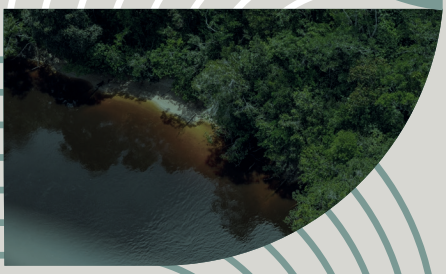
Solving water conflicts

Game theoretic approaches to water allocation in Peru

Zoila del Rosario Gómez Gamarra







Propositions

1. Conflicts caused by water scarcity result from misunderstandings of the strategic interactions among agents. (this thesis)

2. Water allocation solutions are inefficient if institutional monitoring and enforcement are weak or decision-making is guided by short-term horizon. (this thesis)

3. Power asymmetries are softened by strong institutions that reshape agents' incentives to balance efficiency and equity.

4. Case studies suggest that scientific evidence only improve policy outcomes and welfare if institutions integrate it into decision-making.

5. Reliable open data contribute to building trust and commitment which improve decision making at the individual and institutional levels.

6. Under conditions of scarcity, shared values become utopian when transparency and accountability are limited.

Propositions belonging to this thesis, entitled

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Solving water conflicts:
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Solving water conflicts:
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Chapter 1

Introduction



1.1. Water scarcity and conflicts

Water scarcity has emerged as a growing global challenge threatening the capacity of populations and economic systems to meet their basic water needs. Beyond its direct impacts on health and livelihoods, water scarcity can generate significant risks to economic development, environmental stability and social cohesion. Addressing this challenge requires a deep understanding of water users' behaviour within an institutional framework. The institutional framework provides incentives which shape agents' decision making on water use and safeguarding quality in the context of water scarcity (Braden & van Ierland, 1999; Zhang et al., 2010; Baccour et al., 2024). The interlinkages between institutional framework and agents' behaviour are essential determinants of the trade-off between efficiency and equity of water management. Understanding these interlinkages allows for exploring mechanisms to mitigate conflicts and enhance cooperation.

Population growth, the adverse effects of climate change on water systems, and inefficient water management exacerbate both the depletion and degradation of water resources. Pollution – caused by solid waste, industrial and domestic effluents and emergency events such as oil spills – further reduces the availability of clean water for human and ecological purposes. Vulnerable ecosystems, including drylands, highlands, and rainforests are also increasingly impacted by water stress.

Water scarcity is commonly assessed by using the UN water stress indicator. Water stress is defined as the proportion of freshwater withdrawn by all economic activities in the total renewable freshwater resources available (UN-Water, 2024)[1]. Western Asia and North Africa exhibit the highest water stress. In Western Asia the indicator increased from 58% in 2015 to 63% in 2021; in Northern Africa it grew from 105% to 121% over the same period increasing the pressure on groundwater resources (UN-Water, 2024). In contrast, Latin America is currently a region without water stress. The regional water stress

[1] According to UN-Water, (2024) a territory is under water stress when it withdraws 25% or more of its freshwater resources. Water stress is the indicator to monitor the SDG 6.

index has been assessed at 6.0% in 2021 (a water stress index below 25% is not considered to be water stress). However, such regional averages conceal severe problems at a local scale.

In shared river basins, water scarcity often becomes a source of conflict, especially when water allocation and pollution are perceived as unfair. Economic, social and cultural asymmetries among water users can exacerbate such tensions (Wolf, 2007; Wang et al., 2025). In 2023, global, water-related conflicts increased by 50% compared to 2022, reaching 347 events. Western Asia comprises 38% of global water conflicts which have increased by 75% in 2023 compared to the previous year (Gleik & Shimabuku, 2023; Pacific Institute, 2024).

Historically, in transboundary river basins, water conflicts have emerged from issues such as hydropower dam construction in upstream countries, conflicting irrigation demands, and river diversions, among others. River basins with enduring conflicts include the Nile, the Tigris-Euphrates, and the Mekong (Kaufman et al., 1997; Wolf, 2007; Dinar et al., 2013). Moreover, conflicts may also arise in river basins shared by different states or provinces within a country due to inequitable water sharing (Wolf, 2007). The Cauvery river basin in southern India illustrates such disputes between the states of Karnataka and Tamel Nadu, which have conflicting water demands for irrigation (Gosh et al., 2018).

This thesis focuses on the challenges of water scarcity in Peru in terms of conflicts and water pollution under a weak governance. Peru shows a moderate water stress index. However, it has been increasing from 5.6% in 2015 to 7.2% in 2021 (UN-Water, 2024). Peru's geography – characterised by arid coastal areas, highlands exceeding 3800 meters above sea level, and extensive rainforests – features an uneven distribution of water-endowments. The challenge lies in the mismatch between freshwater availability and the spatial distribution of population and economic activities.

Peru has three watersheds, Pacific, Amazon and Titicaca, that illustrate this imbalance. The Pacific watershed which supports 66% of the national population and 80% of the GDP, has only 2% of the country's freshwater resources. In contrast, the Amazon watershed has 97% of available freshwater but sustains 31% of the national population. The Titicaca watershed stands for 1% of available freshwater supporting

3% of the national population (Autoridad Nacional del Agua [ANA], 2013). This spatial water mismatch is exacerbated by climate change effects which are different by regions. For instance, extreme rain falls and floods occur in the coastal areas while severe droughts occur in the highlands (Ministerio del Ambiente [MINAM], 2016; Servicio Nacional de Meteorología e Hidrología del Peru [SENAMHI], 2021).

In Peru, water scarcity and pollution have led to various conflicts. For instance, the integrated Ica river basin conflict between the upstream indigenous community in Huancavelica and the downstream agricultural producers in Ica has lasted for more than 70 years. Underlying the conflict was the national government intervention and public infrastructure investment in 1945, without considering the economic, social and environmental consequences on the upstream water users. On the other hand, conflicts related to water oil pollution are mainly concentrated in Loreto. In Loreto, the hydrocarbon sector stands for 92% of the conflicts in the region (Defensoría del Pueblo, 2022). These characteristics make Peru a 'laboratory' for analysing water scarcity and related conflicts at the subnational level.

Yet, conflicts can also be an opportunity for welfare improvement, if the causes of conflict, such as weak governance and unclear property rights issues are properly addressed (Wolf, 2007; van Rijswick et al., 2014). In order to settle conflicts, effective rules for water sharing are essential. Agreeing on such rules implies allocating clearly defined property rights to water among users.

The literature on river sharing identifies relevant factors that can improve water allocation (Ambec & Sprumont, 2002; Olmstead, 2010; Ansink & Weikard, 2012; Beal et al., 2013). In their seminal paper, Ambec & Sprumont (2002) emphasize that water allocation should be based on principles such as stability and fairness. Ambec and Sprumont conclude that agents' location along the river determines the quantity of water each agent controls and, in turn, the welfare derived from it. Water allocation under scarcity has been analysed from the bankruptcy perspective. The bankruptcy approach focuses on agents' claims which cannot all be satisfied, given an endowment. Therefore, a rule is necessary to deal with scarcity in an efficient and fair manner (Thomson, 2003; Madani & Dinar, 2013). This approach has been useful to solve transboundary water allocation and conflicts. Ansink &

Weikard (2012) interpret the river sharing problem as a bankruptcy problem of sequentially ordered agents where agents' claims exceed the endowment. Integrating agents' location and the spatial distribution of water in the conventional bankruptcy problem, the authors provide allocation rules based on first principles (axioms). (Sechi & Zucca, 2015) include willingness to pay to establish a claimant's priority in the allocation rule. Willingness to pay and priority have a positive relationship. The authors applied a willingness-to-pay based allocation rule in Sardinia, Italy, where the multipurpose Tirso-Flumendosa-Campidano water system provides water to urban, industrial and agricultural users. Including weights in the bankruptcy rules, based on the willingness-to-pay for priorities, provides an allocation that favours users with a higher willingness to pay.

Other authors use a combination of approaches to define allocation rules. For instance, Janjua et al. (2025) propose a three-stage water allocation mechanism composed of bankruptcy rules, Nash Bargaining Solution (NBS) and the Technique for Order of Preference by Similarity to Ideal Solution - TOPSIS[2]. They apply this mechanism to the Indus river in Pakistan which is shared by four provinces. The model application considers three water flow scenarios: low, median and maximum. The model includes water risks and water needs. The three-stage water allocation are as follows: (i) applying different bankruptcy rules; (ii) maximising the agents' total utility based on cooperation and negotiacion applying the NBS, which incentivises cooperative decision making among the agents; and (iii) including potential risks and uncertainty in TOPSIS (e.g. water scarcity, water depletion, groundwater reduction, seasonal variability). The authors conclude that this combined approach, including risks and water needs, balances equity and efficiency in water allocation. Thus the allocation would be accepted by the four provinces, reducing the potential for conflicts. Similarly, Degefu et al. (2017) combine the Nash Bargaining Solution and bankruptcy rules and apply them to the Nile river basin. This river basin has been a centre of water conflicts. The authors

[2] TOPSIS is a multicriteria decision-making tool for one agent, not considering agents' interaction.

conclude that the combined procedure leads to a water allocation that can avoid water conflicts, allowing riparian countries to get benefits from a transboundary water sharing. Degefu et al. (2017) include stochasticity and uncertainty of river flow in transboundary bankruptcy allocation rules, which makes it more challenging to apply them. The authors suggest that the following factors should be taken into account: temporal and spatial variation of river flow, and geographic, economic and political conditions within countries to capture the barriers that constrain the design of an allocation mechanism.

Besides river sharing and allocation rules for surface water, there is a worldwide concern about the depletion of groundwater resources which is exacerbated by climate change effects and pollution (Jasechko et al., 2024). Groundwater as a common pool resource (CPR) has been extensively studied with tools of game theory, pointing out how gains can increase through cooperation, leading to reductions of negative externalities associated with pumping costs and the depletion of the resource (Parrachino et al., 2006). Moreover, institutions play a role in creating conditions for stable cooperation (Asprilla-Echevarria, 2021). Cooperation among agents is critical to reduce overexploitation drought damage cost and improve ecosystems protection (Esteban & Dinar, 2013; Kahil et al., 2016).

Linking surface water and groundwater allocation has been mainly addressed with simulation models to optimise overall water use (Safavi et al., 2016; Sabale et al., 2023). The value of the results, however, is often constrained by data availability. This thesis complements this literature by contributing a conceptual model of water allocation from two sources, surface water and groundwater which are connected by the recharge. Surface water allocation affects groundwater recharge and, therefore, its availability and eventual allocation.

Water scarcity is also linked to water pollution because it limits freshwater availability to other water users, which can lead to conflicts. To address the issue, the thesis focuses on oil pollution of water resources caused by the hydrocarbon industry in the Peruvian Amazon.

Water scarcity and conflicts still demand urgent attention, due to their economic, social and environmental consequences, particularly when

weak governance prevails. This thesis contributes by extending the analysis of water sharing problems and shedding light on how water allocation rules and investments can improve welfare and mitigate conflicts. Regarding water pollution, side payments and credible punishment are considered as a mechanism to mitigate negative externalities and conflicts. Moreover, by analysing the strategic interaction between the government and firms it is possible to derive (institutional) conditions under which firms have incentives to pollute or not.

1.2. Institutional framework for water resource management

An institutional economics perspective provides a framework for understanding how institutions and governance shape incentives, efficiency and welfare in resource management. Institutions are defined as a set of rules and norms that govern individual and collective behaviour (Ostrom, 1986, 2007; North, 1989, 1990). Governance refers to the decision-making process to provide public services and the degree of stakeholder participation (Fukuyama, 2016).

Effective governance requires not only technical and administrative capacities, but also mechanisms to prevent rent seeking, corruption and the erosion of public trust (Dethier, 1999). In this thesis, water-related challenges are addressed from an institutional and governance perspective.

When promises and obligations cannot be enforced, a commitment problem arises (North, 1990). Agents may have incentives to break promises when the expected cost of punishment is lower than the benefits of defection (Cooter & Ulen, 1996: Acemoglu et al., 2005). The commitment problem is exacerbated when there is lack of trust and a history of conflict (Bueno de Mesquita, 2016; Acemoglu & Wolitzky, 2024)

The institutional framework for water resource management has been widely analysed (Dombrowsky, 2007; Madani & Dinar, 2012; Dinar et al., 2013; Houba et al., 2013; Jaeger, 2015;). The complexity of water institutional frameworks reflects the nature of water, agents' strategic behaviour given a multitude of choice options. Water has particular

characteristics: it is available in different forms (surface water, groundwater, ice, precipitation), its availability is volatile over time and spatially differentiated, and it has multiple competing users (Jaeger, 2015). Therefore, institutions have a critical role to align the incentives to lead to a sustainable water use.

In sum, institutional design and water governance are central for solving both water allocation and pollution challenges. Without strong institutions and enforcement mechanisms, even technically elaborated allocation schemes can fail to deliver sustainable outcomes. Institutional changes can lead to a transition from conflict to cooperation or vice versa.

1.3. Objectives and research questions

This thesis addresses key challenges related to water allocation and water pollution, emphasizing the strategic interactions between agents at the subnational level. These issues are particularly acute in river basins, where underlying factors such as water scarcity, conflicts and weak governance affect both welfare and the performance of economic activities.

The overarching objective of this thesis is to offer solutions to real water conflicts, taking into account the strategic behaviour of the agents under water scarcity and weak governance. The geographic focus is Peru. Two specific objectives are linked to the general objective. First, to propose water allocation mechanisms to improve welfare and mitigate conflicts between the agents. To achieve this objective, on the one hand, I study water allocation rules in an applied setting with multiple water sources (river water and groundwater). I explore the implication of the rules for Ica valley, a dryland in Peru. On the other hand, I examine the role of joint infrastructure investments to improve water allocation and reduce conflicts by cooperative agreements in a shared river basin, the Ica river basin shared by the highlands (upstream) and the drylands (downstream). The second specific objective is to propose solutions to water pollution and to derive the conditions for implementing the solutions. For this objective, on the one hand, I analyse the role of side payments in the resolution of water pollution conflicts in the Peruvian Amazon. On the

other hand, I analyse how the risk of asset stranding can be mitigated or exacerbated through the stringency of environmental policy making focusing on investments of oil firms in the Peruvian Amazon.

More specifically, the following four research questions are addressed:

1. How can water resources be allocated to surface water and groundwater users when allocation and availability are interdependent? This question addresses an equity-efficiency trade-off. (Chapter 2)
2. How can infrastructure investments be designed to solve conflicts and improve welfare? This question explores the potential of investments to transform a conflict into a win-win situation. (Chapter 3)
3. To what extent can side payments mitigate negative externalities and facilitate stable and peaceful outcomes with improved welfare, when weak governance prevails? This question studies a solution to conflicts when law enforcement is weak or absent. (Chapter 4)
4. How can a stringent environmental policy and enforcement incentivise clean production and how does it affect the risk of assets stranding? Addressing this question sheds more light on government's (lack of) incentives to enforce the law. (Chapter 5)

1.4. Methodology

The thesis proposes and analyses solutions to real water allocation and pollution problems, related to scarcity and conflicts using game theory. Game theory is the core theory that this thesis is based on, because it enables us to study the strategic behaviour of agents in interdependent relationships. The game theoretic approach has been a commonly used approach to understand the strategic interactions of different water users in real situations. Moreover, water allocation and pollution problems need to consider the institutional framework. The thesis attempts to integrate game theory and institutional economics. Each water problem presented includes the institutional setting to understand the incentives under which the agents interact.

Particularly, the thesis uses case studies and micro-economic modelling. The four case studies inspire the model design and give valuable information to understand the incentives underlying the

strategic interaction between agents. The cases are based on water conflicts in Peruvian regions. They provide information on agents, their preferences and their choice options which are the necessary ingredients to analyse strategic interaction and the role of the institutional frame in which agents are embedded.

The microeconomic models used are general enough and abstract from details to be widely applicable. At the same time, they are sufficiently specific to allow for an understanding of real problems. The models' main purpose is to highlight the mechanisms underlying conflictive situations. Although tailored to the Peruvian situation, the models can be applied to other locations or industries with similar problems, bringing insights into long-lasting problems that are common worldwide. The models are based on both cooperative and non-cooperative game theory. Four models are developed, one for the analysis of each research question.

The methodological approach to each research question is as follows.

Water allocation rules and hydro-economic integration (Chapter 2). A cooperative game theoretical model of water sharing (Yang et al., 2025) is modified and extended to analyse the allocation of both surface water and groundwater in an integrated way, where recharge has a critical role. A unified hydro-economic model is developed where water users have claims to both water sources at their location, extending the sequential river sharing literature (Ambec & Sprumont, 2002; Ansink & Weikard, 2012). Two allocation rules are proposed: the Proportional Rule and a rule that gives Upstream Priority to Surface Water.

Cooperative water-sharing agreements (Chapter 3). A cooperative game approach is used to analyse a conflictive water sharing problem in an upstream-downstream setting. This chapter is built on Atwi & Chóliz (2011), Houba et al. (2013) and Degefu et al. (2017), however joint infrastructure investments are included to assess its contribution to welfare and cooperation improvements. The agents are two regions characterised by economic, social and cultural asymmetries. A bargaining model is applied and use two solution concepts: the Nash Bargaining Solution and the Kalai-Smorodinsky solution.

Oil pollution conflicts and side payments (Chapter 4). A sequential game is developed to analyse the strategic interaction between a firm and a community under oil pollution externalities. The model derives the conditions under which side payments and compensations can deter the community retaliation and avoid violent conflicts, while influencing the firm's environmental effort decision in the presence of penalties and threats.

Oil pollution and stranded assets (Chapter 5). A sequential game with incomplete information is used to model the strategic interaction between the government and a firm. Chapter 5 highlights the role of agents' beliefs under uncertainty. Based on one's belief about the other's strategy, an agent chooses her own strategy. Conditions for assets getting stranded are derived to understand the government's incentives to monitor or not and the firms' decisions to produce clean or not.

1.5. The study areas

The theoretical models are inspired by water allocation and pollution problems in three regions in Peru: Huancavelica, Ica and Loreto. These regions host a variety of ecosystems, indigenous communities livelihoods and economic activities. The models are constructed to capture the key variables related to the real situation in each region and answer the research questions but they do not represent all aspects of the complex reality.

Water allocation is analysed within the integrated Tambo-Santiago-Ica river basin which encompasses two regions, Huancavelica and Ica. Huancavelica, located upstream, serves as an important source of freshwater. The Ica river originates in the highlands of Huancavelica, at an altitude over 3800 meters above sea level. This area is particularly vulnerable to the effects of climate change, including the melting of glaciers, changes in rainfall patterns and ecosystem degradation, which have reduced water resources. Andean communities in the highlands rely almost entirely on rainfall for rearing alpacas and sheep and growing crops for self-consumption such as potatoes and beans. Water and technology constraints affect the development of cultivated

pastures, which in turn limits alpacas' fur productivity and communities' income.

In contrast, downstream, the Ica river flows through the Ica province, supporting the economic development of the Ica valley. The Ica valley is situated in one of the driest areas in the world (UNEP, 2006).The Ica province depends on both surface water and groundwater, with groundwater being the main source of irrigation for agri-export crops. Ica's agri-export value increased by 59% between 2020 and 2023. However, water infrastructure, built in the mid-20th century, primarily favoured the economic development of Ica contributing to a historical conflict between the two regions (Huancavelica and Ica). Chapter 2 focuses on water claims for surface water and groundwater for agricultural use in the Ica valley. Chapter 3 focuses on water allocation between Ica and Huancavelica, in a conflictive situation.

Water pollution is analysed in Chapter 4 and Chapter 5 for Loreto, a region where oil pollution has led to conflicts. Loreto is an Amazon region which hosts a valuable biodiversity and indigenous communities. A complex aquatic ecosystem based on rivers and lagoons provides a resource base to indigenous communities. The hydrocarbon industry started its operations in 1970, beginning a history of water pollution that has affected communities' resource base and health. In this context, Chapter 4 analyses the conditions under which side payments with credible threats can solve water pollution conflicts, where weak governance prevails. Chapter 5 analyses how stringent policy enforcement can align incentives for clean production but may also lead to asset stranding, depending on the agents' beliefs and strategic behaviour.

1.6. Thesis outline

The next chapter, **Chapter 2**, focuses on a water allocation problem, extending the water sharing problem to a situation where two related water sources (surface water and groundwater) are allocated among users who have claims to both water sources. The water users are agricultural producers who have tensions for water allocation in an arid area. In this chapter, two allocation rules are proposed, the Proportional Rule and Upstream Priority to Surface Water Rule to

address claims over interconnected water sources. It highlights the role of groundwater recharge and discusses the trade-off between fairness and efficiency in the allocation.

Chapter 3 shows how institutional changes triggered by investments and new technologies can improve water-use efficiency and mitigate conflicts in a shared river basin. A mechanism such as a cooperative agreement between water users in the highlands and drylands can improve their welfare. The cooperative agreement relies on a joint infrastructure investment which can improve water allocation between two regions with asymmetric economic, social and cultural conditions, turning a conflictive situation into a cooperative one.

Chapter 4 analyses oil pollution and negative externalities that have affected indigenous communities in Loreto. A model with side payments and compensation mechanisms shows that conflicts can be mitigated, enhancing cooperation particularly under economic, social and cultural asymmetries between the agents.

Chapter 5 investigates the interaction between the government and an oil producing firm. It shows how stringent environmental policies can incentivise clean production and, under certain conditions, lead to asset stranding. It highlights the importance of uncertainty and agents' beliefs in guiding the decisions of both government and oil producing firms.

Chapter 6 synthesises the main findings of the thesis in light of its overarching objectives. It discusses common themes across chapters and acknowledges methodological and data limitations. Policy implications are suggested and, finally, further research is proposed.

Chapter 2

Water allocation rules and hydro-economic integration



Abstract

From a normative point of view the allocation of scarce water resources has been studied for two benchmark cases, (i) sequential water allocation applicable to river water, and (ii) water extraction from a common pool, applicable to water from a lake or to groundwater resources. We develop a unified model framework which comprises both situations as special cases. We study an allocation problem in which water users hold claims on two interdependent water sources: surface water and groundwater. We propose two allocation rules: the Proportional Rule and Upstream Priority to Surface Water. We apply these rules to Ica valley, an arid region in Peru characterised by significant agricultural production and water scarcity. We discuss their contributions to, and limitations in achieving, a feasible and equitable water allocation.

Keywords: Water sharing, surface water, groundwater, role of recharge, drylands, Ica-Peru.

2.1. Introduction

In the 21st century, water allocation is still a challenging problem, not only because of growing population and increasing water and food demand but also due to climate change. Climate change exacerbates rainfall variability, changes snow melting patterns, and therefore changes river flows and groundwater recharge (Intergovernmental Panel on Climate Change [IPCC], 2022). Intensified agriculture has increased the pressure on groundwater resources, particularly in arid and semi-arid areas where aquifers have dried up, affecting agricultural productivity and human well-being (IPCC, 2022). Moreover, long-term water scarcity reveals the States' failures to manage it, leading to depletion and degradation of water resources. As a result, dependent ecosystems and their services are at risk threatening livelihoods and economic activities (Madani, 2026).

The aim of this chapter is to analyse allocation of scarce water when two water sources are interdependent (e.g., surface water and groundwater). Agents with claims to water are located from upstream to downstream along a river. They have access to two water sources: surface water and groundwater which are linked by recharge. Surface water availability declines along the river due to extraction and infiltration. Groundwater is limited but recharged through infiltration, and available to all as a common pool resource. We assume that agents have separate claims to surface water and to groundwater. Claims may relate to historical water use rights, water needs depending on crop types, land area size, or other. We develop a unified framework to study water allocation that combines river sharing and common pool resource use. Within this unified framework we analyse the trade-off between efficiency and fairness. Thus far, in the literature, these allocation problems have been treated separately. We combine them because the use of surface water from the river is linked to groundwater use in two ways. First, groundwater availability depends on the recharge of the aquifer through infiltration of surface water. Second, for an equitable allocation, claims to surface water and to groundwater should have equal standing, subject to feasibility constraints.

