen University for an EU research project on the economics of agri-environmental programmes. In 2004 he started his PhD research at the Environmental Economics Group of Wageningen University. In 2008 he made a visit to the Department of Economics at Queen Mary, University of London, and he successfully completed the doctoral training programs of the Netherlands Network of Economics (NAKE) and of the graduate school SENSE. Results of his PhD research have been presented at international conferences and published in peer-reviewed journals. He is currently employed as a post-doctoral researcher at Wageningen University.

Training and supervision plan

SENSE PhD courses:

- Environmental Research in Context (WUR);
- Research Context Activity: ”Writing of integrating chapter on “Conceptual models in river basin management” for book on ”Groundwater Science and Policy”;
- Natural Resources and Intergenerational Justice (WUR).

Other PhD courses:

- Microeconomics I (NAKE);
- Macroeconomics I (NAKE);
- Advanced Econometrics (WUR);
- Game Theory (NAKE);
- Experimental Economics (NAKE);
- Economic Theory I (NAKE);
- Behavioral Economics (NAKE);
- Techniques for writing and presenting scientific papers (WUR);
- Basiscursus Didactiek (WUR).

Other activities:

- Research visit Queen Mary, University of London, 15 September 1 December 2008, London, United Kingdom.

Oral Presentations:

- CREE 2006, Wolfville, Canada;
- NAKE Conference 2006, Amsterdam, The Netherlands;
- EAERE 2007, Thessaloniki, Greece;
- EPCS 2008, Jena, Germany;
- EAERE 2008, Gteborg, Sweden.

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