Our analysis is inspired by water conflicts in Ica valley, a dryland in Peru with significant agricultural production which is dependent on

irrigation. Our model captures the main features of a hydro-economic system, in particular the link between surface water and groundwater, that is, how surface water allocation affects groundwater availability and, in turn, its allocation for irrigation.

A normative, axiomatic approach to river sharing problems has been pioneered by Ambec & Sprumont (2002) who characterise allocation rules in the welfare domain allowing for side payments. Here we are interested in the allocation of water rights; we do not introduce a utility or welfare framework but we acknowledge that agents have claims to water. Recent work that is close to our analysis is by Yang et al. (2025) who study the allocation of pollution rights to agents located along a river. Since pollution by upstream agents imposes pollution damage on downstream agents, efficiency and equity principles suggest different allocations. Yang et al. (2025) propose a compromise solution. Our model displays a similar feature for surface water. If only surface water is considered, infiltration reduces surface water flow along the river. Therefore, satisfying downstream claims to surface water is associated with infiltration. In particular, supplying surface water to downstream agents is associated with more infiltration compared to upstream agents. In that sense it more "expensive" to serve downstream agents. While water allocation proportional to claims might be fair, it will be inefficient when downstream claims have to be served. In such case, the efficient solution is to allocate water giving priority to upstream claims.

However, in this chapter, we go beyond the river claims problem as we also consider groundwater which is a common pool resource (CPR), rival but non-excludable. In this setting infiltration is associated with groundwater recharge, and water losses are relevant only if groundwater claims are small. The novelty of our paper is the integrated approach to surface *and* groundwater allocation acknowledging that surface water allocation has a role in aquifer recharge (Reichard, 1995) and claims to both types of water are relevant.

We propose and compare two rules for water allocation. (i) The Proportional Rule allocates all water, surface water and groundwater, proportional to claims, subject to feasibility constraints. (ii) We introduce a new rule called Upstream Priority to Surface Water. This rule favours surface water allocation to upstream users. As the reduction of

surface water flow depends on upstream surface water use and the recharge rate, this rule is of importance in situations where infiltration rates are high and groundwater claims are small. In such cases surface water is scarce but not groundwater. The rules we consider were selected based on the characteristics of the water sources, their interdependence, and their use for irrigation. The proportional rule is widely applied to water allocation problems as it is considered fair and transparent and is easy to implement and verify. Priority rules are applied in sequential settings in which agents' locations along the river are relevant (Ambec & Sprumont, 2002; Ansink & Weikard, 2012). Alternative rules, such as bankruptcy rules (e.g., Constrained Equal Awards (CEA) and Constrained Equal Losses (CEL) (Ansink & Weikard, 2012; Zheng et al. 2022), are more complex to implement and face limitations in terms of efficiency or political acceptability.

The structure of this chapter is as follows. The next section offers a literature review to describe the gap that our paper addresses. Section 2.3 explains the features of our hydro-economic model and formally defines the two rules to allocate both, surface water and groundwater. Section 2.4 presents our case study of the Ica valley. We calibrate the model and demonstrate its applicability. Details of the calibration are relegated to an appendix. Section 2.5 offers a discussion and concludes.

2.2. Water allocation with claims on river sharing and common pool resources

Two benchmark problems have been discussed in the normative literature on water allocation: the river sharing problem and groundwater allocation as a common pool resource. The river sharing problem discusses how the river flow should be distributed among water users who are ordered linearly from upstream to downstream along the river. Water users can be countries, regions, cities, or farmers; they are called agents. The agents' location determines the volume of water that each can control along the river (Ambec & Sprumont, 2002). Water is scarce as agents are non-satiated or have claims which in sum are larger than the endowment (Ambec & Sprumont, 2002; Ansink & Weikard, 2012; Beal et al., 2013).

River flow has a role in groundwater recharge. An integrated management of surface water and groundwater is necessary to improve recharge, particularly in arid areas. Recharge assessment requires to monitor the runoff in varying circumstances such as wet, normal and dry years (Wable et al., 2021). Moreover, rising threats to groundwater recharge such as climate change or local anthropogenic factors like land use change and water management can increase competition for scarce water affecting livelihoods and economic activities. Measures to improve groundwater recharge require strong governance that foster regional cooperation and integrated water management (Granata & Di Nunno, 2025).

Groundwater is a common pool resource (CPR). It is a well-established result that CPRs will be overexploited in the absence of regulating institutions (Ostrom et al., 1994; Nazari et al., 2020). In contrast, well-designed institutions can facilitate cooperative behaviour to reduce losses from negative externalities, increase gains and sustain resources (Madani & Dinar, 2012; Asprilla-Echevarria, 2021).

River basins are increasingly contested due to increasing water demands and the risk of water shortages. Economic and social asymmetries can further exacerbate the potential for conflicts (Degefu & He, 2016). In such context, the implementation of an allocation rule becomes essential to prevent or solve disputes. An allocation rule is defined as *"a general principle used with respect to an entire class of similarly structured allocation problems, for which there is no objective way to attribute value (cost) to specific members*" (Hougaard, 2009).

Commonly used allocation rules include the proportional and priority rules. The proportional rule aims to distribute resources fairly among agents based on their claims and given the legitimacy of those claims and the limited endowment. In contrast, a priority rule allocates resources according to criteria related to agent's specific characteristic, such as location (Flores-Swagrzak et al., 2020). Madani & Dinar (2011) apply the proportional rule to reallocate overexploited groundwater. They find this rule to be particularly effective when water users are more alike and there is little uncertainty about their behavioural characteristics. Another application of the rule is in the allocation of irrigation water among agricultural users with productivity asymmetries in the Ebro river basin in Spain. The sequential rule (a

priority rule) can improve efficiency compared to the proportional rule especially when water price and heterogeneity across farms are high (Goetz et al., 2008). Successful application of allocation rules requires agents' consent which can be assumed if rules result from fair negotiations (Madani & Zarezadeh, 2012).

River sharing and CPR problems have both been addressed with cooperative game theory models. Specific sharing rules are characterised by sets of axioms such as efficiency, resource monotonicity, and others (Ambec & Sprumont, 2002; Ambec & Ehlers, 2008; Beal et al., 2013). While the seminal work of Ambec & Sprumont (2002) studies water allocation in a welfare framework, where agents get utility from water use, others impose axioms directly on the allocation of water (e.g., Ansink & Weikard, 2015). This chapter follows the latter approach. Our approach also relates to the literature on bargaining with claims (Chun & Thomson, 1992; Bossert, 1993) and the bankruptcy literature where agents' claims cannot all be satisfied and a sharing rule is employed to deal with scarcity in an efficient and fair manner (Thomson, 2003; Madani & Dinar, 2013).

Madani (2026) explains the evolution of the definitions to address water scarcity, such as water stress, water crises and water bankruptcy. The latter refers to situations in which water rights holders are unable to satisfy their legal or institutional claims. Therefore, transformative mitigation and adaptation measures are urgent to prevent future damages that can be prevented, while recognizing those that are already irreversible.

Water endowments are sensitive to climate variability, which affects river flow, introducing uncertainty in the water flow. This has motivated applications to transboundary water allocation applying a stochastic bankruptcy approach without and with uncertainty where the river flow varies in each riparian countries, which make the allocation more challenging. Rules including uncertainty provide strategic information for a sustainable water sharing and management (Ansink & Ruijs, 2008; Degefu et al., 2017).

While joint management of surface water and groundwater has been extensively analysed using simulation or optimisation models in empirical studies, we approach the issue from a normative angle. Thus far, empirical models have identified an optimal allocation of surface

water and groundwater (Hao et al., 2022; Sabale et al., 2023), but the efficiency-equity trade-off has not been addressed in a unified framework comprising both surface water and groundwater. We amend two prominent allocation rules, demonstrate the role of infiltration that links surface water and groundwater availability, and explore the role of the link for allocating water. This interaction has not been discussed previously in water claims problems.

2.3. The model

Our model analyses a water allocation problem with two types of claims. Agents are located along a river and may have claims to surface water and groundwater. We consider a set of n agents, $N = \{1, \dots, n\}$; $n \geq 2$. Typical agents i, j are located along the river such that $i < j$ means that i is upstream of j; see Figure 2.1. The remainder of this section, first, explains the main features of the hydrological system. Then, we introduce the agents and their claims to water. Finally, we propose two rules to distribute water among the agents.

2.3.1. The hydrological system

We provide a stylized description of the hydrological system of drylands with a given water endowment E. The water endowment is available as surface water s_i or groundwater g_i at agent i's location. Surface water, the river flow, is directed from upstream to downstream. Flow decreases along the river, depending on withdrawal by upstream agents and natural infiltration. Surface water is extracted from the river and fed into ponds for irrigation and infiltration. Infiltration serves groundwater recharge. Groundwater can be pumped up for irrigation use by any agent (Figure 2.1).

As we study a dryland setting, we do not consider tributaries and assume that all water is supplied at the location of the most upstream agent. More formally, the hydrology of the river is described as follows. The water endowment E is available for surface water use S or groundwater recharge R.

$$E \geq S + R. \tag{2.1}$$

The river flow at the location of agent i is f_i. We have $f_1 = E$ and, due to aquifer recharge,

$$f_{i+1} = (1-\rho)f_i - s_i;\ i = 1, \dots, n-1. \tag{2.2}$$

Here $\rho \in (0,1)$ is the coefficient that describes recharge through infiltration and reflects the geo-hydrological conditions.

Any water e_i extracted by agent i enters a pond. A fraction ρe_i recharges the aquifer; the remainder $s_i = (1-\rho)e_i$ is available for irrigation. This implies that any water used for irrigation s_i is associated with extraction $e_i = \frac{1}{(1-\rho)} s_i$ and recharge $r_i = \frac{\rho}{(1-\rho)} s_i$. In addition, there is natural recharge from the remaining flow such that $f_{i+1} = (1-\rho)(f_i - e_i)$, which is equivalent with Eq. (2.2).

Finally, we assume that the last agent extracts all remaining water, for use or recharge, such that no water is lost, i.e., $r_n = f_n - s_n$. This assumption is not essential for our analysis, but eases exposition. We will drop it in the application of the model to Ica valley in the next section.

Total groundwater recharge is given by

$$R = \sum_{i=1}^{n-1} \rho\, f_i + f_n - s_n. \tag{2.3}$$

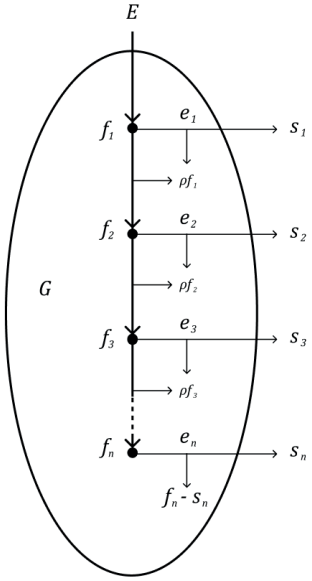


Figure 2.1: Hydrological system. The hydrological system shows the relationship between surface water and groundwater through recharge r. There is a total water endowment denoted by E. Agent i extracts e_i from the flow f_i for irrigation with surface water s_i. A fraction ρ of the surface water infiltrates along the river flow and while it is stored for irrigation. The recharge $r_i = \rho f_i \quad (i = 1, \dots, n-1)$ feeds into groundwater G. The last agent extracts the entire remaining flow for groundwater recharge or use $e_n = f_n = r_n + s_n$.

2.3.2. Agents' water use

Each agent $i \in N$ has two types of claims $c_i \geq 0, d_i \geq 0$, for surface water and groundwater, respectively. Agents' claims are written as vectors $c = (c_1, \dots, c_n) \in \mathbb{R}^n_+$ and $d = (d_1, \dots, d_n) \in \mathbb{R}^n_+$. We use capital letters to refer to sums of claims, i.e., $C = c_1 + \cdots + c_n$ and $D = d_1 + \cdots + d_n$. As we are interested in the allocation of scarce water, we will generally assume that claims weakly exceed the endowment, $C + D \geq E$, which is a sufficient condition for water scarcity. However, due to recharge, water scarcity can also occur when E exceeds $C + D$ as we will explain below.

Each player uses surface water s_i and groundwater g_i for irrigation. We adopt the notation $S = s_1 + \cdots + s_n$ and $G = g_1 + \cdots + g_n$.

In this setting a water claims problem is a triple (c, d, E). A solution to a water claims problem is a rule that determines a feasible water allocation (s, g), where $s = (s_1, \dots, s_n) \leq (c_1, \dots, c_n)$ and $g = (g_1, \dots, g_n) \leq (d_1, \dots, d_n)$ for every given water claims problem (c, d, E). A water allocation is feasible if for all agents $s_i \leq f_i(1 - \rho)$, water flow satisfies Eq.(2.2), $G \leq R$, and R satisfies Eq. (2.3).

2.3.3. Water allocation rules

Since we have two types of water claims, it is possible that either surface water is scarce or groundwater or both. Notice that a larger recharge parameter ρ increases surface water scarcity and improves groundwater availability. Our model offers a unified framework to study water allocation problems combining river sharing and common pool resource allocation. There are two special cases. (i) If all surface water claims are zero and therefore $(s_1, \dots, s_n) = (0, \dots, 0)$, then no agent takes surface water and all water will become available as

groundwater ($E = R$). Groundwater is a common pool resource where all agents have equal access. (ii) If all groundwater claims are zero and therefore $(g_1, \dots, g_n) = (0, \dots, 0)$, then we have a conventional river claims problem with the refinement, however, that water is lost along the river due to infiltration. Our water claims problem combines both situations and reflects the links between the two.

As we account for two different types of water claims, we allow water allocations to follow different principles. While location matters for surface water availability, we assume equal access to groundwater. For allocating the latter it is, thus, natural to adopt a proportional rule. Using a proportional rule for surface water is less straightforward since surface water infiltrates along the river and recharges the aquifer. Just from the perspective of surface water users it is, therefore, more expensive to serve downstream users. We consider two different rules for surface water allocation. The Proportional Rule (P) gives each agent the same proportion of their claim. We will see that this rule can lead to inefficiencies. These inefficiencies can be reduced, even minimised, under Upstream Priority to Surface Water (U). We will define both rules in turn and illustrate their implications for a set of stylized situations. In Section 4 we will apply the rules to water allocation in the Ica valley, Peru.

Definition: Proportional Rule (P). The available groundwater R is allocated proportional to groundwater claims, i.e., $g_i = \gamma\, d_i$ for all i with $\gamma \in [0,1]$ and $\gamma = min(\frac{R}{D}, 1)$. Surface water is allocated proportional to surface water claims, i.e., $s_i = \sigma\, c_i$ with $\sigma \in [0,1]$ and

$$\sigma = min\left(\frac{E}{\sum_{i=1}^{n} \frac{1}{(1-\rho)^i} c_i}, \gamma\right).$$

Parameter γ is the largest equal share of the groundwater claim that can be satisfied given the recharge. For surface water the rule gives agents the largest possible equal share of their claims if this does not exceed the share of groundwater claims that can be satisfied. To obtain σ as specified by rule P, notice that $E = f_1$ and a feasible water allocation must satisfy $s_1 \leq f_1(1-\rho)$. From Eq.(2) we have $f_2 = f_1(1-\rho) - s_1$ and the allocation must satisfy $s_2 \leq f_2(1-\rho)$.

Substituting and generalizing for n agents we must have

$$E = f_1 \geq \sum_{1=1}^{n} \frac{1}{(1-\rho)^i} s_i$$

for a feasible water allocation $(s_1, \dots, s_n)$.

Hence, a proportional allocation $s_i = \sigma c_i$ requires $E \geq \sum_{i=1}^{n} \frac{1}{(1-\rho)^i} \sigma c_i$ and the largest feasible equal share is given by

$$\bar{\sigma} = \min\left(\frac{E}{\sum_{i=1}^{n} \frac{1}{(1-\rho)^i} c_i}, 1\right). \tag{2.4}$$

Given this feasibility constraint for surface water allocation, we will have water losses if recharge is high and groundwater claims are low such that $R \geq D$. A possibility to reduce water losses in such case is to allocate a larger than proportional share of surface water to upstream agents.

Definition: Upstream Priority to Surface Water (U).

The available groundwater R is allocated proportional to groundwater claims, i.e., $g_i = \gamma\, d_i$ for all i with $\gamma \in [0,1]$ and $\gamma = min(\frac{R}{D}, 1)$. Surface water is allocated according to claims in the order of the agents, such that each agent receives $s_i = min\big(c_i, f_i(1-\rho)\big)$, where f_i is constructed recursively using Eq. (2.2).

Rule U ensures that as little water as possible is wasted. This is particularly relevant when the recharge rate ρ is high and groundwater claims are low. Loosely speaking, rule U favors efficiency while rule P favors fairness.

A numerical example helps to compare these rules in the following illustrative situations: (i) only surface water claims, (ii) only groundwater claims, and (iii) surface water and groundwater claims.

There are three players $N = \{1,2,3\}$, a water endowment $E = 120$, and two situations with recharge parameters $\rho = 0.5$ or $\rho = 0.1$. The claims and solutions are presented in Table 2.1. For further details we refer to Appendix A2.1.

This numerical example illustrates the relationship between surface water and groundwater through recharge, and the relevance of ρ. Situation (i) with only surface water claims shows that if ρ=0.5, Rule P allocates a proportion σ of the claims, where σ is constrained by recharge. In this case, less surface water is available to satisfy claims due to high infiltration. Rule P leads to 32.8 units of surface water allocated and 87.2 units are infiltrated and lost because there are no

groundwater claims. Rule U allocates 60 units of surface water to Agent 1, improving the efficiency of surface water allocation and reducing water loss by 27.2 units of water. If ρ=0.1, Rule P still gives a water loss of 19.6 units of water. Rule U gives the two most upstream agents their full claim. Agent 3 receives what is left over. Water loss is reduced compared to Rule P, favoring efficiency. Hence, if there are no groundwater claims, water loss is inevitable. Water loss is more pronounced if ρ is high.

Situation (ii) features only groundwater claims. This situation illustrates the allocation of a common pool resource. Since no surface water is taken, we have full infiltration of the endowment ($E = R$). In our example, all agents' claims are satisfied under both rules. Note that both rules coincide when there are only groundwater claims.

Table 2.1: Water allocation according to rules P and U. $E = 120$.

Claims	Rule	ρ=0.5 Solution	ρ=0.1 Solution
(i) Only surface claims $c = (60, 40, 20)$ $d = (0, 0, 0)$	**Rule P**	$s = (16.4, 10.9, 5.5)$ $g = (0, 0, 0)$	$s = (50.2, 33.5, 16.7)$ $g = (0, 0, 0)$
	Rule U	$s = (60,0, 0)$ $g = (0, 0, 0)$	$s = (60, 40, 2.9)$ $g = (0, 0, 0)$
(ii) Only groundwater claims $c = (0, 0, 0)$ $d = (60, 40, 20)$	**Rule P**	$s = (0, 0,0)$ $g = (60, 40, 20)$	$s = (0, 0, 0)$ $g = (60, 40, 20)$
	Rule U	$s = (0, 0,0)$ $g = (60, 40, 20)$	$s = (0, 0,0)$ $g = (60, 40, 20)$
(iii) Surface water and groundwater claims $c = (30, 20, 10)$ $d = (30, 20, 10)$	**Rule P**	$s = (16.4, 10.9, 5.5)$ $g = (30, 20, 10)$	$s = (30, 20, 10)$ $g = (30, 20, 10)$
	Rule U	$s = (30, 15, 0)$ $g = (30, 20, 10)$	$s = (30, 20, 10)$ $g = (30, 20, 10)$

Situation (iii) considers surface water and groundwater claims. If $\rho = 0.5$, Rule P leads to a total surface water allocation of 32.8 units of water and a water loss of 27.2 units. While Rule U allows an allocation of 45 water units, which fully satisfies Agent 1's surface water claims and part of Agent 2's claims. Therefore, Rule U leads to less water loss (15 units). Groundwater claims can be fully satisfied under both rules. If $\rho = 0.1$, recharge is small enough so that surface water claims can be fully satisfied under both rules. In our example, where endowment equals claims, all groundwater claims can also be satisfied and there is no water loss.

In summary, this numerical example illustrates how the two water sources are linked through recharge and can be analysed in a unified framework. We highlight that agents have different access to surface water and that location matters.

2.4. Ica valley: agricultural production and water scarcity in a dryland

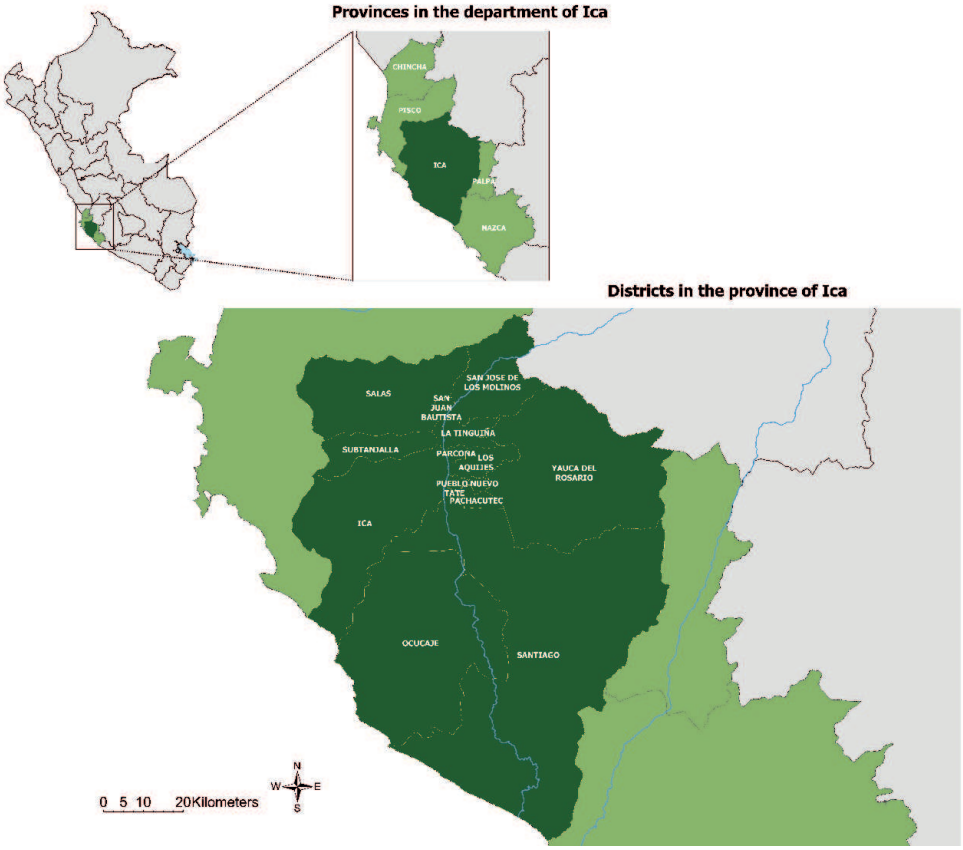
2.4.1. Study area

Ica valley is located in Ica province on the Peruvian southern coast, within the Ica department. Ica valley is part of a dryland and it is well known for its fertile soils and adequate weather for agriculture since time ago. It is one of the most fertile valleys on the coast. Production, however, is constrained by water scarcity.

Ica province comprises fourteen districts (Figure 2.2). There are three water sources: the Ica river, the regulated Choclococha system and groundwater from Ica's aquifer. The Ica river's seasonality leads to abundant water from January to March, while from September to November the Choclococha system provides surface water (MINAM, 2020). Additional to seasonality, Ica valley is vulnerable to extreme events such as floods and droughts that affect water availability (Presidencia del Consejo de Ministros [PCM], 2014). Groundwater is provided by the Ica's aquifer. In Peru, there are 49 aquifers and Ica's aquifer is the most important one, accounting for 35% of all groundwater extracted in Peru (ANA, 2012). Over the past two decades, the highest extraction of 385.5 MCM was reported in 2007.

The groundwater extraction has decreased since then but is still higher than average annual recharge (179.4 MCM), leading to overexploitation of the aquifer. Ica's aquifer has sustained agriculture since 1950 (ANA & Ministerio de Desarrollo Agrario y Riego [MIDAGRI], 2017). There are 2116 borewells in total in Ica valley, of which 898 (42%) are in use by different sectors (agriculture, households, industry). Agricultural use stands for 71% of the borewells in use (ANA & MIDAGRI, 2017). Water users in Ica are mainly agriculture and households. Agricultural use stands for 99% of consumptive surface water use (Instituto Nacional de Estadística e Informática [INEI], 2023b) and 83% of groundwater extraction (ANA & MIDAGRI, 2017).

In Ica province, the agricultural area across the fourteen districts is used by farms of different sizes. Small and medium sized farms together stand for 64% of the area. The area of large farms with 100 ha or more stands for 36% of the agricultural area. Large farms are mainly located in the districts of Salas and Ica (INEI, 2013). Larger farms are generally agri export crop producers, while small and medium sized farms produce domestic market crops (Muñoz et al., 2014; Salmoral et al., 2020). In the following we assume that water claims for surface water and groundwater depend on crop type.



Source: INEI (2007), IGN (2007).

Figure 2.2: Location of Ica valley in Peru

Ica is a leading agri export region, with 20% of the Peruvian agri export value in 2023. Ica's agri export value increased by 59% between 2020 and 2023 (Ministerio de Comercio Exterior y Turismo [MINCETUR], 2023). The main agricultural export crops are water intensive such as asparagus, grapes, avocados. This agri export growth is heavily dependent on groundwater (Muñoz et al., 2014; Salmoral et al., 2020; Pronti et al., 2024). The main crops for the domestic market are yellow corn, cotton, potato, butter bean, and pecan. These are less water intensive, are grown on smaller farms, and depend on surface water.

Growing agricultural production and water scarcity have motivated different responses by agricultural producers and the government. One measure adopted to limit aquifer overexploitation has been a ban on borewells since 1970. The ban has been renewed periodically and

the last renewal was in 2017 (ANA & MIDAGRI, 2017). Meanwhile large agricultural producers have invested in water saving technologies such as drip irrigation. Recently, local surface water and groundwater associations have agreed to allow surface water extraction for aquifer recharge during the rainy season from January to March in the upstream highlands, the origin of the Ica river.

Water scarcity in Ica valley has been extensively studied from the perspective of water justice and political ecology, highlighting power and access to groundwater (Damonte et al., 2016; Damonte, 2019) , asymmetries between agri exporters and small and medium producers and access to water sources (Muñoz et al., 2014; Salmoral et al., 2020; Pronti et al., 2024) and changes in hydro-social territories (Damonte & Boelens, 2019). The hydro-social territories are understood as a space where complex human interactions are developed regarding water flow, hydraulic infrastructure, institutions and socio-cultural and ecological dimensions (Damonte & Boelens, 2019; Hommes et al., 2022).

Groundwater management has also been analysed as a common pool resource, highlighting factors such as increasing prices of agri-export crops, access to modern irrigation technology which leads to non-cooperative behaviour and increasing groundwater extraction (Muñoz et al., 2014; Muñoz & Zuñiga, 2018). This work highlights the importance to strengthen institutions that favour cooperation among the agents to improve groundwater use.

Water governance in Ica has changed in recent decades. Since 2009, the new Water Law facilitates sustainable water management and use of surface water and groundwater. Water authorities were created such as the National Water Authority as well as water authorities at regional and local levels (Oré & Geng, 2014; Damonte et al., 2018). The access to water sources for agricultural use requires a license which is issued by the water authority (Ley No. 29338, 2009). In this context, water management for agricultural use is still a challenge as it needs to cope with a growing agricultural production and water scarcity.

2.4.2. A proposed water allocation for Ica valley

In the following we specify agents, water endowment, and water claims. We assume the agents are the 14 districts of the province of Ica; see Figure 2.2 and Table 2.2. We consider the allocation of irrigation

water. The water claims are determined according to the agricultural area by crop type and district (INEI, 2013) as we observe that agri export crops are mainly irrigated with groundwater while domestic crops grown by medium sized and small farms are mainly irrigated by surface water. We take into account that water requirements differ per crop. Appendix A.2.2 explains the details.

Since Ica valley is in a dry area vulnerable to natural extreme events, we calibrate the model for three river flow situations: low, medium and high. Surface water infiltrates along the river, according to a recharge rate ρ. Recharge reduces surface water availability for downstream agents. In our calibration, detailed in Appendix A.2.2 and based on national official information (ANA, 2017; INEI, 2023), we set $\rho = 0.0495$.

We assume:

a. Water endowment only serves agriculture.
b. Agri export crops use only groundwater, and domestic market crops use only surface water.
c. Groundwater use is limited by recharge to guarantee sustainability.

Two rules are applied for water allocation: Proportional Rule (P) and Upstream Priority to Surface Water (U).

Table 2.2 reports the claims for each district in Ica province sorted from upstream to downstream. Claims are calibrated based on water needs of crops grown in each district. Since water endowments vary widely across years we distinguish three situations: dry years with low river flow, normal years with medium river flow, and wet years with high river flow (see Appendix A.2.2).

In a low river flow situation, Rule P distributes water according to the proportion $\sigma = \gamma = 0.130$, which is the largest feasible equal proportion of agents' claims (see Section 2.3). The agents receive 13% of their claims and allow infiltration to serve groundwater claims. Rule P favours equity but leads to 51 MCM water loss. Rule U allocates surface water according to agents' location, upstream water users receive their full surface water claims and downstream agents receive what is left. Rule U leads to reduced water infiltration which affects serving groundwater claims. Therefore, applying Rule U, γ is recalculated (γ=

0.104) to serve groundwater claims. Rule U avoids water loss in this particular situation (Table 2.2).

With medium river flow, the endowment more than doubles compared to low river flow. Rule P distributes water according to $\sigma = \gamma = 0.282$, meaning that 28.2% of each agent's water claims can be satisfied. Rule P generates a water loss (104.1 MCM). Rule U serves all the surface water claims, infiltration is minimised which results in a lower γ parameter ($\gamma = 0.257$) compared to Rule P ($\gamma = 0.282$). In this situation, Rule U improves efficiency compared to Rule P, by reducing water loss by about two thirds (Table 2.2). The high river flow situation is similar to the medium river flow situation, meaning that surface water claims are fully served under Rule U and the water loss of 94.5 MCM is almost 40% lower than under Rule P (Table 2.2).

Summarising, when there is medium or high river flow, surface water claims can be fully satisfied under Rule U. However, with low river flow surface water is insufficient to satisfy claims. We calculate from Eq. 4 that the minimum water endowment necessary to satisfy all surface water claims under rule U is 201.97 MCM.

If the recharge rate is higher compared to our preferred calibration (ρ= 0.0495), for instance $\rho = 0.06$, losses are generally lower. Rule P favours groundwater claims more pronouncedly because a proportional surface water allocation helps to recharge and facilitates serving groundwater claims as compared to Rule U. In contrast, Rule U serves first upstream surface water claims, limiting losses but also recharge, thus affecting the groundwater allocation. However, Rule U leads to a water loss which stands for 19% and 55% of the water loss associated with rule P, respectively in the medium and high river flow situation. These percentages are lower compared to a lower recharge $\rho = 0.0495$ (see Table A2.2 in the Appendix).

Table 2.2: District water allocation: two rules by river flow (MCM) $\rho = 0.0495$

		Low river Flow		Medium river Flow			High river Flow
Districts	**Claims**	**P Rule**	**U Rule**	**P Rule**	**U Rule**	**P Rule**	**U Rule**
	(*c*, *d*)	$E = 127$ σ=γ=0.130	γ=0.104	$E = 269$ σ=γ=0.282	γ=0.257	$E = 394$ σ=γ=0.412	γ=0.392
San Jose de los Molinos	(7.3, 17.1)	(0.9,2.2)	(7.3, 1.8)	(2.1, 4.8)	(7.3, 4.4)	(3.0, 7,0)	(7.3, 6.7)
Salas	(5.9, 239.6)	(0.8, 31.1)	(5.9, 25)	(1.7, 67.5)	(5.9, 61.5)	(2.4, 98.7)	(5.9, 93.9)
San Juan Bautista	(1.7, 7.4)	(0.2,1.0)	(1.7,0.8)	(0.5, 2.1)	(1.7, 1.9)	(0.7, 3.0)	(1.7, 2.9)
La Tinguiña	(4.2, 24.8)	(0.5, 3.2)	(4.2, 2.6)	(1.2, 7.0)	(4.2, 6.4)	(1.7, 10.2)	(4.2, 9.7)
Subtanjalla	(0.5,12.6)	(0.1, 1.6)	(0.5, 1.3)	(0.1, 3.5)	(0.5, 3.2)	(0.2, 5.2)	(0.5, 4.9)
Parcona	(3.1, 1.0)	(0.4, 0.1)	(3.1, 0.1)	(0.9, 0.3)	(3.1, 0.3)	(1.3, 0.4)	(3.1, 0.4)
Ica	(4, 11.6)	(0.5,1.5)	(4.0,1.2)	(1.1, 3.3)	(4.0, 3.0)	(1.6, 4.6)	(4.0, 4.5)
Los Aquijes	(5.7, 9.5)	(0.7, 1.2)	(5.7, 1.9)	(1.6, 2.7)	(5.7,2.4)	(2.3, 3.9)	(5.7, 3.7)
Pueblo Nuevo	(1.5, 11)	(0.2, 1.4)	(1.5, 1.1)	(0.4, 3.1)	(1.5, 2.8)	(0.6,4.5)	(1.5, 4.3)
Tate	(1.5,0)	(0.2, 0.0)	(1.5, 0)	(0.4, 0)	(1.5, 0)	(0.6, 0)	(1.5, 0)
Pachacutec	(1.5, 36.6)	(0.2, 4.8)	(1.7, 3.8)	(0.4, 10.3)	(1.7, 9.4)	(0.7, 15.1)	(1.7, 14.3)
Yauca del Rosario	(4.5, 5.7)	(0.6, 0.7)	(4.5, 0.6)	(1.3, 1.6)	(4.5, 1.5)	(1.9, 2.3)	(4.5, 2.2)
Santiago	(49.7, 84.4)	(6.5, 11.0)	(36.4, 8.8)	(14.0, 23.8)	(49.7, 21.7)	(20.5, 34.8)	(49.7, 33.1)
Ocucaje	(24.2, 8.2)	(3.1, 1.1)	(0, 0.9)	(6.8, 2.3)	(24.2, 2.1)	(10.0, 3.4)	(24.2, 3.2)
Total Prov. Ica	**(115.5, 469.5)**	**(15.0, 61.0)**	**(78.0, 49.0)**	**(32.6, 132.3)**	**(115.5, 120.6)**	**(47.8, 193.4)**	**(115.5, 184.0)**
Loss		**51.0**	**0**	**104.1**	**32.9**	**152.8**	**94,5**

Sources: SENAMHI (2009); INEI (2013); MINAM (2020). Own calculations.

In summary, this application of water allocation rules for interdependent water sources in an arid area accounts the differences among agents in terms of location and farm size. The latter is associated with crop type and water claims. We provide solutions to the water allocation problem considering the role of recharge. Since surface water allocation affects recharge and therefore groundwater allocation, comparing rules P and U shows a trade-off between fairness and efficiency. In Ica valley water for irrigation stands for 99% of the

consumptive surface water use. Surface water that is not used for agricultural production or recharge is discharged into the ocean. It is thus lost for agricultural production. Rule P favours fairness, serving equally surface water and groundwater claims but leads to water loss. Rule U favours efficiency giving priority to upstream surface water claims which reduces or avoids water losses.

2.5.Discussion and Conclusions

This chapter analyses a water allocation problem. A unified hydro-economic model is developed where water users hold claims to both surface water and groundwater, and users' location along the river affects allocation outcomes. Two rules are applied: the Proportional Rule (P) and Upstream Priority to Surface Water (U). Rule P allocates water proportionally to claims. In contrast, Rule U prioritises upstream users, accounting for the impact of location on water use efficiency (Flores-Swagrzak et al., 2020).

The novelty of this chapter is to include the role of recharge in the allocation rules, including recharge changes the feasibility constraint for water allocations compared with previous river sharing models (Ambec & Sprumont, 2002; Ansink & Weikard, 2012). The model is applied to the Ica valley, a dryland region in Peru, characterised by a growing agricultural sector and increasing water scarcity. Rule P generates more equitable outcomes under conditions of water scarcity by ensuring that all users receive a proportion of their claims. However, consistent with the literature (Goetz et al., 2008), Rule P may generate inefficiencies as it leads to water losses. By contrast, Rule U favours efficiency. Since upstream agents' surface water claims are served first, less water is lost but also less water can infiltrate for groundwater use.

In Ica valley, each water user would prefer a water allocation rule based on their geographical location. Each rule has different effects on agents depending on farm size and crop type. Upstream small and medium-scale producers would prefer Rule U. However, when flows are low downstream surface water users may receive no water.

Thus, there is a trade-off between efficiency and equity. This trade-off is more pronounced when the rate of infiltration is larger as we illustrate in Table A2.2 in the Appendix. When river flow is low, Rule U can be useful to save valuable water.

Rule U distributes surface water sequentially, starting from the most upstream user. It is worth noting that in our model an implicit assumption is that distances between any two agents are equal. However, this is a simplification which does not well represent the situation in Ica valley where upstream districts are closer to each other (e.g. Parcona, Los Aquijes, Pueblo Nuevo) compared downstream districts. Although our model does not properly account for spatial distance, incorporating this would be a promising extension for future research.

In situations where groundwater claims exceed surface water claims, recharge becomes critical to serve groundwater claims. This highlights the importance of monitoring recharge and understanding its behaviour under different hydrological conditions.

Our hydro-economic model is general and provides insights into how surface water allocation can influence groundwater availability. Although the calibration is specific to the Ica valley, the approach contributes to identify key factors that should be considered for water allocation decisions in other dryland regions, such as flow variability and the critical role of recharge.

Future research should explore seasonality and side payments. A dynamic model may analyse seasonality of river flow, water requirements of crops and recharge on a monthly basis. This can enhance allocation strategies, but so far data availability is a limiting factor. Moreover, the role of recharge is an opportunity to explore side payments, where groundwater users can pay to surface water users for implementing measures that enhance recharge, such as infiltration ponds, reforestation or other nature-based solutions. These cooperative arrangements could be formalized as cost-sharing games, providing insights for further economic analysis on the role of recharge.

In conclusion, effective water allocation under severe scarcity, requires rules which incorporates the relationship between surface water and groundwater and the role of recharge. Rules P and U and potentially combinations of these can contribute to design water management systems that promote recharge, particularly in regions where scarcity is exacerbated by climate change and agricultural expansion.

Appendices

Appendix A2.1

In this Appendix we illustrate the application of the rules and the role of the recharge parameter ρ.

We have three players $N = \{1,2,3\}$, water endowment $E = 120$. We consider two values of ρ: ρ =0.5 and ρ =0.1.

Only surface water claims

$c = (60, 40, 20)$, $d = (0, 0, 0)$.

a. Consider ρ= 0.5.

Proportional Rule (P)

The largest equal share σ is given by Eq.(2.4).

$$\sigma = \frac{E}{\sum_{i=1}^{n} \frac{1}{(1-\rho)^i} c_i} = \frac{3}{11} \approx 0.27$$

$$s_i = \sigma c_i$$

$$s = (16.4, 10.9, 5.5)$$

There are no groundwater claims and, hence, $g = (0,0,0)$

Upstream Priority to Surface Water (U)

The allocation is determined recursively in the order of the agents. We start with agent 1.

$s_1 = \min\big(c_1, f_1(1-\rho)\big) = \min(60, 60) = 60.$

Next, we calculate f_2 using Eq.(2.2).

$f_2 = (1-\rho)f_1 - s_1 = 60 - 60 = 0$

There is no surface water left for subsequent agents and we obtain

$$s = (60, 0, 0)$$

Since there are no groundwater claims: $g = (0, 0, 0)$. There is a water loss of 60 units due to recharge not used.

b. Consider ρ=0.1.

Proportional Rule (P)

$$\sigma = \frac{E}{\sum_{i=1}^{n} \frac{1}{(1-\rho)^i} c_i} \approx 0.836$$

Therefore, $s = (50.2, 33.5, 16.7)$

Since there are no groundwater claims, $g = (0, 0, 0)$. We observe a water loss of 19.6 units.

Upstream Priority to Surface Water (U)

$$s_i = \min\left(c_i, f_i(1-\rho)\right)$$

$s_1 = min(60{,}108)$. Then, $s_1 = 60$ and the flow received by Agent 2 is 48.

$s_2 = \min(40, 43.2)$. Then $s_2 = 40$ and the flow received by Agent 3 is 3.2.

$s_3 = \min(20, 2.9)$. Then $s_3 = 2.9$.

$$s = (60, 40, 2.9)$$

Since there are no groundwater claims, $g = (0, 0, 0)$.

A lower ρ allows Agents 1 and 2 to fully satisfy their surface water claims. There is a water loss of 17.1 units of water which is much lower than when the recharge is higher (ρ=0.5). We also observe that rule U reduces the water loss as compared to rule P by 2.5 units.

Only groundwater claims

$$c = (0, 0, 0), d = (60, 40, 20)$$

No agent takes surface water. Then, according to our assumption, all water is used to recharge the aquifer, $R = E$.

In this case rules P and U coincide.

$$\gamma = \frac{R}{\sum_i^n d_i} = 1$$

$$g_i = d_i$$

Since $\sum_i^n d_i = R$, all agents receive their groundwater claim.

$$s = (0, 0, 0)$$

$$g = (60{,}40{,}20)$$

Surface water and groundwater claims

$E = 120$ as before. The claims are as follows: $c = (30, 20, 10)$ and $d = (30,20,10)$

a. Consider $\rho = 0.5$

Proportional Rule (P)

The largest equal share σ is given by Eq.(2.4).$\sigma = \frac{E}{\sum_{i=1}^{n} \frac{1}{(1-\rho)^i} c_i} = \frac{6}{11} \approx 0.55$

$$c = (30, 20, 10).$$

$$s_i = \sigma c_i$$

$$s = (16.4, 10.9, 5.5)$$

The remaining water infiltrates and all groundwater claims can be granted,
$g = (30, 20, 10)$.

Upstream Priority to Surface Water (U)

$$s_1 = \min(30, 60) = 30$$

$$s_2 = \min(20, 15) = 15$$

$$s_3 = \min(10, 0) = 0$$

$$s = (30, 15, 0)$$

The remaining water infiltrates and all groundwater claims can be granted,
$g = (30, 20, 10)$.

b. Consider $\rho = 0.1$.

Proportional Rule (P)

The largest equal share σ, given by Eq.(2.4). In this case, it is feasible to grant all claims.

$$\sigma = 1$$

$$s_i = \sigma c_i$$

$$s = (30, 20, 10)$$

The Upstream Priority to Surface Water (U)

$$s_1 = \min(30, 108) = 30$$

$$s_2 = \min(20, 70.2) = 20$$

$$s_3 = \min(10, 50) = 10$$
$$s = (30, 20, 10)$$

A lower ρ allows to fully satisfy the surface water claims. The remaining water infiltrates and all groundwater claims can be granted, $g = (30, 20, 10)$.

Appendix A2.2: Calibration details

This Appendix explains details of the model calibration as introduced in Chapter 2.4. Data sources are provided in Table A2.3 below.

1. Water endowment

Water endowment includes surface and groundwater. We present three situations of water endowment, according to river flow: low, medium and high. The data source is the National Service of Meteorology and Hydrology (SENAMHI), who keeps records from the Ica river discharge since 1960 to 2012. Table A2.1 shows the ranges of the river flow and the water inflow.

Table A2.1: River flow

River Flow	Flow m3/s	Number Years	Average Inflow (MCM)
Low	1-5.99	15	127
Medium	6-9.99	19	269
High	10 or more	17	394

Source: SENAMHI (2009); MINAM (2020).

Surface water includes the Ica river and the regulated Choclococha system. According to (ANA, 2017) the annual rate of recharge is 38%. We assume sustainable water use, meaning that groundwater extraction is based only on recharge.

2. Water requirements of crops

We distinguish two groups of crops in Ica valley, one is export crops, the other is for the domestic market. Generally, the production of export crops is more water intensive. We calculate the weighted average water requirements per group of crops, we include the most

relevant crops covering 23% and 21% of the agricultural area in Ica department, for export and domestic crops respectively. We include as export crops asparagus, grapes and avocados and as domestic crops cotton, yellow corn, potato, pecan, mango, tomato, butter beans and olives. The crop area is reported at the department level by the System of Integrated Agrarian Statistics (SEIA-MIDAGRI). We calculate the weighted average water requirements by crop.

Water requirements for export crops:

$$W_e = \frac{\sum_{i=1}^{3} area_i * requirement_i}{\sum_{1=1}^{3} area_i} = 10803 \text{ MCM/ha};$$

$i = \{\text{asparagus, grapes, avocado}\}$.

Water requirements for domestic crops:

$$W_d = \frac{\sum_{i=1}^{8} area_i * requirement_i}{\sum_{1=1}^{8} area_i} = 6583 \text{ MCM/ha};$$

$i = \{\text{cotton, corn, potato, pecan, mango, tomato, beans, olives}\}$.

3. Water claims

The Agricultural Census provides the area by water source and district. The water claims by water source result from the area by water source times the average water requirement. It is assumed that export crops are irrigated only with groundwater and domestic crops are irrigated only with surface water.

4. Infiltration

The National Water Authority assesses the recharge of the Ica aquifer. The rate of recharge in Ica aquifer is 38% (ANA, 2017) . The districts are the agents (i). ρ denotes the rate of infiltration of surface water at each location. As long as the river flows, agents extract surface water for irrigation. Therefore, the extraction and the recharge reduce surface water availability for downstream agents. We assume the recharge parameter (ρ) is the same at each location and equals to $\rho = 0.0495$.

5. Water loss

Water loss results from the difference between the endowment minus water allocation (S, G).

Table A2.2: Water loss (MCM)

River flow	$\rho = 0.0495$		$\rho = 0.060$	
	Rule P	**Pule U**	**Rule P**	**Rule U**
Low	51.0	0	39.3	0
Medium	104.1	32.9	88.0	17.0
High	152.8	94.5	124.9	69.2

Table A2.3: Variables and data sources

Variables	Time period	Spatial extension	Source
River flow	1960 - 2012	Ica river	SENAMHI. Monthly river flow by river basins.
Recharge	2017	Ica valley	(ANA, 2017). Estudio hidrogeológico del acuífero de Ica
Water requirements	N. A.	Ica valley	https://repositorio.inia.gob.pe Experts interviewed
Agricultural area by main crops	2022	Department	https://www.gob.pe/institucion/midagri/informes-publicaciones/2730325-compendio-anual-de-produccion-agricola
Agricultural area by water source	2012	Department / province / district	(INEI, 2013). Censo Nacional Agropecuario.

Chapter 3

Cooperative water sharing agreements between highlands and drylands: The Tambo-Santiago-Ica river basin in Peru[3]

[3] This chapter is based on R. Gómez & H.-P. Weikard (2023). Cooperative water-sharing agreements between highlands and drylands: the Tambo-Santiago-Ica river basin in Peru. International *Journal of Water Resources Development 39*(5), 796 – 818.

Abstract

Inefficient water allocations in river basins limit economic benefits and feed conflicts. We study how institutional change triggered by investments and new technologies can improve water-use efficiency and mitigate conflicts. We develop a bargaining framework to analyse the Peruvian Tambo-Santiago-Ica river basin which shows important economic and social inequalities. We model agents' welfare changes when joint investments are implemented that are instrumental in overcoming conflict. While upstream communities are poor and rely on rain fed agriculture and cattle raising, downstream agricultural producers are well-off and produce high value crops. We find that joint investments can increase both regions' payoffs and gains from cooperation can be strengthened by side-payments.

Keywords: Water conflicts, conflict resolution, bargaining over water, river basin management, Peru.

3.1. Introduction

This chapter analyses how water users' welfare levels change when infrastructure investments are designed to foster cooperation. Water sharing remains to be a challenge in the 21st century despite efforts to resolve conflicts. Growing population and economic development leading to increasing water demand are drivers of water conflicts. Moreover, climate variability threatens water supply (Dinar, 2015; Rahman et al., 2019. Therefore, water infrastructure investments are growing to satisfy water demand. Infrastructure investments have different impacts according to regions' economic, social, ecological and institutional characteristics. They can affect the hydrological system, increase a river basin's vulnerability to climate change and lead to conflicts (Dinar, 2009; De Stefano et al., 2017; Qin et al., 2019). Conflicts are common in transboundary river basins. There are 310 international river basins, according to the updated Transboundary Freshwater Dispute Database, home to 52% of world´s population (McCracken & Wolf, 2019).

The main regions affected by water conflicts are Western Asia, Southern Asia and Sub-Saharan Africa. Latin America region ranked fourth, standing for 14% of the global water conflicts in 2023. (Pacific Institute, 2024).

However, the flipside is that conflicts provide an opportunity for cooperation based on benefits and cost sharing arrangements (Ansink & Houba, 2015; Petersen-Perlman et al., 2017; Li et al., 2019; Grünwald et al., 2020;). Effective cooperation requires strong and reliable institutions to support the fulfilment of the agreement (Parrachino et al., 2006; Houba et al., 2013; Ansink et al., 2017). Institutions can support economic improvements as well as agents' equitable access to benefits by reducing transaction costs and providing information to minimise uncertainty (Jaeger, 2015; Arjoon et al., 2016) .

Unsolved water sharing problems affect agents' welfare from a perspective of efficiency and equity (Arjoon et al., 2016; Hu et al., 2016; Qin et al., 2019). Many sharing problems include externalities as a source of conflict. Policies addressing only economic efficiency may not curb conflict, while addressing distribution and bargaining power can improve equity (Hu et al., 2016; Mehrparvar et al., 2016; Qin et al., 2020).

Cooperative game theory has provided a framework for facilitating agents' change of behaviour from conflict to cooperation (Dinar et al., 1992; Dinar & Wolf, 1997; Ambec & Ehlers, 2008; Houba et al., 2013; Mianabadi et al., 2014; Ansink & Houba, 2015; Arjoon et al., 2016; Qin et al., 2019). Different solutions, such as bankruptcy rules, Nash Bargaining Solution (NBS) or the Kalai-Smorodinsky solution (KS) have been applied to water sharing problems. Among those, NBS is most frequently used. It defines a way to uniquely divide the gains from cooperation and can explain water allocation in transboundary river basins with unequal bargaining power due to economic, social or political differences (Houba et al., 2013; Qin et al., 2019). Houba et al., (2013) describe the relationship between institutional strength and welfare applying NBS to the Mekong river basin. They compare the welfare effects of strengthening the governance of the Mekong River Commission, which includes only the lower basin countries, with the joint management of the entire river basin, including China. They conclude that Lower Mekong Basin countries can increase their welfare by strengthening the Mekong River Commission because strong governance increases water use efficiency.

While the NBS is useful and widely applied, it may be less convincing when new opportunities become available. For instance, under NBS, when gains from cooperation appear sequentially an agent may get worse off after an increase of the potential benefits, i.e. after an enlargement of the bargaining set. We suggest therefore to consider Kalai-Smorodinsky solution (KS) and compare the benefits derived from improved opportunities under each solution. While our case study is an example where both agents would become better off when new opportunities for welfare arise, still NBS and KS differ. Given the asymmetries in the river basin, we introduce side-payments to facilitate stability and equity of the agreement. Side-payments are a tool for transferring gains from cooperation from one agent to the other.

Efficiency and equity are needed for solving the water sharing problem. While equity, fairness and distributive justice have their particular definitions, we do not consider them as distinct for the purpose of this paper. Ansink & Houba (2015) argue that equity provides stability to an agreement, while Gauthier (1978) and Weikard (1994) discuss how fairness relates to mutual advantage for the agents

involved. Roemer (1986) points out that bargaining theory considers the utilities of the agents after a threat point is defined, while distributive justice is concerned more fundamentally with rights, needs and preferences. Water sharing agreements need to consider equity, mainly when the context and social and economic differences among the agents are relevant in order to provide stability to the agreement (Dinar & Wolf, 1997; Kalai, 2008; Atwi & Chóliz, 2011; Arjoon et al., 2016).

This chapter focuses on the interactions between agents that are located in highlands (upstream) and drylands (downstream). Water allocation between highlands and drylands has gained importance since increasing demand by multiple water users lead to increasing externalities and conflicts. The construction of dams for hydropower or irrigation systems in the highlands have changed access to water. The highlands are also an important source of recharge for downstream aquifers. For example, in North West China, the water run-off from highland rivers accounts for up to 80% of the total groundwater recharge (Food and Agriculture Organization [FAO] et al., 2011). Dryland ecosystems cover 41% of the world's terrestrial surface and 44% of cultivated systems. Increasing water demand in drylands has been facilitated by infrastructure investments such as dams and boreholes to increase water supply (Jackson et al., 2001; Safriel et al., 2005; Boelee et al., 2013). Furthermore, highlands and drylands not only interact as ecosystems but are also vulnerable to climate change and pressures from increasing population and economic development (Bates et al., 2008; FAO et al., 2011; Magrin et al., 2014; Davies et al., 2016).

The objective of this chapter is to analyse how joint infrastructure investments can improve cooperation, water-efficiency and welfare. For this purpose, the case study highlights elements such as water and technological constraints in each region and the water institutional changes that facilitate joint investments, strengthening cooperation[4].

[4] The case analyses a bi-regional water conflict and a proposed solution, involving a new institution to facilitate bi-regional investments. However, changes in regional authorities limited the implementation of this solution. Consequently, the calibration of the benefits associated with

Building on previous theoretical work that uses bargaining models to solve river sharing problems (Atwi & Chóliz, 2011; Houba et al., 2013; Qin et al., 2019), we explain the bargaining situation by historical, hydrological, institutional and economic facts which are observed in the case study. We amend the standard model to analyse bargaining over water, tailoring it to include the specific hydrological characteristics of this case study and highlighting the importance of the water institutional framework to reach a cooperative situation. Our case study illustrates how investments increase the welfare of both agents. Our case is the Tambo-Santiago-Ica river basin in Peru with the highlands of Huancavelica department and the drylands of Ica department. In our particular setting the highland- dryland interaction is characterised by rain-fed small-scale agricultural production with cattle raising upstream and export oriented high-value agricultural production downstream using irrigation to support higher productivity. This situation defines particular features of the bargaining situation. Coordinated infrastructure investments which benefit both regions fosters cooperation through increased water access year-round for upstream producers and improved aquifer recharge for downstream irrigated agriculture.

Our case study motivates the development of a more general framework. At the same time, it serves as a 'proof of concept'. On the theory side, we build new features into a cooperative bargaining game, relevant for regions where technological constraints, water constraints and water conflicts are common. The case highlights the need for an adequate institutional water framework to promote coordinated investments.

The chapter is organized in six sections. The next section presents a literature review. Section 3.3 explains the materials and methods used to develop the case study. Section 3.4 explains the main economic, social and institutional characteristics of the case study area. Section

potential joint investment relies on value transfers for technical coefficients of fiber alpaca yields with irrigated pastures, from a neighbouring department, where communities have characteristics comparable to those of Huancavelica and are similarly engaged in alpaca herding.

3.5 develops a bargaining model which is applied to the case study. Section 3.6 discusses the results and concludes.

3.2. Conflicts, cooperation and bargaining

Water conflicts are likely to continue in the future because of increasing water demand (Kaufman et al., 1997). The water sharing problem is multidisciplinary, including geographical, hydrological, socioeconomic and institutional factors. Here we focus on the latter two and do so from a game-theoretic angle in order to structure the strategic interaction between agents.

The remainder of this section considers three phases of conflict resolution: conflict, negotiation and bargaining.

3.2.1. Conflicts

Conflicts over water arise when agents seek control over water disregarding the following factors: (i) the degree of scarcity or misallocation of water among users; (ii) the interdependence of regions regarding common water resources and particularly an upstream-downstream relationship; (iii) the historical context of water ownership between regions; (iv) whether a protracted conflict underlies the water dispute; (v) the existence of

alternative sources of water or options for a negotiated agreement; and (vi) the relative power of the parties (Wolf, 1998; Dinar et al., 2013; Petersen-Perlman et al., 2017). Water is a resource with particular features such as: (i) public and private goods characteristics; (ii) being a flow; (iii) being variable in space and time; and (iv) its importance for production and consumption (Ansink & Houba, 2015).

Recent contributions introduce agents' location to analyse water conflicts and negative externalities (Just & Netanyahu, 1998, 2000; Ambec & Sprumont, 2002; Ambec & Ehlers, 2008; Ansink & Houba, 2015). Therefore, identifying the conflict requires to understand the geographical and historical relationships between upstream and downstream in a river basin (De Stefano et al., 2017). Unilateral decisions without considering previous interactions may generate negative externalities and inequity conditions in the river basin but

are often adopted to impose threats and seek advantage in later negotiations (Dinar & Wolf, 1997; Wolf, 1998; Dinar et al., 2013; Mehrparvar et al., 2016; De Stefano et al., 2017).

3.2.2. Negotiation

Conflicts and cooperation have different time patterns. Conflicts may emerge at any time while establishing cooperation requires a negotiation process. The negotiation process is driven by internal and external factors. The internal factors refer to agents' preferences that reflect agents' interests, alternatives to negotiate an agreement and approaches to manage the conflict. The external factors comprise economic, political, geographical and environmental interdependences.

In a negotiation process third parties' participation can facilitate conflict resolution (Kimbrough et al., 2020) or get in its way (Ansink & Weikard, 2009).

A negotiation process entails transaction costs related to time and resources allocated to gathering information, monitoring and enforcement (De Bruyne & Fischhendler, 2013; Ansink & Houba, 2015). However, the process engages the agents to develop an understanding of their interdependencies and of each other's preferences through interactions. Negotiations prepare the ground for cooperation which, in turn, can generate further benefits. We approach the distribution of these benefits as a cooperative bargaining game.

3.2.3. Bargaining

Reaping the gains from cooperation may not be easy as the distribution of the gains can become a new source of conflict. Ansink et al. (2017) find that strong free-rider incentives may block cooperation leaving potential gains unexploited when there are more than three agents. However, coordinated investments can incentivise cooperation, facilitating efficient and equitable solutions for water allocation problems (Dinar, 2001). Nash (1950) frames the bargaining problem as an opportunity for collaboration between agents for mutual benefit. Bargaining models analyse the water sharing problem using different solutions. For instance, Ansink & Weikard (2012) introduce sequential sharing rules for water allocation when agents are ordered from

upstream to downstream and have resource endowments and claims to water. They point out that agents' positions and endowments are critical for the solution. In a similar framework Mianabadi et al. (2014) suggest a rule to distribute water deficits. Mehrparvar et al. (2016) consider benefits reallocation among water users to enhance cooperation and apply different solution concepts.

The Nash Bargaining Solution (NBS) has been widely applied to analyse water sharing problems. It suggests to share benefits such that the product of the individual gains is maximised. Despite its wide-spread use, it may not seem to be convincing in some circumstances where gains from cooperation become available sequentially. NBS violates a monotonicity property that requires that no agent gets worse-off when the bargaining set, i.e. the set of feasible options, increases. NBS leads to different outcomes when we compare the immediate distribution of a prize X with the sequential distribution of X_1 and X_2 with $X_1 + X_2 = X$, i.e. when the prize becomes available in two steps. Intuitively, we require a bargaining solution that is consistent in the sense that it would not depend on whether or not the prize is paid in instalments. To meet such requirement Kalai & Smorodinsky (1975) suggest an alternative to NBS that satisfies the monotonicity condition as long as the agents' aspiration levels (i.e. what an agent can maximally expect to get) remain constant. The Kalai-Smorodinski solution (KS) suggests to share the benefits of cooperation proportional to aspiration levels. The monotonicity property can be interpreted as a minimum equity condition.

Atwi & Chóliz (2011) consider a two-player game for the Jordan river basin and estimate that cooperation increases welfare by 20% compared to the *status quo.* They apply NBS and KS solution and include the option of side-payments, i.e. monetary transfers between the agents, which further improves efficiency but also affects the distribution of the cooperative gains.

Infrastructure development enhances benefits, facilitates sharing and may contribute to equitable solutions. For instance, Li et al. (2019) study how to share water benefits associated to future water infrastructure (reservoirs, dams), among five stakeholders (China, Laos, Vietnam, Thailand and Cambodia) in the Lancang-Mekong basin. The authors conclude that future damming plans will enhance

cooperation in the river basin and additional benefits would be particularly high in the dry season. Cooperation requires compensation for China and Laos to operate their reservoirs to benefit downstream agents, reallocating the incremental benefits from cooperation in the river basin. Moreover, infrastructure investments such as dams or irrigation systems designed to increase economic benefits can enhance cooperation, mainly through issue linkage. Dinar (2001) analyses a problem of optimal size of a joint facility combined with benefit and cost sharing using NBS. In summary, infrastructure investments can be instrumental for enhancing cooperation.

The literature on water sharing highlights the importance of equity in the water allocation solution (Atwi & Chóliz, 2011; Ansink & Houba, 2015; Arjoon et al., 2016), however there are concerns about how it is conceptualized. It is agreed that an equitable or fair allocation does not refer to equal allocation. Equitable water allocation is more related to the right to access shared water considering needs. To assess equity, stakeholder participation seems crucial for addressing local river basin conditions (Arjoon et al., 2016; Qin et al., 2020). From a conceptual perspective, however, distributional properties of the benefits derived from water use offer relevant assessment criteria (Ansink & Weikard, 2015). Equitable water sharing is relevant in order to assure stability of the water allocation agreed among water users.

In summary, bargaining games have provided solutions to water sharing problems, offering a perspective on how to overcome conflict and foster to cooperation. In this context, we analyse how joint investments create opportunities for cooperation to the benefit of the agents in a river basin.

3.3. Materials and method

The objective of this chapter is to analyse how joint investments can improve cooperation, water-efficiency and welfare in the Tambo-Santiago-Ica river basin located in Peru. For this purpose, a case study was used to highlight institutional changes in the river basin that have facilitated cooperation as well as water and technological constraints. Secondary data and technical reports were used to document our case. The main sources of information were reports by the Ministry of

Agricultural Development and Irrigation [MIDAGRI], the National Water Authority [ANA], and the National Institute of Statistics and Informatics [INEI] (Appendix Table A.3.1).

The Tambo-Santiago-Ica river basin illustrates a water conflict where many stakeholders are involved (MINAM, 2020) displaying extreme socio-economic asymmetries. Therefore, for a deeper understanding of the problem, we complement the secondary information with expert interviews. The interviewees were representatives of both public and private sector. Interviewees selection was based on a set of criteria. At least one of the following criteria was required to be met: (i) involved in the negotiation process; scientific or practical experience on (ii) water management, (iii) asparagus production, (iv) alpaca raising and pasture productivity, (v) ecosystem development in the river basin. The list of interviewees is reported in Table A.3.2 in the Appendix.

To analyse how infrastructure can enhance cooperation and welfare, Nash Bargaining Solution and Kalai Smorodinsky solution are applied. It is assumed that each region produces only one product, which is alpaca fiber by communities upstream and asparagus by producers downstream. We calibrate production functions depending on water use for alpaca and asparagus producers. For this purpose, data related to prices, production volume, yields, production cost is gathered from secondary sources and complemented by interviewees information (for details see Table A3.2.1 and Table A3.2.2 in the Appendices).

3.4. The Tambo-Santiago-Ica river basin

3.4.1. River basin characteristics

The Tambo-Santiago-Ica river basin is located in the southern part of Peru and covers 7,300 km^2. Its geographic altitude ranges between 300 m and 4,625 m. (MINAM, 2020). Two provinces share the water, which are Huaytara province in Huancavelica department and Ica province in Ica department (Figure 3.1).

This bi-regional river basin comprises highlands and drylands. In the highlands, the hydrological system is characterised by lagoons, Andean wetlands and rivers which provide surface water for upstream and downstream. The Andean wetlands are an important ecosystem as

they contribute to hydrologic regulation services and serve as habitat for different types of vegetation besides being a source of water (The International Union for Conservation of Nature [IUCN], & World Wildlife Fund [WWF], 2006). Farmland is limited in the highlands. In Huancavelica department, 56% of total land available is not suitable for productive use because of steep slopes or deficient soil quality. Further, 24% of the land is suitable for pastures; the remaining is for forestry (16%) and agriculture (4%). Upstream producers face technology and water constraints. Technology constraints are due to a lack of infrastructure to store water and of adequate irrigation systems. As a result, water constraints affect agricultural production and cattle raising during the dry season (Ministerio de Desarrollo Agrario y Riego [MIDAGRI] & Gobierno Regional de Huancavelica [GORE Huancavelica], 2008).



Adapted from MINAM (2020).

Figure 3.1: Tambo-Santiago-Ica river basin map

Downstream, drylands are dominated by desert and some small valleys (Gobierno Regional de Ica [GORE Ica], 2018). The desert has changed to intensive agricultural production over the last two decades. Agricultural producers increased the cultivated area (mainly asparagus). In Ica department, between 2000 and 2018, the asparagus area grew by 3.3% annually from 8,269 ha in 2000 to 14,821 ha in 2018 while yield grew by 2.3% annually (MIDAGRI, 2023). Nowadays, there

is a portfolio of agri-exports such as grapes, avocados and mandarins, among others. There are three water sources for agriculture in the drylands: the Ica river, groundwater and the Choclococha system which is a public infrastructure to transfer water from Huancavelica to Ica during the dry season.

There are significant social and economic differences between the regions. Social differences are related to population size, poverty and access to social services. Downstream generates 94% of the total GDP in the river basin and concentrates 92% of the population (Seminario & Palomino, 2022). Upstream, in Huaytara, the population decreased by 0.9% annually between 1993 and 2019; a reduction from 23319 to 18529 inhabitants. In contrast, in Ica province, the population increased 2.2% annually in same period, from 244,741 to 433,860 inhabitants (INEI, 2019). Regarding poverty, in Huancavelica, 70% of the population is poor while in Ica the rate is 10% (INEI, 2017). Freshwater and energy access are also limited. In Huaytara only 22% of households have access to freshwater by indoor pipes while in Ica it is 69% (See Table A3.4 in the Appendix).

Economic differences are related to the size of the agricultural production units, technology and market participation. Huaytara comprises 29 communities, out of 640 in the department. Communities have historical communal land rights and preserve cultural values. Communities depend on rainfall to rear alpacas and sheep and grow some crops for self-consumption (i.e. potatoes and beans). Alpaca fiber is the main source of income and it is sold without classification to the textile industry. Alpacas are raised in a traditional system, feeding mainly on natural pastures with low productivity (GORE Huancavelica & MINAM, 2018). Lack of water hampers the development of cultivated pastures which, in turn, limits alpacas' weight as well as fiber length and volume (Fernandez et al., 2016). Peru is the dominant alpaca fiber producer in the world and Huancavelica represents 2.3% of the national alpaca fiber production. Additionally, well managed pastures also contribute to improve water catchment, infiltration and water recharge, sedimentation control, climatic and hydrologic regulation. However, pastures are sensitive to droughts and irregular rainfall. Currently, the lack of infrastructure investments in small reservoirs and water harvesting systems limit pasture

Ica province comprises 35% of the department's farmland. There are two types of agricultural producers: (i) small-medium producers and (ii) large scale producers mainly agri-exporters. The small-medium producers use surface water. They use "*pozas*", small ponds, to store water during the rainy season for use in the dry season; traditional gravity irrigation systems are used for agricultural production. However, some medium asparagus producers also have borewells to extract groundwater. The agri-exporters cover 88% of the province's development farmland (GORE Huancavelica & MINAM, 2018). They use mainly groundwater for crops (asparagus, grapes, avocado) with hi-tech irrigation systems. Groundwater has sustained agricultural area growth. From the total irrigated area, groundwater irrigated area increased from 27% in 1994 and to 58% in 2012 (Table 3.1) (INEI, 1994, 2012). Irrigation efficiency varies according to farm size, water source and technology. For instance, water efficiency of drip systems is 90% while it is 60% for gravity systems using surface water (Correa-Cano et al., 2022).

Table 3.1: Irrigated area in Ica province by water source

Water source	1994	2012
Only river	38%	14%
Only groundwater (borewells)	27%	58%
River and groundwater	9%	11%
Only lagoons ("pozas")	5%	8%
Other combinations	21%	5%
Others	---	4%

Source: INEI (1994, 2012). Information according to latest available Agricultural Census.

Water deficit is a critical issue in Ica. The Ica river has two seasons: rainy and dry. The rainy season lasts from January to March where 90% of the total annual precipitation falls. The heavy rains are in February and March (GORE Ica, 2018). The dry season spans from April to December and accounts for the remaining 10% of rainfall (Instituto Nacional de Recursos Naturales [INRENA], 2003).

Growing asparagus production, as well as other agri-export crops (e.g. grapes) have increased groundwater extraction, threatening Ica's aquifer sustainability and agricultural production. Since 1970, technical reports have pointed to the aquifer's overexploitation. To reduce aquifer overexploitation, a ban on new boreholes was

introduced to improve groundwater management. Still, due to lack of monitoring, the number of borewells increased.

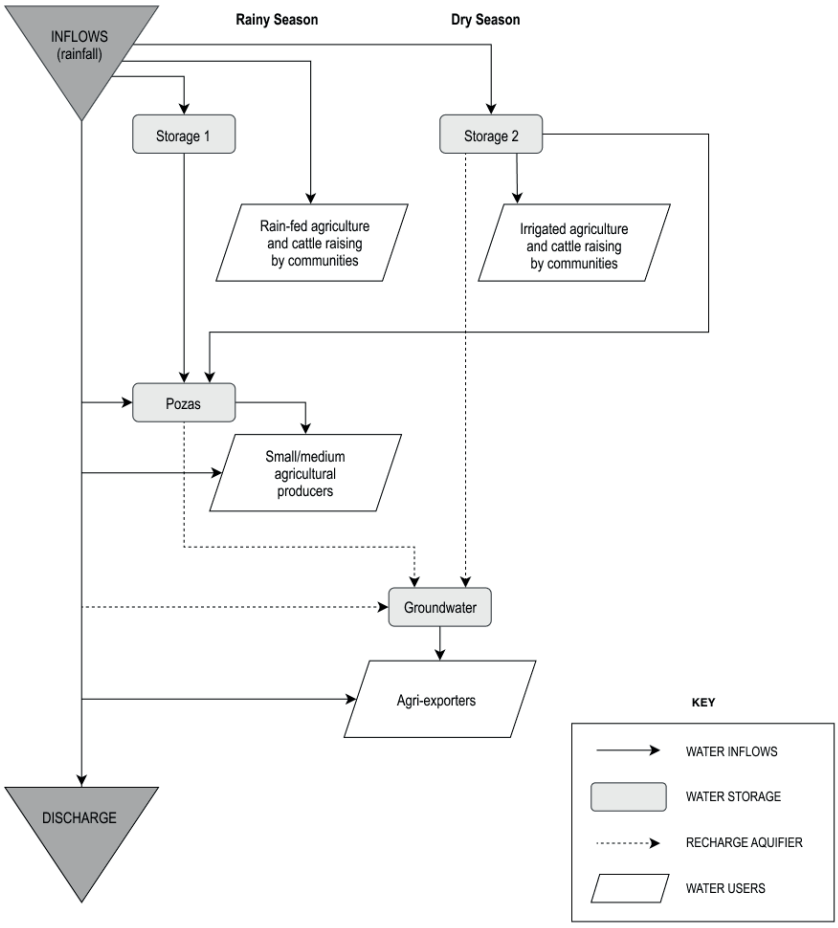


Figure 3.2: Water flows and water users in the Tambo-Santiago-Ica river basin

There is an overexploitation of the aquifer, with an extraction of 232 million of cubic meters (mcm) annually while the annual natural recharge is 179 mcm. The Water National Authority ([ANA] is the Spanish acronym) estimates that the aquifer descends 0.6 m every year. For that reason, the ban on new borewells still remains. The aquifer recharge depends on the water availability coming from rivers Tambo and Santiago in Huancavelica, that feed the Ica river and comprise 57% of the recharge. The other recharge sources are water

conduction loss in the irrigation systems (11%) and return flows from irrigation (32%). The larger part of the aquifer recharge (70%) happens from December to April (ANA & MIDAGRI, 2017); see Figure 3.2 for an overview of the water system.

3.4.2. The water conflict and negotiations

There is a history of tension and conflict between upstream and downstream driven by previous national government interventions and public investment design. Ica's large agricultural producers, economically and politically powerful, were influencing the national government. This economic power is visible since 1945 when the National Government approved the Law No. 10253 (Ley No. 10253, 1945) to transfer water from Huancavelica to Ica. At that time, until the agrarian reform in 1969, the main crop in Ica valley was cotton to supply the national textile industry and for exports. Cotton production was mainly concentrated in large scale production units where latest technology was used.

The public investment did not consider the economic, social and environmental consequences in the river basin, in particular the adverse effects on communities in Huaytara. Public investment refers to the irrigation infrastructure built by the national government (i.e. reservoirs and canals) to provide water only to downstream. The social and economic consequences for communities were (i) income reduction due to lack of water which reduced pastures and alpacas' feed; (ii) increased poverty; (iii) increased conflict between community representatives and national and regional authorities; (iv) division of the Carhuancho Community into two parts, with the families from the lower area being forced to migrate. The environmental consequences were the disappearance of the Parionacocha Lagoon which changed the hydrological system degrading water infiltration and aquifer recharge conditions. Environmental degradation became visible over the long term, specifically the destruction of Andean wetlands and natural pastures, (iv) soil degradation and biodiversity loss due to habitat alteration (Centro Peruano de Estudios Sociales [CEPES], 2009).

Overall, the public infrastructure investment generated negative externalities to the upstream communities. Communities faced irreversible losses in their means of living (water, land, Andean cattle

and alpacas) and income, leading to conflict (Boelens, 2014; Urteaga, 2014; Damonte et al., 2018; Damonte, 2019).

Furthermore, building the infrastructure in the highlands was decided without local and regional stakeholders' participation. In particular, upstream communities were not included in the dialogue nor could they benefit from water transfers. Different studies have argued that the basis of the conflict was uneven bargaining power between the two regions (Oré & Geng, 2014; Damonte, 2019). The history of tension and conflict between Ica and Huancavelica is described in Box 3.1.

Different factors contributed to the enduring conflict, mainly (i) the lack of an institutional water framework to support benefits sharing between different producers in the river basin; (ii) lack of an integrated water management perspective in the river basin; (iii) information asymmetries responsible for a lack of trust between the parties (CEPES, 2009; Zeisser & Gilvono, 2016), see Box 3.1.

3.4.3. Political and institutional water framework

The political and institutional water framework has changed in the course of the water conflict. Water governance changed when the National Water Authority (ANA) was created in 2008 and a new Water Resources Law was approved in 2009 (Ley No. 29338, 2009). The new law establishes not only the integrated water management but also recognizes the communities´ water rights. The previous water law (Decreto Ley No.17752, 1969) had established that water is a State patrimony, i.e. the State defines water access through permits or licenses. Still, because of lack of enforcement, informal water use was common.

According to experts, favourable factors to overcome conflict and exclusion of the communities from dialogue and negotiations were (i) the change in the political and institutional water framework; (ii) that regional governors decided to solve the conflict; (iii) stakeholder participation including regional and local authorities, communities´ authorities and NGOs a new stakeholder providing technical support to communities; and (iv) international cooperation providing resources to enhance technical capacities (see Table A3.2 for the list of interviewed experts in Appendix).

Box 3.1: Ica-Huancavelica: A history of conflict and opportunities for cooperation

Phase 1: Lack of trust

Ica has been an important agricultural production area. In 1945, a public infrastructure was built to transfer water from Huancavelica to Ica. Communities affected did not receive any compensation for the negative impacts despite their property rights to land and water being recognized since 1713.

In 1990, the National Institute for Development (INADE) created the Special Project Tambo-Ccaracocha (PETACC) to rehabilitate the hydraulic infrastructure and to identify new alternatives to transfer water from Huancavelica to Ica. PETACC mainly focused on water transfers to Ica without taking into account the communities' goals, water recharge projects, pastures and Andean wetlands restoration.

In 2003, PETACC´s administration changed from national government (INADE) to Ica´s Regional Government without considering that the Choclococha Lagoon and the 90% of the irrigation infrastructure is located in Huancavelica. The communities and PETACC´s representatives faced violent conflict.

In 2006, the national government declared a water reserve of 52 mcm, only for Ica. For that purpose, the Ingahuasi canal (73 km) would be constructed to collect water from springs and streams to channel them to Choclococha system. The canal would affect hundreds of Andean wetlands. There was neither an environmental impact assessment (EIA) nor communities' participation. The bi-regional conflict worsened.

In 2007, Communities sued the national and regional governments in the Latin American Water Tribunal. The Court resolution established: (i) to stop the Ingahuasi canal Project; (ii) to prepare the EIA and (iii) to establish a compensation system.

In 2014, after attempts to begin a dialogue between the two regions, negotiations ended unsuccessfully and conflict returned with violent events when the communities denied access to PETACC representatives for infrastructure maintenance. Finally, the Ingahuasi canal project was cancelled.

Phase 2: Bi-regional efforts for a joint water management
In 2015, a Dialogue Board was established with the participation of the different stakeholders. The Dialogue and Sustainability National Office which is part of the Prime Minister's Office, participated in the Dialogue Board.
In 2016, new regional governors were elected and dialogue began based on stakeholder participation and regional alignment of agendas. The agreements showed regional authorities´ willingness to keep a power balance. The agreements were the following: (i) joint water management (ii) population including from Santiago and Tambo will have access to water that comes from Choclococha; (iii) further establishment of the Water Council of the Tambo-Santiago-Ica river basin; (iv) constitution of the Biregional Special Ecosystems Committee Choclococha.

Phase 3: Cooperation is feasible
In 2016, a Dialogue Board started negotiations based on five principles: Equity, justice, mutual respect, trust and environmental conservation. The common goals are: (i) to increase water availability and (ii) to share benefits from infrastructure investments. In 2017, a bi-regional institution, called Regional Mancomunity Huancavelica-Ica (MANRHI) was established. A Memorandum of Understanding was signed to promote agriculture development in Ica and Huancavelica based on the construction of two dams and construction of irrigation systems; (iii) a permanent payment from Ica to Huancavelica which will be used for ecosystems conservation and water infrastructure maintenance.

Sources: CEPES (2009); Guerrero & Verziljl (2015); Zeisser & Gilvono (2016); GORE Huancavelica & MINAM (2018); Mancomunidad Regional Huancavelica Ica [MANRHI] (2018).

These factors provided the conditions to create a bi-regional institution with the following objectives: (i) to build, maintain and rehabilitate hydraulic infrastructure to improve agricultural production; (ii) to develop projects for energy generation and ecosystem services conservation to improve integrated water management; (iii) to promote a diversified and competitive interregional production (MANRHI, 2018). Aligned with the objectives the regions agree on infrastructure investments projected to make 100 mcm per year available for use in the Tambo-Santiago-Ica river basin and increase welfare based on efficiency and equity, see Box 3.1.

3.5. Analytical framework

In order to quantitatively assess the gains from cooperation, we develop a bargaining model. Our model is based on Atwi & Chóliz (2011), Houba et al. (2013) and Degefu et al. (2017) but extended to include investments. Different from Houba et al. (2013), who focus on the welfare effects in 2030 from strengthening the Mekong River Commisssion versus the joint management at the river basin; we highlight the role of joint investments to increase profits at a subnational river basin, when the water institutional framework is changed. Joint investments are instrumental in incentivising cooperation. Our model approach explicitly accounts for the role of investments changing the standard bargaining models used to analyse river sharing. Our model is tailored to include the specific hydrological characteristics of case study area and the water institutional framework. A limitation of our assessment of the gains from cooperation is that we take into account gains from specific economic activities (alpaca raising and asparagus production). However, there are other benefits from the joint investments such as aquifer recharge and water cost reduction downstream, as well as additional revenue from crops during the dry season and freshwater availability for the household upstream. Lack of information limits the assessment. In this section, we first explain the main features of the problem and then we calculate the net gains from cooperation and their distribution. The model does not take into account climate change effects on water variability but can be extended to do so.

3.5.1. The basic setting

The agents in the game are two regions, upstream and downstream who have the possibility to cooperate in order to improve water-use efficiency. The results show that cooperation triggered by investments can improve water-use efficiency and create benefits for both regions.

In our bargaining game upstream producers raise cattle (alpacas) and downstream producers cultivate crops (i.e. asparagus) and, for simplicity, water is the only input for both activities. Each activity employs different water-use technologies. Upstream producers use conventional technologies and their economic activities depend on rainfall while downstream producers use the latest irrigation

technologies (i.e. drip irrigation) for agri-export crops. These technological differences are an opportunity for cooperation, however, technological improvements have underlying factors such as financial resources and production practices which are constraining factors upstream.

Before any investment has occurred, each region produces based on its water endowment. Upstream is water-constrained in the dry season lacking the capacity to store water in the rainy season, while downstream is water-constrained by the natural geography. In our case, previous public investments have generated a contentious situation where water is reallocated to downstream at the expense of upstream through a reservoir (Storage 1) and a canal (*grey infrastructure*); see Figure 3.2. This coercive reallocation through initial investments is described in Box 3.1. Previous investments have affected important upstream water sources limiting economic activities indicated by a move from point M to point d in Figure 3.3.

Point d is located on the truncated benefit possibility frontier PF_1 representing downstream's gains when receiving more water (moving from d towards point A), while upstream is constrained by lacking options to transfer water from the rainy to the dry season (the vertical part of PF_1). New opportunities for joint investments allow to exploit technological options facilitated by cooperative planning of infrastructure such as the construction of a big reservoir, canals (grey infrastructure) and *cochas* (green infrastructure), both located upstream, to distribute water between both regions, where upstream is the first user. Joint investments are feasible due to changes in the institutional framework, as described in Box 3.1. Joint investments expand opportunities for production and benefits for both agents as reflected in an outward shift of the frontier from PF_1 to PF_2. Joint investments create a bargaining situation with disagreement point d and a bargaining set S limited by PF_2, see Figure 3.3.

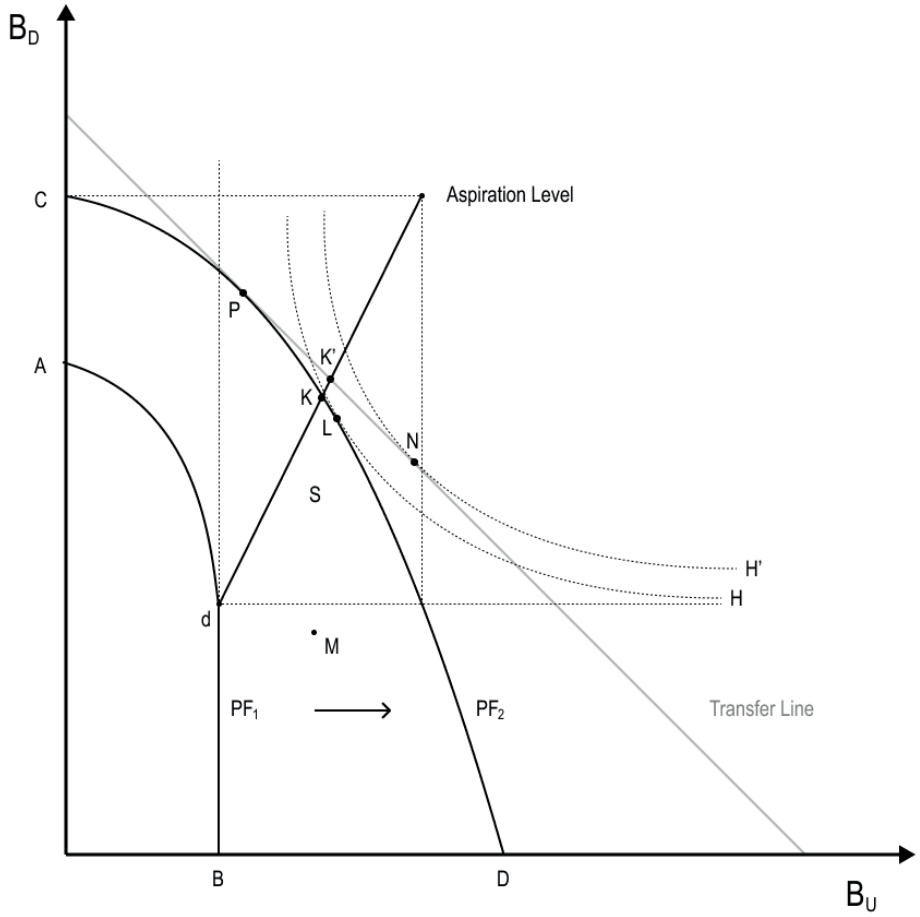


Figure 3.3: Infrastructure investments and side-payments. The initial allocation leads to benefits depicted by point M. Initial investments have shifted water to downstream increasing their benefits at the expense of upstream, illustrated by point d. New joint investments create a bargaining situation with Nash Bargaining Solution at point L where the highest feasible social welfare level H is reached, see the dotted hyperbola. Side-payments (water trade) can further improve benefits and the Nash Bargaining Solution becomes N, located on the social welfare level represented by the H' curve. Point P indicates the efficient water allocation without side-payments. Points K and K' are the Kalai-Smorodinsky solutions for the respective bargaining sets.

In practice, joint investments allow upstream to store water and use it in the dry season. Upstream communities can improve pastures which in turn improve alpaca fiber quantity and quality. Furthermore, upstream communities can receive a compensation for the maintenance of the green water infrastructure serving aquifer recharge for downstream producers who can increase irrigated farmland and production. The literature called this compensation as payment for ecosystem services (PES). The PES is an instrument to transfer benefits among agents for environmental conservation, compensating for the opportunity cost of doing or giving up an activity and can help for conflict resolution (Perevochtchikova et al., 2021; Wang & Nuppenau, 2021).

Such investments were not feasible before the creation of the bi-regional institution, as explained in Box 3.1. The financial resources for the joint investments can have different sources such as national government (Ministry of Economic and Finance, Ministry of Agriculture and Irrigation), regional governments of Ica and Huancavelica, and the multilateral banks, among others.

Side-payments can further improve welfare. Given that downstream's marginal value of water is higher than upstream's, water transfers to downstream combined with a side-payment further improve overall production and benefits in the river basin. Water transfers implement point P reflecting the optimal water allocation.

With side-payments the bargaining set is enlarged and becomes the triangle up and to the right of point d limited by the downward sloping 45° line in Figure 3.3. Points L and N show the NBS without and with side-payments, respectively. NBS with side-payments increases the social welfare level from H to H´. The side-payments can be interpreted as the result of water trade.

Comparing the NBS with and without side-payments, it is notable that increasing the bargaining set through water trade can be to the disadvantage of one party. In Figure 3, N gives less benefits to downstream than point L. For the KS solution both agents always benefit from introducing side-payments, provided aspiration levels remain constant. For our model calibration, presented in the next subsection, we find that side-payments (through water trade) increase benefits for both players under both solutions, NBS and KS.

3.5.2. The Tambo-Santiago-Ica River Basin in Peru

In this section we introduce the numerical calibration of our bargaining model. The game is applied to the river basin Tambo-Santiago-Ica in Peru, where each region's benefits ($B_i, i = U, D$) depend on water use.

Huaytara, located upstream, rears alpacas for fiber production. Ica, located downstream, grows asparagus as the main crop. Joint investments build infrastructure upstream to store water in the rainy season to make it available during the dry season. Therefore, managed pastures are available in the dry season improving alpacas' feed which, in turn, increase alpacas' fiber volume and quality. However, there are limits to improving pastures. Yields are lower at higher altitudes because of soil and climate conditions and steep slopes in the highlands.

On the other hand, downstream can take new farmland into production when water constraints are relaxed. As a result, both regions bargain over water that increases benefits from increasing production.

The calibration of the bargaining game focuses on opportunities from joint investments, the construction of a reservoir to distribute water to regions. We do not include the green infrastructure mentioned in Section 3.2 for lack of information on production impacts. Joint investments establish an irrigation system upstream that contributes to improve pastures and alpacas' fiber production. The downstream region improves aquifer recharge and increases farmland.

After joint investments are undertaken, benefits increase in both regions which is reflected under NBS and KS solutions. Applying NBS, an efficient solution is reached at point L (Figure 3.3), resulting in net gains amounting 1.93 million soles for upstream and 105 million soles for downstream (Table 3.2). Applying KS, the payoffs are 1.87 million soles for upstream and 107.6 for downstream.

Increasing water availability, upstream increases water productivity (intensive margin) because of the introduction of an irrigation system that allows to manage water all year round. It also increases the extensive margin by increasing managed pastures area. Downstream

also increase the intensive margin, improving productivity and extensive margin, thru incorporating new farmland.

The Appendix includes the technical details to calculate the disagreement point, the Nash Bargaining Solution and Kalai-Smorodinsky solution.

Although the NBS and KS solutions show benefits improvements compared to the *status quo*, side-payments can further enhance welfare. Downstream compensates upstream for water transfers to secure water access and avoid conflicts. Side-payments improve efficiency and bargaining facilitates equity.

3.6. Discussion and conclusions

We analyse how joint investment is instrumental to increase mutual benefits of agents. The results show that the Nash Bargaining Solution (NBS) and the Kalai-Smorodinsky solution (KS), annual gains are higher than in the non-cooperative situation. Upstream payoff increases because production is feasible in the dry season, after joint investments. Therefore, alpaca fiber quantity increases as well as quality. Downstream payoff increases due to farmland expansion for asparagus production. Thus, joint investments alleviate the water and technological constraints for each agent, enlarging the bargaining set. Side-payments will further increase the gains from cooperation. With side-payments NBS and KS give the same payoff in the overall river basin but distribute the gains differently (Table 3.2).

Table 3.2: Summary of solutions: Nash Bargaining Solution and Kalai-Smorodinsky

Variables	Nash Bargaining Solution (NBS) (point L)	NBS with side-payments (point N)	Kalai-Smorodinsky solution (KS) (point K)	KS with side-payments (point K´)
Water use (mcm)				
Upstream	14.6	1.74	12.5	1.71
Downstream	85.4	98.26	87.5	98.29
Payoff (net gains)				
Upstream				
Million Soles	*1.93*	2.14	1.87	2.10
Million Dollars	*0.572*	*0.635*	*0.555*	*0.623*
Downstream				
Million Soles	*105*	120.86	107.6	120.9
Million Dollars	*31.16*	*35.86*	*31.93*	*35.88*
River basin				
Million Soles	106.96	123	109.47	123
Million Dollars	*31.73*	*36.50*	*32.48*	*36.5*

Exchange rate: US$1=3.37 soles

Source: Calibration details are provided in the Appendix.

The case illustrates how the previous infrastructure affected negatively upstream welfare, as it is explained in section 3.3. As a consequence, upstream was worse off and a conflict was created. Different from other studies, our study points out the role of investments facilitating welfare gains for both agents. The case shows how changes in the water institutional framework allow joint investments in the river basin. Joint investments store more water during the rainy season for mutual benefits of both regions. Moreover, for the first time, upstream communities can access water during the dry season, improving water distribution in the river basin and welfare. The interregional investments were not feasible before the creation of the bi-regional institution for joint water management. PES is an instrument to foster welfare in the river basin while requires to consider institutional, ecological, social and economic factors on its design (Brouwer et al., 2011; Dextre et al., 2022).

The analysis of both solutions (NBS and KS) has particular features when one or both agents have a satiation point, meaning that cannot absorb the total additional water due to, for example, land constraints. This is represented by a truncated bargaining set (see Figure 3.3 and the Appendix). In our case, upstream receives the maximum payoff at less than the available water, implying that some water is uncontested. We assume that side-payments will not exceed a level that gives upstream the payoff level associated with maximum productive water use (Table 3.2).

The case also suggests that water markets can increase agents´ payoffs. For instance, assuming upstream has the market power to sell water at a price 2.13 soles/m^3 and has all rights to uncontested water. Then the payoffs are 79.8 million soles, 133.1 million soles for upstream and downstream, respectively. On the other hand, if the agents first bargain and implement the NBS water distribution, without side-payments, upstream gets 14.6 mcm and downstream 85.4 mcm (see Table 3.2). Trading water, they could earn 31.1 million soles and 181.9 million soles, respectively. Thus, water markets increase agents´ payoffs.

The bargaining situation is feasible due to changes in the water institutional framework that allows a regional water management. Two solutions are applied to assess the bargaining situation. Both solutions show that the distribution of gains, strengthen cooperation. The water sharing problem underlies the trade-off between efficiency and equity. Equity stands for a fair allocation where each agent has the right to a reasonable part in the use of the water shared (Atwi & Chóliz, 2011). The literature points out that both solutions approximates equity. The Kalai-Smorodinsky solution uses the ratio of the aspiration levels of the agents and Nash Bargaining Solution focuses on sharing the net gains such that the highest level of social welfare is achieved (Bertsimas et al., 2012). According to the literature (Arjoon et al., 2016; Qin et al., 2020), both solutions, to some extent, include the equity or fairness objective.

The case study shows the relationship between agents with asymmetries, that can change from conflict to cooperation, through investments to improve water efficient allocation, increase profits and welfare. Five lessons can be learned: First, an adequate water institutional framework is necessary to support joint investments and

agreement compliance. A water institutional framework that promotes stakeholders' participation, water-use efficiency and compensation mechanisms provides conditions to foster cooperation in a river basin. The lack of an adequate regulatory framework limits the use of instruments, such as side-payments, that help to improve equity. Second, to solve a water sharing problem requires to choose a solution that better captures the economic and social conditions of the river basin. The case study shows how both solutions (NBS and KS) generate gains from cooperation. Third, water satiation gives a particular interpretation of the KS solution because the agent will not have claims to uncontested water. Fourth, water markets development is feasible given increasing water needs in the river basin. Competitive water markets contribute to efficient water allocation. Fifth, following previous studies, the equity objective in a water sharing problem is relevant to support a stable agreement (Ansink & Houba, 2015; Arjoon et al., 2016). However, there is a trade-off between efficiency and equity that needs to be assessed (Bertsimas et al., 2012; Qin et al., 2020). In fact, the complexity of a water sharing problem and the characteristics of the agents involved in the bargaining requires active agent participation to agree on a rule to distribute the benefits and ensure equity in the water sharing solution.

The current analysis is static, however, further analysis can be dynamic, considering changes in the disagreement point. It means, considering the latest solution as a disagreement situation when a new investment is implemented. Additionally, future research can also be oriented to include climate change effects (i.e. rainfall reduction, increasing droughts). Uncertainty of water availability raise the question to what extent joint investments would help to improve water access also in the long run. Moveover, the model could consider short-term dynamics between the wet and dry season explicitly as in Houba et al. (2013). However, as we are interested in the analysis of long-term agreements this seems less appropriate for our purpose. Another research topic is the role of green infrastructure development such as artificial ponds/lagoons (*cochas*) as a complementary investment that would increase water availability and improve downstream aquifer recharge and further shift the bargaining frontier.

Appendices

Table A3.1: Data sources

Data source	Variables/parameters	Units	Span
Ministry of Agricultural Development and Irrigation	Alpaca fiber volume	TM TM	2014-2018
	Asparagus production volume	Hectares	2014-2018
	Asparagus production area	Soles/kg	2014-2018
	Asparagus price		2014-2018
Water National Authority	Aquifer natural recharge	MCM MCM	2017
	Aquifer extraction	soles/cubic	2017
	Surface water tariff in Huancavelica	meter. soles/cubic	2018
	Surface water tariff in Ica	meter.	2018
	Water delivered by Choclococha system	MCM	
Consortium for Sustainable Development of the Andean Ecoregion (CONDESAN)	Water use for managed pastures	m^3/ha	2018
Experts opinion (TableA.3.2)	Asparagus average groundwater cost	Soles/m^3	
	Alpaca fiber price	Soles/lb $_m3$	
	Alpaca water requirements	Soles/m^3	
	Water price upstream		

Table A3.2: Interviews with experts

No	Name	Institution	Topic
1	Fernando Cilloniz	Former Ica´s Regional Governor	Bi-regional agreement, MANRHI creation.
2	María Teresa Oré	Professor-researcher at Pontificia Universidad Católica. Expert on Huancavelica-Ica water conflict.	The water conflict evolution.
3	Juan Soto	Regional Office SUNASS (*Regulatory National Agency on Water and Sanitation*), CEO	The water conflict process resolution
4	Beatriz Salazar	CEPES researcher. Expert on the Huancavelica-Ica conflict	The water conflict evolution.
5	José Nieto	Ica´s Asparagus producer	Water use for asparagus Production
6	José Mulanovich	Asparagus producer and agribusiness consultant	Water use for asparagus Production
7	Alfredo Sotil	Junta de Usuarios de Aguas Subterráneas del valle de Ica (Juasvi), (*Association of Water Users of Groundwater in Ica valley*), CEO	Groundwater management
8	Jorge Ganoza	Instituto Nacional de Investigación Agraria (INIA)(*National Institute of Agricultural Research*), CEO Former Water Administrative Authority in Ica (AAA)	Water management in river basin
9	Gastón Pantoja	Autoridad Nacional del Agua [ANA], expert on water resources	Water management in river basin
10	Raul Sayas	Consultant for PRODERN-Huancavelica (*Strategic Development of Natural Resources Program)*	Alpaca management in Huaytará
11	Alberic Hibon	Consultant on Agribusiness and Sustainable Value Chains.	Alpaca management in highlands
12	Andres Casas	Professor-researcher at Universidad Nacional Agraria La Molina.	Asparagus and water in Ica
13	Wilder Trejo	Professor-researcher at Universidad Nacional Agraria La Molina. Consultant for Camélidos and sheeps	Alpacas raising and pastures
14	Alberto Delgado	Regional coordinator for CEPES-Huancavelica Program	Alpacas raising and Pastures
15	Eduardo Arias	Former CEO at the Huancavelica Regional Government	Managed pastures water requirements
16	Rufino Quilla	Alpaca fiber and pastures producer.	Managed pastures water requirements

Table A3.4: Regional characteristics

Component	Upstream (Huaytara-Huancavelica)	Downstream (Ica-Ica)
Geographical characteristics (altitude, climate, water provision)	Huaytara stands for 29% of the department extension. Altitude ranges between 1950 to 4492 m.a.s.l.; 62% of the districts are located over 3000 m.a.s.l. The rainy season is from December to April.	Ica province stands for 37% of the department extension. Altitude ranges between 334 and 833 m.a.s.l.; 86% of the them are below 500 m.a.s.l.
Total population in the province (2019)	18529 inhabitants	433860 inhabitants
% of department	4.6%	46%
% urban in the province	29%	93%
% rural in the province	71%	7%
% agro population	16%	10%
Population density (inhab/km^2)	3.56 in the province, while in the department 22.53.	46.46 in the province, while in the department 37.27.
Province economic activities	Small scale agriculture Cattle raising by communities or individual peasants (alpaca, sheep)	Agriculture Tourism (adventure sports, amenities view) Services
Departmental share of National Gross Value Added	0.7%	3.5%
Province social issues		
Access to services (1)		
% households access to freshwater with infrastructure inside the house	22%. 49% of the households use water from river, small canals.	69%
% households access to sanitation	5%. 78% does not have the service.	54%. 11% does not have the service.
% households with energy	39%	81%
Poverty (2)		
% poor population	70.6%. 41.5% of the poor population are in extreme poverty	10.4%. There is no extreme poverty.

Source: INEI (2009); Instituto Cuanto (2016).
Own elaboration

Appendix A3.2: Model and calibration

1. Data

Table A3.2.1: Upstream data

	Units		Without joint investments	With joint investments
Price of alpaca fiber	Soles/lb	(3)	8	10
Water fee	Soles/m^3	(2)	0.0011	0.0011
Yield	lb/alpaca	(3)	8	10
Revenue	Soles/lb		8	10
	Soles/ha		64	5,000 – 100 (b)
	Soles/m^3		0.016	0.5-0.01
Cost	Soles/lb Soles/ha		7.1 (a)	6.57 - 7.65
Production cost	Soles/m^3		56.8	3,285 – 76.5
			0.014	0.33 – 0.008
Rangelands/pasture	Ha		6,241	6,241
Carrying capacity	alpacas/ha	(3)	1	50 – 1
Water withdrawal	m^3/ha	(3)	4,000	10,000
Average annual production 2014-2018	lb	(1)	49,930	
Profit	Soles/lb		0.9	3.43 - 2.35
	Soles/ha			1715 – 23.55
Profit gain	Soles/m^3			
	Soles		7.2	0.286 – 0.0039
Disagreement Payoff	Soles		44,937	2.14 million – 0

Source: (1) MIDAGRI. (2): ANA. (3) Expert interviews and technical reports.
Notes: (a) Production cost excluding water is 6.55 soles/lb. Water cost is 0.55 soles/lb. (b) Range of revenues on the most and least productive land, similarly for carrying capacity, cost and profit. The value depends on the amount of water obtained.

Table A3.2.2: Downstream data

	Units		Without joint investments	With joint Investments
Price of asparagus	Soles/kg	(1)	4.75	4.75
Yield	kg/ha	(1)	12,337	12,337
Water withdrawal	m^3 /ha	(3)	12,000	12,000
Revenue	Soles/kg		4.75	4.75
	Soles/ha		58,601	58,601
	Soles/m^3		4.88	4.88
Cost				
Production cost	Soles/kg	(3)	3.0 (a)	3.0 (a)
	Soles/ha		37,011	37,011
Indirect cost	Soles/kg	(3)	0.55	0.55
	Soles/ha		6,785 (b)	6,785 (b)
Total production cost	Soles/kg		3.55	3.55
	Soles/ha		43,796	43,796
Water cost	Soles/m^3	(2,3)	0.62 (c)	0.62(c)
Irrigated land	ha	(1)	11,680	16,897- 20,013
Farmland gain				5,213 – 8,333 (d)
Profit	Soles/kg		1.2	1.2
	Soles/ha			14,805
Profit gain	Soles/m^3			1.23
	Soles		14,805	77 million-123 million
Disagreement payoff	Soles		172,922,400	

Source: (1) MIDAGRI. (2) ANA. (3) Expert interviews and technical reports.
Notes: (a) Includes water cost
(b) Indirect cost includes certification cost (Global G.A.P.), gasoline and maintenance cost for administrative vehicle, office services (telephone, energy, water).
(c) Water costs consistof: bombing cost, water fee per m3, water price. The bombing cost and water fee is 0.34 soles/m3. The water fee is set by the National Water Authority. Producers rent land buy water. The latter is called a water bombing service. They pay 50 soles/hour which brings 50 lts/seg. This gives 0.28 soles/m3.
(d) Joint investments can increase irrigated land by 5,213 ha if upstream keeps 37.45 mcm (i.e. 62.55 mcm are uncontested water) or 8333 ha if all additional water goes to downstream.

2. Parameters estimation

Table A.3.2.3: List of index, variables and parameters

Index/Variables/Parameters		Definition
Index		
	i	U= Upstream; D= Downstream
Variables		
	w_i	Water withdrawal by region i
	B_i	Payoffs/benefits of region i
	d_i	Disagreement payoff of region i
Parameters		
	α_i	Technology parameter
	β_U	Elasticity of production upstream
	γ_i	Marginal benefit per m^3 in region i
	p_i	Price of each product in region i

Upstream:

At the disagreement point (before joint investments) total benefits for upstream are

d_U = 44937 (Soles).

Additional water that becomes available through joint investment increases pasture productivity. We assume that a high stocking rate of 50 alpaca/ha can be implemented on the 10 percent most fertile land while on the marginal land stocking rate remains at 1 alpaca/ha. We calibrate the benefit function of the upstream region depending on additional water use as a piecewise defined function

$$B_U = \begin{cases} \gamma_U * w_U \quad \text{if } w_U < 624 * 6000 \\ \alpha_U w_U^{\beta_U} + \delta_U \text{ if } 624 * 6000 \leq w_U \leq 6241 * 6000 \end{cases}$$

Using the marginal benefit function $B'_U = \beta_U \alpha_U w_U^{\beta_U - 1}$ and the fact that marginal benefits at $624 \cdot 6000\text{m}^3$ and at $6241 \cdot 6000\text{m}^3$ are 0.286

and 0.0039, respectively we find

$\gamma_U = \frac{1715}{6000} = 0.286$

α_U = -5.78 × 10^{11}

β_U = -0.863

δ_U = 2.31 × 10^6

With this calibration we obtain additional benefits of 1.07 × 10^6 soles when the 10% most fertile lands are intensively managed and benefits of 2.14 × 10^6 if the entire rangeland is intensified.

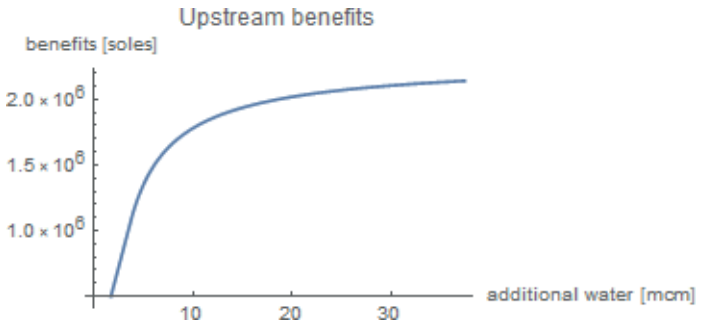


Figure A3.1

Downstream:

The disagreement payoff of downstream is 172,922,400 soles. With joint investments downstream can cultivate an additional ha of land for each 12,000 m^3 of additional water received. The benefit function is, thus, linear.

$B_D = \gamma_D \, w_D$

γ_D = 1.23

The maximum benefit downstream can obtain when receiving all the water (100 mcm) is:

$B_D(w_D = 100 \times 10^6) = 123 \times 10^6$ soles.

We normalise the bargaining game by focusing on the gains that can be obtained beyond the disagreement point. In other words, we normalise the disagreement point to be d = (0,0), see also Figure A3.2.

The frontier of the bargaining set is defined piecewise in the benefits space (see Figure A3.2). Up to a level of upstream benefits of 1.07 million soles (when upstream uses 3,74 mcm of additional water) the frontier is a straight downward sloping line with slope $\frac{1.23}{0.28} = -4.3$. Using data from Tables A3.2.1 and A3.2.2. numbered (1), (2) and (3) in the benefits interval (1.07 million, 2.14 million) the frontier is given by:

$$B_D = \gamma_D \left\{ W - \left(\frac{B_U - \delta}{\alpha_U} \right)^{\left(1/\beta_U\right)} \right\}$$

Where

$$W = 100 \text{ mcm}$$

Beyond upstream benefits of 2.14 million soles (when upstream is water-satiated at 37.45 mcm) the frontier becomes vertical.

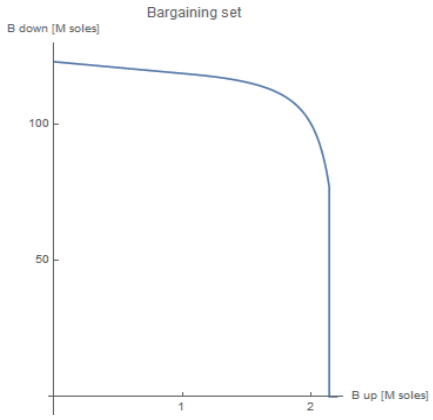


Figure A3.2

3. The bargaining solutions

3.1.1. Solutions without side payments

The NBS is achieved by maximizing an objective function that depends on each regions´ benefits and the disagreement point (d_i).

$$Max\ F = (B_U - d_U)(B_D - d_D) : (B_U, B_D) \in S\ and\ d = (0,0) \qquad \text{(A3.1)}$$

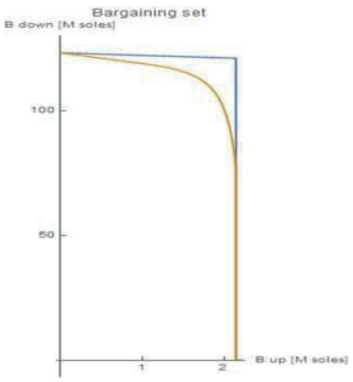
$$w_U^{NBS} = 14.6 \text{ mcm}$$
$$w_D^{NBS} = 85.4 \text{ mcm}$$
$$B_U^{NBS} = 1{,}93 \text{ million soles}$$
$$B_D^{NBS} = 105 \text{ million soles}$$

$$w_U^{KS} = 12.5 \text{ mcm}$$
$$w_D^{KS} = 87.5 \text{ mcm}$$
$$B_U^{KS} = 1{,}87 \text{ million soles}$$
$$B_D^{KS} = 107.6 \text{ million soles}$$

3.2. Solutions with side payments

If downstream gets all additional water, the maximum benefits can be 123 million soles. As indicated previously, upstream become satiated at 37.45 mcm, which generate 2.14 million soles benefit. At the maximum upstream benefit, downstream gets 120.86 million soles (Figure A3.3).

$$B_U^{NBS,SP} = 2.14 \text{ million soles}$$
$$B_D^{NBS,SP} = 120.86 \text{ million soles}$$
$$B_U^{KS,SP} = 2.10 \text{ million soles}$$
$$B_U^{KS,SP} = 120.90 \text{ million soles}$$



Legend
Orange line: Without side payments
Blue line: With side payments

Figure A3.3: Bargaining set

Chapter 4

Oil pollution conflicts, side payments and pacification



Abstract

Environmental damages caused by the oil extracting industry often lead to conflicts between polluters and local communities. We analyse to what extent side payments can mitigate negative externalities and facilitate stable and peaceful outcomes with improved welfare, in particular when weak governance prevails. Side payments are defined as a resource transfer between agents who face economic and social asymmetries, and share scarce resources. The side payments provide incentives to change agents' behaviour under an institutional design. Our work is inspired by observing the conflict between oil firms and indigenous communities in Loreto Department in the northern Peruvian Amazon, where side payments are used as a mechanism for conflict resolution. In this area, oil industry operations have caused oil spills that have polluted rivers and lagoons. As a result, indigenous communities have been losing their resource base, in particular freshwater, soil fertility and biodiversity, and are suffering from health problems. Despite institutional reforms aimed at improving environmental management, conflicts persist due to a limited understanding of the strategic behaviour of firms and communities, as well as weak regulatory enforcement. We analyse a sequential two-agent game involving a firm and a community. Our analysis suggests that including a side payment into agreements changes the stakes of the conflicting parties and offers the potential for peace.

Keywords: Conflict resolution, oil industry, institutions, side payments, water pollution, Peruvian Amazon.

4.1. Introduction

Pollutive industries may threaten the livelihoods of local populations by limiting access to safe drinking water and food resources while also causing health problems. These impacts may lead to conflicts which are often violent (A. Bebbington, 2011; Babatunde, 2020). Our research is motivated specifically by oil pollution conflicts which pose challenges, often in areas of valuable biodiversity such as the Niger, Congo, Mekong, and Amazon river basins. In the Amazon, oil producing countries including Bolivia, Brazil, Colombia, Ecuador, Peru and Venezuela have seen tensions between indigenous communities and oil firms (D. H. Bebbington, 2011; Okamoto & Leifsen, 2012; Pellegrini & Arsel, 2018). We focus on a case study of oil pollution conflict in Loreto, where ongoing experience shows that side payments can be effective to resolve conflict. Loreto is a department in the northern Peruvian Amazon that accounts for 53% of the country's hydrocarbon conflicts, which makes it a relevant case.

Institutions help organizing relationships between agents (North, 1986; Williamson, 1996; Ostrom, 2000). However, weak governance, imply lack of enforcement of law and rules thereby facilitating non-compliance which, in turn, may exacerbate conflicts (North, 1986; Haselip, 2011; Orihuela et al., 2022). While many countries have strengthened environmental and social regulations over time, conflicts often remain unresolved due to a limited understanding of the strategic behaviour of the agents involved. Challenges in conflict resolution are common in regions where non-renewable resources are abundant and extractive industries are pollutive while particularly relevant when institutions are weak (Kimerling, 2006; Holterman, 2014; Babatunde, 2020).

The aim of this chapter is to analyse to what extent side payments can mitigate negative externalities and facilitate stable and peaceful outcomes with improved welfare.

Side payments can facilitate conflict resolution where property rights are poorly defined and unsolved externalities persist. In this chapter, side payments are defined as resource transfers between agents who face economic and social asymmetries, and share scarce resources (Dinar, 2006). A characteristic of side payments is that they are not conditional on producing a good or service, which is a characteristic of

Payments for Ecosystem Services (PES) (Wunder et al., 2008). Side payments provide incentives to change agents' behaviour under an institutional framework. Incentives encourage agents to adjust their behaviour, helping to achieve societal goals such as welfare or equity. Our analysis focuses on side payments implemented under a legal and transparent institutional framework. The literature has analysed different concepts of side payments. In game theory side payments are a device to increase feasible sets of outcomes or implement efficient allocations as equilibria (Ambec & Sprumont, 2002; Ambec & Ehlers, 2008; Dinar & Hogarth, 2015). Environmental economics uses side payments as a mechanism for solving externalities, as part of an institutional framework (Kerr et al., 2014; Wang et al., 2025). Depending on the legal context, side payments can be seen as a bribe, for instance when firms pay bribes to a public official to obtain privileges or tax reductions (Gauthier et al., 2021).

Research on side payments to solve water conflicts has focused mainly on transboundary water sharing problems (Dinar, 2006; Kimbrough & Sheremeta, 2013). However, the role of side payments in local water pollution conflicts has been overlooked, despite their importance particularly in the context of weak governance.

We analyse the strategic behaviour of agents who have a conflict-ridden relationship due to oil pollution. We discuss the incentives that side payments generate to mitigate conflicts. For this purpose, we develop a sequential two-agent game with an oil firm and a local community as agents. We obtain insights into the role of sanctions and compensations which are particularly relevant for policy makers. However, our focus is on understanding the role of side payments agreed upon in a contract and the stability of such contract.

Following a theoretical approach, we develop a model that simplifies the complex reality where economic, social and cultural differences exist between the agents. The scope of the research focuses on side payments and conflict resolution. However, we abstract from decision-making processes within a community.

The chapter is organized in five sections. The literature review presented in the next section defines the place of our work in the research landscape. Section 4.3 explains the conflict between oil firms and communities, zooming in on a case study of Peruvian oil

production in the northern Peruvian Amazon. Section 4.4 offers the set-up of the model to analyse the conflict and its solution. Finally, we present a discussion of our findings and conclusions.

4.2. Conflicts, externalities, side payments and institutions

4.2.1. Externalities and conflicts

The economics of conflict understands conflicts as agents' responses to underlying incentives. Conflicts influence economic outcomes such as production, investment, income and wealth which, in turn, affect conflict in terms of intensity and duration (Anderton & Carter, 2009). In a conflict situation, one agent (e.g., individual, firm or country) inflicts a harm on another, often in response to losses incurred. Factors underlying a conflict generally include disagreements on property rights, problems of costs and benefits sharing, or information asymmetries. Conflicts, if unresolved, lead to resource misallocation, inefficiencies and waste (Ansink & Weikard, 2025). Additionally, it reflects a misunderstanding of the agents' goals and their expected gains, hampering any peace solution (Ahmad, 2023).

There is abundant literature that analyses negative externalities that oil firms impose on local populations (Heinz et al., 2007; A. Bebbington, 2011; D. H. Bebbington, 2011; Okamoto & Leifsen, 2012; Yusta-García et al., 2017). Oil spills pollute water, reducing local communities' access to drinking and irrigation water and to safe food (e.g., fish) (Babatunde, 2020). Additionally, oil spills contribute to both physical and mental health problems. O´Callaghan-Gordo et al. (2021) find high levels of lead in blood of four indigenous communities in the northern Peruvian Amazon near oil extraction sites. Lead exposure affects the brain and nervous system, particularly in children. San Sebastián & Hurtig (2004) find higher rates of skin mycosis, diarrhea, gastritis, red eyes, and cancer in population located closer to the oil production plants compared those located farther away. Moreover, Chong & Srebot (2023) find that people living close to the northern Peruvian pipeline have a higher probability of suffering mental health problems because of oil spills.

4.2.2. Institutions and side payments

An institutional framework provides the rules, norms and instruments to guide agents' behaviour and to align incentives to fulfil contractual obligations (Posner, 1972). A fundamental function of institutions is to provide certainty in interacting agents' expectations. When agents trust the established rules and property rights, they are less likely to engage in opportunistic behaviour or contractual breaches. Conversely, when they do not believe in the rules and norms, uncertainty increases, raising the costs of contracting (North, 1989).

An institutional framework is supported by a governance system. A governance system is able to provide public services and is supported by agent's participation. A strong governance system enhances policy effectiveness, ensures the enforcement of sanctions, and fosters compliance with established rules. In contrast, weak governance lacks consistent policies, public services provision is inadequate, sanctions are not enforced, and agent's participation is limited (Fukuyama, 2016).

In this context, a commitment problem may arise which reflects the agents' incentives to break promises (Cooter & Ulen, 1996; Acemoglu et al., 2005). Commitment problems are exacerbated when there is a history of lack of trust (Bueno de Mesquita, 2016). When promises cannot be enforced, incentives for non-cooperation emerge, while enforceable promises can change a game from conflict to cooperation.

Side payments are useful for solving commitment problems because they align incentives to change agents' behaviour and contribute to conflict resolution, particularly when property rights are not clearly defined, externalities remain and asymmetries between the agents prevail (Dinar, 2006; Kimbrough & Sheremeta, 2013). Side payments can also facilitate cooperation in common pool resource games when the number of competing agents is not too large (Ansink & Weikard, 2020). However, while side payments can support conflict resolution and foster cooperation (Dinar, 2006), they may also be perceived as a bribe (Folmer et al., 1993; Bennett et al., 1998) or may reflect a negotiator's weakness, impacting an agent's reputation negatively (Mäler, 1990).

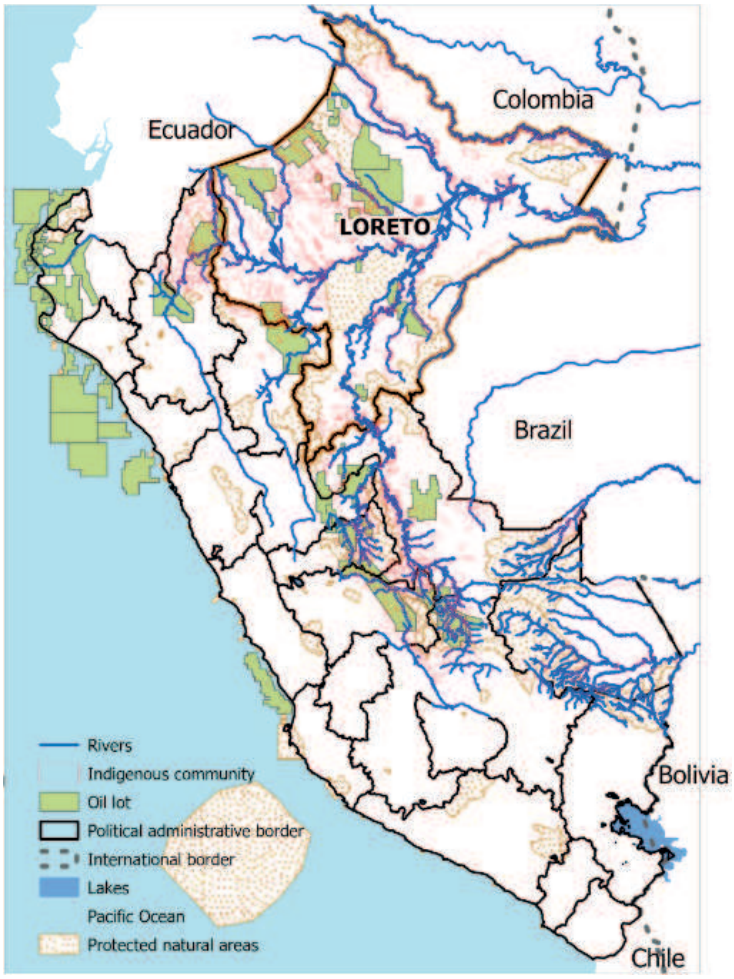
4.3. Oil companies and indigenous communities in Loreto, Peru

In Peru, the number of socio-environmental conflicts increased from 30 to 129 over the years 2006 to 2021 (Defensoría del Pueblo, 2022).

The country has two main oil-producing areas. One is along the northern coast and the other is in the northern rainforest, mainly in Loreto (Figure 4.1). Loreto stands for 27% of the national oil production, and oil contributes 24% to Loreto's GDP. However, oil production in Loreto decreased by 57% between 2010 and 2022 due to conflicts and political instability (INEI, 2021). Still, it holds 41% of the national proven and probable oil reserves (Ministerio de Energía y Minas [MINEM], 2024) .

Loreto department, hosting 55% of Peru's rainforest, is located in the northern Peruvian Amazon. With 32% of its territory covered by wetlands it holds valuable biodiversity (Dourojeanni, 2013). Loreto is home to 64% of national indigenous communities, who live in the extensive rainforest. Indigenous communities' welfare and quality of life rely on the availability of natural resources such as freshwater, fruits, fibers, fish and meat (Montoya, 2010; Ministerio de Salud [MINSA], 2020). Rivers and springs are the main freshwater sources for 73% of the indigenous population (INEI, 2018; MINSA, 2020). Heavy metals related to produced waters and oil spills have affected people's health through respiratory problems, kidney damage, cancer, and mental problems, among others (MINSA, 2020; O´Callaghan-Gordo et al., 2021; Chong & Srebot, 2023) (see Box .4.1).

Agriculture, hunting and fishing are key food sources for indigenous communities. Fish is an important source of protein in Loreto department, with per capita fish consumption (37 kg/capita/year) higher than the average national consumption (17.3 kg/capita/year) (INEI, 2018; MINSA, 2020). Therefore, environmental quality, livelihoods, and community welfare are closely linked to each other and to the sustainability and resilience of the community.



Source: Perupetro (2010); IBC (2023). Own elaboration.

Figure 4.1: Oil lots, indigenous communities and protected areas in Peru

Oil exploration and production in Peru require firms to sign a License Agreement with the State, granting access rights to extract hydrocarbons within designated lots. Loreto holds six lots (192, 8, 64, 67, 39 and 95) (Figure 4.1). Lots 192 and 8 are the oldest ones, and have a five-decade history of oil spills and conflicts (Defensoría del Pueblo, 2018) . Petroperu, the State oil firm, has a License Agreement to operate Lots 192, 8 and 64 with a strategic partner. Lots 39 and 67, located along the Ecuadorian border, in an area designated as PIACI (Indigenous People in Isolation and Initial Contact), have ceased operations due to

conflicts with the Achuar indigenous communities, who strongly oppose oil exploitation in their territory. Meanwhile, PetroTal operates lot 95, where, following a series of conflicts in 2022, the firm implemented a side payment as an alternative conflict-resolution instrument. This side payment is included in the License Agreement which is a contract signed between Perupetro, the State Agency that promotes investments in the hydrocarbon and energy industries, and the firm. The License Agreement has the character of a law. This side payment is managed through a Trust Fund. The side payment amounts to 2.5% of the oil production value which is disbursed monthly to the Trust Fund. The main features of the Trust Fund are the following: (i) the disbursement is conditioned on peaceful behaviour (no attacks); (ii) resources from the fund can be allocated only for social infrastructure (health, education, water and sewage, roads) in favor of the community thus contributing to welfare improvements; (iii) the Trust Fund is managed by a board that includes national, regional and local authorities, as well as firms' and communities' representatives. The Trust Fund is included in the License Agreement.

Oil firms have been a source of seasonal job opportunities for the indigenous population. Some of these activities are to clean pipelines and facilities from green vegetation and to participate in remediation activities in case of oil spills.

During 2000-2019, there were 474 oil spills in the Peruvian Amazon, affecting 41 of the 55 indigenous groups (74%). In Loreto, three sites concentrate 92% of the spills, which are Lot 192 (155 spills), Lot 8 (189 spills) and the National Pipeline managed by Petroperu (94 spills) (León & Zuñiga, 2021). The span between an infraction and the fine imposition can take between two and three years. Additionally, the fines are appealed in more than 70% of the cases which can take years to solve (Organismo de Evaluación y Fiscalización Ambiental [OEFA], 2023). Therefore, the environmental governance system gives little incentives to comply with laws and rules.

Until the 1990s the institutional framework supported a history of conflict in the northern Peruvian Amazon which mainly focused on promoting oil production without including environmental regulations or the protection of indigenous communities' rights. Despite institutional changes since 1993, and the gradual development

of environmental and social regulations, the lack of enforcement limits the achievement of the policy goals of the reforms (Okamoto & Leifsen, 2012) (see Box 4.1).

Reports from regulatory agencies point out that 94% of the spills would be avoided if preventive mechanisms were implemented by the firms. The main causes of the spills were ducts corrosion, operation failures (65%) and sabotage (28%) (León & Zuñiga, 2021). Indigenous communities were affected in different ways. They were forced to leave their place and have suffered from decreasing food provision and health problems (Rada & Farroñay, 2012; Programa de Naciones Unidas para el Desarrollo [PNUD], 2018, 2022). For instance, in lots 192 and 8, of 391 households surveyed, 50% report that their fishing place was affected by oil spills, 41% had their house close to the polluted area and 40% had their hunting area close to the oil spill location (Defensoría del Pueblo, 2018).

New institutions were created to regulate the extractive industry. Moreover, the legal framework has also changed, developing environmental regulations, and signing international agreements such as OIT 169 which recognizes the rights of indigenous people (Ley 29785, 2011). The regulations mainly use command and control instruments that require supervision which is limited. In Peru, the strategy to solve conflicts with communities has been a dialogue process to discuss claims and agree on compensation payments (Damonte et al., 2014). However, such processes can take on average three years or more. In some cases, the agreement among the parties (firm, State and community) is unstable as incentives remain misaligned (see Box 4.1).

4.4. Model setup

We analyse the incentives prevalent in oil conflicts with a focus on the role of side payments to mitigate negative externalities, facilitate conflict resolution, stability, and improve welfare. The model is set in the context of economic, social, and cultural asymmetries between the agents, a history of conflicts and weak institutions.

Box 4.1: Oil industry, communities, and conflicts

Phase 1: A history of conflict

In South America, the first oil well was explored at the Peruvian northern coast in 1863. Oil extraction in the Peruvian Northern rainforest began in 1971. Oil industry has a history of conflict because of insufficient management of social relations with neighbouring communities and unresolved externalities due to the discharge of pollutive effluents and oil spills (MINSA, 2020). Environmental and social regulations for the extractive industries started in 1993.

Before 1993, oil firms were not obliged to give any type of compensation for the negative externalities they had generated. In 1993, the environmental regulations management for hydrocarbon activities began (D.S. 046-93 EM) and were later updated in 2006 and 2014. However, still in 2006, produced waters were dumped directly into rivers. According to the 'Health Condition of the Achuar' Report, 408 million barrels of produced water per year were dumped in the river basins close to lots 8 and 192 with severe environmental and social damages (MINSA, 2007).

Oil spills and produced waters have polluted rivers and lagoons (*cochas*) which are part of a complex and diverse aquatic system in the Amazon. As a result, communities have faced a reduction of their means of living, in particular food, and increased health problems. Heavy metals concentration such as lead in blood exceeds the international standard (5µg/dl). In 2016, a blood lead level study was conducted in the Corrientes River Basin, Pastaza or Tigre. The study included 1047 participants from 4 communities, close to Lot 192 and Lot 8. The results show that 49% of children and 60% of adults have blood lead levels exceeding the international standard. On average, children under 12 year had 8.1 µg/dl and people older than 12 years had 8.8µg/dl. Sources of heavy metals absorption are fish consumption from polluted rivers, participation in remediation activities and drinking of polluted water (O´Callaghan-Gordo et al., 2021) .

The Defensoría del Pueblo Office identifies as main causes of conflicts the following: (i) population is afraid of pollution risks; (ii) population has no trust in State capacity to prevent pollution and land degradation; (iii) population believes that extractive industry is incompatible with agriculture, fishery, cattle raising or tourism activities that are developed by communities; (iv) negative impacts on communities´ natural resources (land, water, forests, biodiversity) which are essential for their living. From 2011-2021, 66% of the socio-environmental conflicts were active and only 8% were settled. Loreto stands for 53% of the total conflicts associated with hydrocarbon activities in the country.

Phase 2: Institutional changes
In 1993, within the Hydrocarbon Law (Ley No. 26221, 1993), PERUPETRO was created as the agency to promote private investment in the extractive industries. The institutional framework provides incentives for private investment. Firms who want to explore and exploit oil, must sign a licence agreement with law status. The license agreement recognizes an area called "lot" for oil exploration and exploitation. The license agreement includes labour, environmental and economic regulations.
New institutions were created to rule and monitor environmental, social, and labour relations, such as Supervision of Energy and Minning Investment Office, OSINERGMIN (founded in 1996); the Ministry of Environment, MINAM (founded in 2008); Environmental Supervision and Inspection Office, OEFA (founded in 2008); Agency of Environmental Certification for Sustainable Investment, SENACE (founded in 2012); Secretariat of Social Management and Dialogue as part of the Prime Minister's Office. However, there is a lack of enforcement which limits the achievement of the goals of policies and regulations.

Phase 3: Dialogue and cooperation opportunities
Since 2010-2011, the main mechanism to solve conflicts has been dialogue. The dialogue process creates a space for the communities to present their claims about damage compensation, land property rights, and social infrastructure such as hospitals, schools, water and sewage, among others. In this negotiation communities and firms reached an agreement with the State as a coordinating party. This task was led by the Prime Minister's Office and the Defensoría del Pueblo *(Ombudsman)*.
The Defensoría del Pueblo's Office assessed 4258 commitments included in 774 acts that correspond to 29 dialogue processes, between 2010-2021. The conclusion was that 54% of the commitments related to social demands were not accomplished. Main reasons are the lack of financial resources, monitoring mechanisms, multisectoral coordination, transparency and accountability.
Additionally, since PetroTal proposed a side payment in the License Agreement, as explained in Section 3, new oil firms can also include a side payment in their contract.

Source: MINSA (2007, 2020); Montoya (2010); León & Zuñiga (2021); O´Callaghan-Gordo et al. (2021); Defensoría del Pueblo (2022).

We study a sequential two-agent game where oil pollution generates conflicts. We call it 'pollution-attack game'. The agents are a firm (F) and a community (C).

We assume perfect information because the relevant characteristics of the agents and their behaviour are readily observable. We examine the game without and with side payments in favor of the community.

Since the goal of this section is conceptual, to spell out how side payments change incentives, we assume, for simplicity, binary action spaces. The firm can engage in environmental effort which is either high or low, $e \in \{\bar{e}, \underline{e}\}$. Environmental effort affects the level of pollution. The community can engage in violent conflict (attack) or abstain from it, $a \in \{\bar{a}, \underline{a}\}$. Attacks affect oil production, for example by strikes or blocking the oil firm's facilities. For ease of exposition, we assume that both choice variables a, e take values 0 or 1; see Table 4.1.

Table 4.1: Notation

Indices	Elements
Agents $i \in \{F, C\}$	F: firm C: community
Strategy sets Firm	$\underline{e} = 0$: no environmental effort $\bar{e} = 1$: environmental effort
Community	$\underline{a} = 0$: no attack $\bar{a} = 1$: attack

The game is played as follows. Without side payment, called the *status quo*, the sequential game begins with the firm's environmental effort decision. The community observes the firm's decision and based on that, decides whether to attack or not in the second stage (Figure 4.2). We consider a pre-play agreement about a side payment. To be effective, the agreement must be accepted by both agents. If at least one agent rejects the agreement, the *status quo* game is played. In the game with a side payment the agents have the same strategies as in the *status quo* game, the payoffs are different, however.

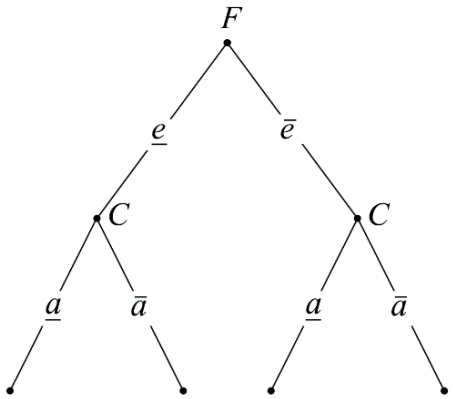


Figure 4.2: The pollution-attack game

We assume that the firm maximises profits (V) while the community maximises utility (U). To specify the payoffs, we present the variables and parameters included in the community's utility function and firm's profit function in Table 4.2.

Table 4.2: Notation

Community	Firm
U: utility of the community x_f: volume of forest products x_m: volume of market products γ: compensation received $\bar{t}$: total hours available t_f: hours for gathering forest products t_w: hours for income wage activities $\bar{t}_a$: hours for attack $\boldsymbol{\delta}$: sanction for attacking without pollution	V: profit of the firm x_o: volume of oil production p_o: oil price c: cost of oil production γ: compensation payment s: sanction for not complying environmental regulations

To further specify the agents' payoffs, we assume that the community derives utility from the consumption of forest goods (x_f) and market goods (x_m). The utility function is

$$U = U(x_f, x_m) \tag{4.1}$$

and is assumed to be increasing and concave in both arguments. The production of forest goods depends on time spent and the state of the environment, i.e., whether the firm has taken environmental effort or not, $x_f = x_f(t_f, e)$.

The community has time and budget constraints. A given total time budget $\bar{t}$ is allocated to gather forest products t_f, earn a wage income from market activities t_w or engage in attack $\bar{t}_a$. We fix the time requirement of an attack, i.e., we do not consider variable intensities of attacks. Thus, the time budget constraint is

$$\bar{t} \geq t_f + t_w + a\bar{t}_a. \tag{4.2}$$

In case of forest products, the productivity of the time input depends on environmental quality, i.e., the environmental effort that the firm takes. We assume $x_f(t_f, 0) < x_f(t_f, 1)$, for all $t_f > 0$, so gathering forest products is more productive when the firm exerts environmental effort, i.e., it does not pollute. With low firm environmental effort, $e = \underline{e} = 0$, productivity will be low, and may mean, in the extreme, the complete loss of forest products. We also assume that x_f is concave in t_f and $x_f(0,0) = 0$.

If the firm's effort is high ($e = 1$) and the state of the environment is good, the optimal time allocated to gathering forest products and earning wages are denoted by t_f^* and t_w^*, respectively. In this situation, if there is attack, then $t_w = t_w^* - \bar{t}_a$. If the firm exerts low effort ($e = 0$) and the state of the environment is bad, the optimal time allocated to gathering forest products and income wage activities are represented by t_f^{**} and t_w^{**}, respectively. In case of attack, $t_w = t_w^{**} - \bar{t}_a$. We assume that $t_w^{**} > t_w^* > \bar{t}_a$.

A monetary budget constraint applies. Money income stems either from wages or from compensation payments γ coerced through attacks ($a = 1$) when the firm exerts low environmental effort ($e = 0$). Money is spent on market goods for consumption and possibly on sanctions δ whenever the firm is attacked without reason, i.e., when attack is

chosen even though the firm has taken effort, $e = 1$. This defines the budget constraint, where income equals expenditure:

$$t_w w + \gamma a(1 - e) = p_m x_m + \delta a e, \tag{4.3}$$

where w is the wage and p_m is the price of market goods. If we normalize $p_m = 1$,

rewriting the budget constraint gives

$$x_m = t_w w + \gamma a(1 - e) - \delta a e, \tag{4.4}$$

and we can rewrite the utility function to get

$$U = U\big(x_f\big(t_f, e\big), t_w w + \gamma a(1 - e) - \delta a e\big). \tag{4.5}$$

The community maximises utility when it allocates time such that the marginal utility from gathering forest products is equal to the marginal utility from market goods , unless we have a corner solution where only one type of good is consumed.

The firm maximises profits. It participates in a competitive (international) oil market where it is a price taker. The firm's profit function is composed of the revenue $(p_o x_o)$, production and environmental effort costs $c(x_o, e)$, the compensation that the firm pays to the community γ, and the sanction s imposed by the regulator. Weak governance implies that the sanction would be low or zero.

The firm's profit function is

$$V(x_o, e) = p_o x_o - c(x_o, e) - (1 - e)(\gamma a + s), \tag{4.6}$$

where c is increasing and convex in x_o.

The firm's decision to exert or not environmental effort has consequences for its marginal costs of oil production (7). If the firm decides to produce with high environmental effort $(e = 1)$, marginal costs are higher for any given level of production compared to low environmental effort $(e = 0)$, i.e.,

$$\frac{\partial c}{\partial x_o}(x_o, 1) > \frac{\partial c}{\partial x_o}(x_o, 0), \text{ for all } x_o. \tag{4.7}$$

Next, we determine the equilibrium of the pollution-attack game, then we will introduce side payments.

A. Without side payment

The community possibly faces two cases.

Case 1: The firm decides to take environmental effort $(e = 1)$. The community compares the payoffs from attack and not attack.

Using (5), for $e = 1$ and, for simplicity, assuming $t_w^* \geq \bar{t}_a$, it pays to attack if:

$$U\left(x_f\left(t_f^*, 1\right), (t_w^* - \bar{t}_a)w - \delta\right) > U\left(x_f\left(t_f^*, 1\right), t_w^* w\right). \tag{4.8}$$

Inequality (8) simply says that it never pays to attack if the firm takes environmental effort (avoiding pollution) since there are opportunity costs of attack $\bar{t}_a w$ and sanctions δ.

Case 2: The firm decides to pollute $(e = 0)$. Now, attack gives the community the opportunity to get a compensation γ for suffering water pollution. In this case, attack is preferred if

$$U\left(x_f\left(t_f^{**}, 0\right), (t_w^{**} - \bar{t}_a)w + \gamma\right) > U\left(x_f\left(t_f^{**}, 0\right), t_w^{**} w\right). \tag{4.9}$$

In this case the community faces a trade-off. Attack is costly with opportunity cost $\bar{t}_a w$ while a compensation γ for the environmental damage can be gained. The condition to attack simplifies to

$$\gamma > \bar{t}_a w.$$

If the compensation is larger than the opportunity cost of attack, then it pays to attack.

As we are specifically interested in analysing violent conflict, we assume that $\gamma > \bar{t}_a w$ holds and the community will attack if the firm does not take sufficient environmental effort.

Knowing that the community will attack if the firm pollutes, the firm decides to pollute $(e = 0)$ if the gain in net profits (higher revenues at lower average cost) is larger than compensation and sanction payments. Using (6), if the firm pollutes, it would have a low environmental protection cost and a high production x_o^h. While if it does not pollute $(e = 1)$, it would have a high environmental protection cost and a low production x_o^l. Hence, the firm pollutes if

$$p_o x_o^h - c(x_o^h, 0) - \gamma - s > p_o x_o^l - c(x_o^l, 1). \tag{4.10}$$

The compensation γ must be paid as it is forced by the community's attack.

If sanctions s and compensation γ are sufficiently high so that (4.10) does not hold, then the firm does not pollute, and the community does not attack. Weak governance, however, means that sanctions are hardly imposed, and the pollute-attack equilibrium is relevant.

B. With side payment

Next, we analyse the situation where a side payment is included which is allocated to a Trust Fund. The purpose of the Fund is to develop projects to improve the community's welfare (see Box 4.1). The side payment (or transfer) T is a fraction τ of the oil revenues, $T = \tau p_o x_o$ where $\tau \in (0,1)$.

The side payment affects the budget constraint of the community and the firm's revenues. The community's utility function with side payment becomes

$$U\big(x_f\big(t_f, e\big), t_w w - \delta + a\gamma + T(1-a)\big) \tag{4.11}$$

The firm's profit function with side payments is

$$V(x_o, e) = p_o x_o - T(1-a) - c(x_o, e) - (1-e)(\gamma a + s) \tag{4.12}$$

Notice that the side-payment is conditional on no attack. As before, the firm can decide whether to exert environmental effort $(e = 1)$ or not $(e = 0)$. Subsequently, the community decides whether to attack $(a = 1)$ or not $(a = 0)$; see Figure 1.

Again, we distinguish two cases.

Case 1: The firm decides not to pollute $(e = 1)$. Comparing the payoffs from attack and no attack, the community attacks if

$$U\big(x_f\big(t_f, 1\big), (t_w^* - \bar{t}_a)w - \delta\big) > U\left(x_f\big(t_f^*, 1\big), (t_w^* w + T)\right). \tag{4.13}$$

Since the firm decides to apply environmental effort, the community would be sanctioned δ, faces the opportunity cost of attack and loses the side payment. In this case, the community does not have incentives to attack.

Case 2: If the firm decides to pollute $(e = 0)$, the community decides to attack if

$$U(x_f\big(t_f^{**}, 0\big), (t_w^{**} - \bar{t}_a)w + \gamma) > U(\, x_f\big(t_f^{**}, 0\big), (t_w^{**} w + T)) \tag{4.14}$$

which simplifies to $\gamma > \bar{t}_a w + T$.

As a result, the community attacks if compensation is larger than the sum of the opportunity cost of attack and the side payment. That is, the side payment makes a difference and contributes to peace if it is large enough such that $\bar{t}_a w < \gamma < \bar{t}_a w + T$.

The firm does not pollute ($e = 1$) if the gain in net profits (lower revenues at higher average cost and side payment) is larger than net profits with higher revenue at lower average cost with side payment under pollution ($e = 0$). More formally, the firm does not pollute if

$$p_o x_o^l - T(1-a) - c(x_o^l, 1) > p_o x_o^h - T(1-a) - c(x_o^h, 0) - \gamma - s \qquad (4.15)$$

In this case, as shown before, the community does not attack.

If the side payment is sufficiently large as well as the opportunity cost of attack, so that (4.13) does not hold, then the community does not attack. Therefore, a side payment contributes to mitigating conflict and fostering peace.

In summary, the equilibrium conditions in the pollution-attack game are presented in Table 4.3.

Table 4.3: Conditions for agents' decision making

A. Without side payments	B. With side payments
The firm does not pollute if:	The firm does not pollute if:
$p_o x_o^l - c(x_o^l, 1) > p_o x_o^h - c(x_o^h, 0) - \gamma - s$	$p_o x_o^l - T(1-a) - c(x_o^l, 1) > p_o x_o^h - T(1-a) - c(x_o^h, 0) - \gamma - s$
The community attacks if:	The community attacks if:
$t_w^* w - \delta > \bar{t}_a w$	$t_w^* w - \delta > \bar{t}_a w + T$
The firm pollutes if:	The firm pollutes if:
$p_o x_o^h - c(x_o^h, 0) - \gamma - s > p_o x_o^l - c(x_o^l, 1)$	$p_o x_o^h - T(1-a) - c(x_o^h, 0) - \gamma - s > p_o x_o^l - T(1-a) - c(x_o^l, 1)$
The community attacks if: $\gamma > \bar{t}_a w$	The community attacks if: $\gamma > \bar{t}_a w + T$

If the firm decides to take environmental effort in both situations, the community would never attack, as explained previously.

If the firm decides to pollute, equilibrium differs depending on the availability of a side payment (Table 4.3). Without side payment, the community attacks if the compensation γ is higher than the opportunity cost of attack. With a side payment that is conditioned to no attack there is an additional incentive to keep peace. With a sufficiently large side payment a polluting firm can avoid attack (Table 4.3).

4.5. Discussion and conclusions

We analyse how side payments can contribute to conflict resolution, mitigate negative externalities and facilitate stable and peaceful outcomes, while improving welfare, particularly when weak governance prevails. We examine the role of side payments in oil pollution conflicts when it includes a punishment clause which change the incentive to generate conflicts. Our study complements other studies that have also examined side payments mainly to solve transboundary water allocation problems (Dinar, 2006; Kimbrough & Sheremeta, 2013).

As discussed in Section 2, any institutional framework is supported by a governance system which can be strong or weak (Fukuyama, 2016). Strong governance implies that inspections and sanctions are effective in enforcing environmental effort, contributing to cleaner oil production and avoiding conflict. In contrast, a weak governance system hardly enforces supervision and sanctions, making pollution more profitable for the firm. In response to pollution, the community reacts by attacking and claiming compensation.

Our theoretical model, a sequential pollution-attack game, offers a framework for analysis and we illustrate the relevance of our set up with a case study. The case focuses on the strategic behaviour between oil firms and indigenous communities. The agents are characterized by economic, social and cultural asymmetries and are engaged in a conflict due to oil pollution.

Our model determines the conditions under which the firm decides whether to pollute or not, and the community decides whether to attack or not. The conditions are stated for two situations: without and with side payment. The model shows that if the firm chooses to take environmental effort and avoid pollution, negative externalities are

reduced, and the community's response would be no attack regardless of side payments (Table 3). Side payments provide incentives to the community to keep peace while helping to preserve their means of living and access to infrastructure through the Trust Fund.

If the firm decides to pollute, saving on environmental effort for a lower production cost, the community may choose to attack or not. In our base case, without side payments, the community decides to attack if the compensation they can force to obtain is greater than the opportunity cost of attack (Table 4.3). In the second case, with a side payment, the community decides to attack if the compensation is greater than the opportunity cost of attack and the side payment. Here, the size of the side payment matters because, if it is large enough to offset the compensation, the community may choose to accept some level of pollution in order to retain the side payment.

However, obtaining compensation involves transaction costs, such as the opportunity cost of attack and negotiation time (see section 4.3). Therefore, the community can obtain higher utility from the side payment; it is thus preferred to compensation. To this extent, the role of the side payment is to change the game compared to the *status quo* where the firm has incentives to pollute and the community to attack.

Thus, a side payment as part of a contract provides incentives for both agents; it encourages the community not to attack and the firm can operate with lower cost of production in conditions of peace. Additionally, the side payment provides stability to the contract by including a credible punishment. The threat of losing welfare obtained from side payments incentivizes the community to keep peace. Therefore, it also can contribute to mitigate the commitment problem as long as cooperation and trust can be enhanced (Bueno de Mesquita, 2016; Acemoglu & Wolitzky, 2024).

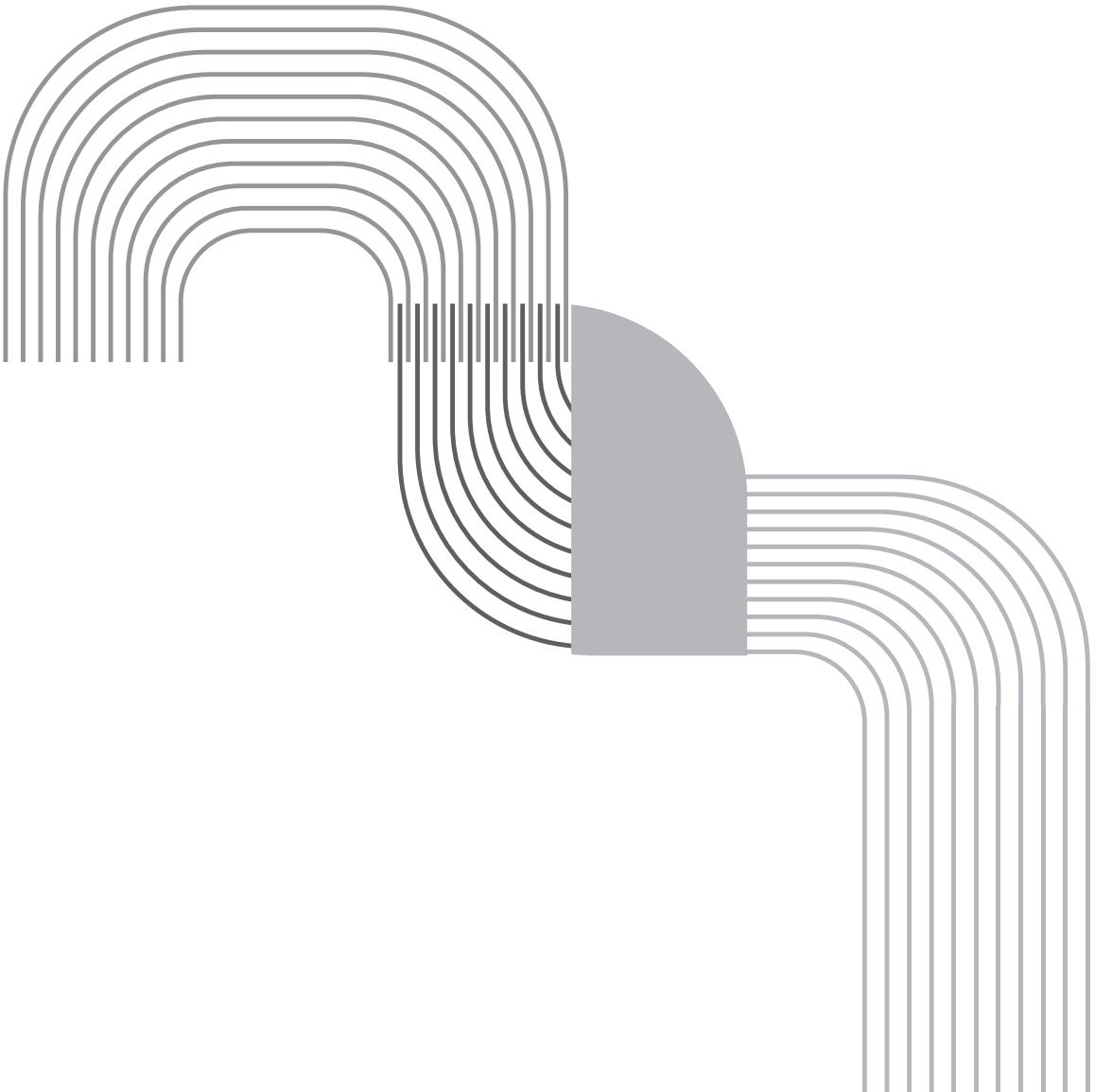
Our findings suggest that side payments may be a complement to command-and-control environmental regulations (e.g., rules enforced by sanctions) which require continuous costly supervision and may fail to provide adequate incentives for firms to engage in environmental effort, particularly when weak governance prevails. Side payments become an instrument to solve conflicts while strengthening the governance system takes time.

Our model can be extended to other extractive industries, where firms and local communities have conflicts due to pollution and are located in far-away areas with lack of infrastructure, social services, and where governance is weak. Side payments can be an instrument to align incentives and solve conflicts.

Further research may expand our model to three agents, where the State, beside firms and communities, has a role in the game by promoting stringent environmental policy, improving governance and law enforcement. The findings suggest avenues for further research, for instance, Ansink & Weikard (2020) conclude that side payments can help to support the grand coalition, as long as the number of agents is low. It would be interesting to analyse the political economy of communities' institutions and their incentives to strengthen the grand coalition or to leave it.

Chapter 5

Oil pollution and stranded assets



Abstract

The aim of this chapter is to derive and analyse the conditions under which stringent environmental policies and enforcement can incentivise clean production but also, under certain conditions, can lead to asset stranding. The incentives to strengthen environmental regulations and to increase compliance are crucial for improving environmental conditions in favour of local populations' livelihoods and for reducing the risk of conflicts. We analyse a sequential enforcement-pollution game with the government and a firm as agents. The findings show that firms who believe that a lenient policy with weak enforcement prevails, will fail to comply with environmental regulations. This can, in turn, lead to asset stranding in case the policy will be strengthened at a later stage. We examine the case of the Peruvian oil industry in the Amazon, where firms have a history of non-compliance with environmental regulations.

Keywords: Water pollution, stranded assets, institutions, monitoring and enforcement, sequential game, Peruvian Amazon.

5.1. Introduction

Environmental regulations and their monitoring play a crucial role in providing incentives for agents to pursue both development and environmental policy goals. The institutional framework plays a critical role in the implementation of the policy goals. Ideally, institutions are accepted and respected, enhancing cooperation which benefits everyone (Binmore, 2010). However, weak monitoring and enforcement mechanisms can cause agents to violate laws and regulations, generating uncertainty and potentially harming others. In the following, we use "monitoring" and "enforcement" interchangeably to refer to all supervision, control, prosecution and punishment activities by government agencies.

At the national level, weak environmental enforcement incentivises firms to minimise environmental effort which can generate negative externalities, affecting not only local populations' welfare but also the economic performance of the polluting industry as pollution causes conflicts with local populations. At the international level, climate change commitments impose pressures on the oil industry. However, the implementation of policy measures is still a challenge for governments, particularly in developing and emerging economies where economic growth ranks high on the agenda and firms pursue profit maximization in the short run, with less attention to long-term risks (Silver, 2017; Ansari & Holz, 2020; Hansen, 2022;). Lenient environmental policy and lack of monitoring may attract investments of firms that are expecting short run benefits, but underrate risks of disaster, of violent conflicts, or of stricter environmental regulations that might threaten investments.

The aim of this chapter is to analyse how environmental policy can reduce water pollution and the risk of asset stranding. We shed light on the deficient incentive structure that causes assets stranding, and we illustrate this for the case of oil production in the Peruvian Amazon. Our study unveils a link between the winner's curse, a well-known problem in auction theory, and the risk of asset stranding. This is a novel contribution to the theoretical literature on institutional design. We analyse a model of the strategic interaction between the government and a firm that has placed the winning bid to obtain a license agreement for oil extraction. The model is a two-agent

sequential game with imperfect information. The government seeks to maximise social welfare, while the firm aims to maximise profits. The government's strategies are whether to implement a lenient or strict policy and whether to monitor or not. The firm's strategies are to invest either in clean or pollutive technologies, i.e., the firm decides to adhere to environmental regulations or not.

Worldwide, oil producing countries have water pollution problems, mainly where enforcement is weak (Soto-Oñate et al., 2017; Olmstead & Zheng, 2019). The Peruvian oil industry is a case to illustrate the relationship between government and oil firms, where regulatory measures to control water pollution creates a risk of assets stranding. The Peruvian oil industry operates in two regions: the coastal area and the Amazon rainforest. Our analysis addresses oil operations in the Amazon. Historically, oil extraction was largely unregulated with little concern about pollution. Environmental regulations were first introduced in 1993; however, despite three decades of improvements on institutional and environmental regulations, water pollution remains to be a significant risk to public health and local livelihoods (León & Zuñiga, 2021).

In the context of international climate agreements oil producing countries have claimed their right to develop. However, weak environmental regulations, or their inadequate enforcement, have contributed to a history of oil pollution and social conflict. Research on oil spills has largely highlighted major international disasters, such as the Deepwater Horizon oil spill, and the Ixtoc spill, which occurred in offshore operations (Jernelov, 2010). In contrast, onshore oils spills have received less attention, despite their severe social and environmental consequences on local populations and indigenous communities, in particular in biodiversity rich regions (A. Bebbington, 2011; Adeola et al., 2022). Oil pollution continues to affect water resources, biodiversity, and the welfare of local populations (Vasquez, 2014; Pesa & Ross, 2021). Pollution and conflicts have led to abandoned oil operations, generating stranded assets.

This chapter is organized in five sections. Section 5.2 reviews the existing literature on oil pollution, institutions and stranded assets. Section 5.3 explains the main characteristics of the Peruvian oil industry and the hydrocarbon regulatory framework, focusing on the

interaction between regulator and oil firms. Section 5.4 presents the model to analyse agents' strategic interaction in cases of strict and lenient environmental policies. Finally, Section 5.5 discusses the findings, provides some lessons for policy-making, and concludes.

5.2. Oil pollution, institutions and stranded assets

5.2.1. Oil pollution

Water is a natural resource critical for both extractive industries and local populations. While extractive industries use it for their operations, local populations depend on freshwater for domestic use and economic activities, making them vulnerable to changes in water availability and quality.

Despite technological improvements to minimise environmental damage, water quality in oil-producing regions continues to be affected by pollutants that exceed national and international standards (Yusta-García et al., 2017; Adeola et al., 2022). Additionally, inadequate maintenance of infrastructure by oil firms exacerbates the risk of spills, further deteriorating water quality (Jernelov, 2010). Water pollution has had negative consequences on freshwater ecosystems and fisheries, reducing household income, food security and welfare. As a result, a long history of conflict and distrust between oil firms and indigenous communities has emerged in the Amazon, a topic extensively analysed in the literature (A. Bebbington, 2011; Haselip, 2011; Cuba et al., 2014) and in Chapter 4.

5.2.2. Institutions, enforcement and stranded assets

The institutional framework is fundamental to understand agents' behaviours. Institutions are defined as rules and norms that govern individual and organizational behaviour (Ostrom, 2007) . They shape decision-making by establishing incentives and providing a shared belief system (Orihuela, 2018; Ansari & Holz, 2020). The institutional framework is associated with a governance system. One definition of "governance" focuses on the decision-making process in providing public services and the degree of stakeholder participation. Weak governance is characterized by lack of coherence in public policies,

inadequate social services provision, and limited stakeholder participation (Fukuyama, 2016). A vulnerable or ineffective judicial system and corruption also weaken governance. When institutions fail to enforce laws and rules, significant social costs arise (Shavell, 1984), including public health problems, loss of livelihoods, and constraints on social and economic development.

Some examples of weak governance in the Amazon are presented by (Orihuela, 2018) who analyses the performance of institutions in the oil industry in Ecuador and Peru, highlighting the negative environmental and social impacts of oil production on ecosystems and indigenous communities. The author points out the importance of geographical and socio-economic contexts for institutional effectiveness and agents' behaviour. Similarly, Okamoto & Leifsen (2012) analyse the strategies of firms to manage the effects of oil pollution in the Peruvian Amazon, and to sidestep their responsibilities, often taking advantage of information asymmetries related to knowledge about technical and financial resources.

A commitment problem arises in contexts characterized by weak governance, where lack of trust between the agents generates uncertainty leading to inefficient outcomes. Uncertainty is not commonly addressed in the traditional water economics literature. Policy uncertainty has effects on environmental quality and economic growth, depending on agents' risk aversion and their strategic behaviour (Bretschger & Soretz, 2021). Under uncertainty, foreign firms are often reluctant to invest in countries where the risk of expropriation or abrupt legal changes prevails, leading to the loss of mutually beneficial investment opportunities (Bueno de Mesquita, 2016). Conversely, countries with weak governance frameworks may attract investments that seek to evade stringent regulations in more institutionally robust economies, potentially fostering economic activity in the short run but constraining long-term sustainable growth and development (Bos & Gupta, 2018). In general, weak governance is associated with larger uncertainties including a possible strengthening of regulations.

Under uncertainty agents must base their actions on beliefs. Beliefs are critical to analyse games with incomplete information where agents

assign probabilities to other agents' possible strategies (Harsanyi, 1967; Kreps, 1989; Dominiak & Eichberger, 2021).

Such uncertainties can lead to stranded assets. For further analysis we adopt the following definition: *"Stranded assets are assets that have suffered from unanticipated or premature write-downs, devaluations, or conversion to liabilities"* (Caldecott, 2017). Several factors contribute to asset stranding, including operational or management risks, environmental regulations, declining oil prices, increasing competitiveness of renewable energy, reductions in clean technology costs, shifting social norms (i.e., fossil fuel divestment campaigns), and risks associated with water resources (Caldecott et al., 2016; Buhr, 2017). The stranded assets concept is related to sunk costs, characterised by irreversibility and lack of recoverability (Harnett, 2018).

The oil industry faces growing risks of assets stranding due to factors such as governments' commitments to greenhouse gas abatement, decreasing cost of renewable energy, and increasingly stringent environmental regulations (Caldecott et al., 2016; van der Ploeg & Rezai, 2016). Existing literature on stranded assets has mainly focused on risks of investors who hold shares of oil firms, while less attention has been given to the institutional framework that oil-producing countries provide and the incentives that they generate for oil firms. For instance, the lack of enforcement of environmental regulations can lead to pollution and conflicts that can threaten economic growth and development. The economic consequences of asset stranding due to climate change policy transitions are significant, with potential macroeconomic effects that threaten financial stability and investment returns (Sen & von Schickfus, 2020; Caldecott et al., 2021; Daumas, 2023; von Dulong et al., 2023; Delis et al., 2024).

There is a broad consensus in the literature regarding the risk of stranded assets in the fossil fuel industry (Curtin et al., 2019; Draeger et al., 2022; Hansen, 2022). Hansen (2022) points out that, oil reserves will face a devaluation and half of this is due to price reduction along the climate stabilization scenario. This price reduction would also affect low-cost producing countries, potentially incentivising short-term increases in fossil fuel extraction. Ansari & Holz (2020) analyse the risk of stranded assets in developing countries with particular

focus on China, Middle East and Latin America. Their findings suggest that, on average, the risk of stranded assets is moderate across these regions. However, China is more susceptible to coal stranding while Middle East and Latin America are prone to oil stranding. The authors highlight the role of institutions in facilitating a low-carbon transition. In Latin America, the institutional framework is less rigid than in China and Middle East, yet economic resilience remains uncertain due to additional factors such as political stability and income distribution challenges.

The risk of stranded assets represents a potential profit loss for the firms. Hansen, (2022) assesses that climate stabilization will lead to a devaluation of the fossil fuel reserves, which can explain industry resistance to stringent climate policies. Additionally, incentives in favour of renewable energy, such as subsidies, would incentivise firms to accelerate fossil fuel extraction in the short term, increasing emissions and exacerbating global warming (van der Ploeg, 2020). Asset stranding receives less attention in countries who focus on economic growth, despite underlying uncertainties such as energy systems transition and climate policies (Bos & Gupta, 2016).

In some cases, national governments unilaterally decide to leave oil reserves underground, which can also result in stranded oil resources. An example is Ecuador's Yasuni Initiative, introduced in 2007. The Initiative sought to keep underground 846 million barrels of crude oil in the Yasuni National Park, with the double goal to reduce CO_2 emissions and protect biodiversity and isolated indigenous people (Vallejo et al., 2015; Sovacool & Scarpaci, 2016; Kingsbury et al., 2019). The initiative failed to collect the necessary compensation for leaving oil underground. As a result, the Ecuadorian government proceeded with the oil extraction in the area. It is an example of ill-aligned incentives. As Bos & Gupta (2019) point out, international compensation for leaving oil underground is inefficient because compensation schemes can create perverse incentives, encouraging countries to identify additional reserves only to demand compensation for avoiding extraction. In contrast, European countries are subsidising energy transition measures. Moreover, European countries are exploring alternative schemes to reduce use of fossil fuel energy sources such as coal. For instance, Germany is paying

compensations for early coal phase-out based on auctions (Srivastav & Zaehringer, 2024).

Governments worldwide are implementing policies and instruments to manage climate risks. For instance, European countries are developing regulatory instruments to achieve their climate goals (Creutzig et al., 2014). In contrast, Latin American and Caribbean countries still focus on attracting investment to drive short-term economic growth, often prioritizing immediate economic gains over long-term stranded asset risk (Caldecott et al., 2016; Bos & Gupta, 2018; Ansari & Holz, 2020).

Additionally, falling costs of renewable energy and policy instruments in their support, aim to reduce fossil fuel demand to comply with climate policy goals. Increasing use of renewable energy follows different pathways in developed compared to developing countries. While most research has focused on developed economies, developing countries have received less attention despite the complexities and challenges in their energy markets, institutional frameworks, and economic growth dynamics.

Considering that oil firms are competing for licenses for oil extraction they are vulnerable to the *winner's curse*. If bidders are insufficiently informed about the true value of the oil exploitation license, the most optimistic bidder wins the bid. In such case it is the winner's curse to bear a high risk of incurring a loss (McAfee & McMillan, 1987).

5.3. Loreto: oil pollution and institutional framework

Loreto is a department in Peru's northern Amazon region, covering 29% of the national territory, home to 3% of the country's population, and responsible for 27% of national oil production. This department hosts the greatest diversity of indigenous groups and the largest indigenous population in the Amazon. Additionally, Loreto accounts for 41% of the country's proven and probable oil reserves (León & Zuñiga, 2021).

Peruvian oil production has shown a declining trend, with 44% reduction between 2010 and 2022. Key factors contributing to this reduction include falling international prices and conflicts with

indigenous communities. Following the national oil production trend, Loreto's oil production decreased by 57% from 2010 to 2022, even more than the national average (Appendix A5.1). Although more than 20 firms signed contracts for oil exploitation and exploration in nine lots in Loreto, the number of active firms and lots has decreased. From 2018 to 2020, four firms were active in oil production, while in 2021 and 2022 only two firms remained operational in Loreto: Petrotal in Lot 95 and Perenco in Lots 67 and 39 (Appendix A5.2). In 2022 Petrotal produced 92% of Loreto's oil. In 2024, Perenco withdrew its contract due to conflicts and the establishment of a protected area within its operational zone. In 2024, two new oil firms, Upland and Altamesa signed contracts, to operate lots 8 and 192, respectively, both of which are the oldest lots in Loreto. Altamesa withdrew the contract in 2025 due to financial problems. The Peruvian government, through the Hydrocarbon Investment Promotion Agency (Perupetro) and in potential conflict with its climate policy goals (see Box 5.2), is actively seeking new firms to invest in oil exploration and extraction in the Amazon region.

In Loreto, oil production contributed to significant water pollution, primarily from heavy metals in produced water and from oil spills. During 2000-2019, Lot 192 reported 1372 polluted sites and 189 spills while Lot 8 reported 1380 polluted sites and 155 oil spills. Although Lot 192 ceased operations in 2021, there were still 27 oil spills in 2022 due to inadequate maintenance of the infrastructure (Pueblos Indígenas Amazónicos Unidos en Defensa de sus Territorios [PUINAMDT], 2022). As a result, the indigenous communities have experienced degradation of their livelihoods, with increasing health problems linked to water pollution, including cancer, skin and gastrointestinal diseases (MINSA, 2020; Chong & Srebot, 2022). The levels of heavy metals in the affected areas have far exceeded both national and international environmental standards (Yusta-García et al., 2017; Espinoza-Guillen et al., 2022). The communities perceive the pollution as a loss of a source of safe drinking water as well as food (Rada & Farroñay, 2012).

Firms faced uncertain situations such as overlapping territorial claims between the oil lots and indigenous communities, the creation of a new protected area in one lot area, and opposition from communities to oil exploitation. The negative externalities cause conflicts between the firm and local communities which, in turn, hampers oil production.

Additionally, firms with financial problems cannot maintain the operations (Altamesa, Lot 192) or pay fines for not complying with environmental regulations (Pluspetrol, Lot 8). Subsequently firms withdrew from contracts leaving oil infrastructure stranded (e.g., in Lots 64, 67, 39 (Appendix A5.2), (Viale, 2024).

Peru's hydrocarbon institutional framework has evolved since 1993. The State manages the national natural resources, owned by the nation. The State aims to attract investments and improve the efficiency of extraction. Oil producing firms have applied and pay for licenses to extract oil. Environmental regulations have been incorporated into license agreements (Box 5.1). These regulations are primarily based on command and control instruments, setting standards and limits to air and water pollutants (Box 5.1).

Box 5.1: Oil industry and institutions

The Hydrocarbon Law (Ley No. 26221, 1993) was enacted in 1993, establishing Perupetro S.A. as the agency responsible for promoting investment in hydrocarbon activities. Access to fossil fuel resources is based on a License Contract, which is signed between Perupetro S.A. and the operating oil firm.

The institutional framework for the hydrocarbon industry involves national and regional authorities. At the national level, key entities include the Prime Minister's Office, the Ministry of Energy and Mining, the Ministry of Environment, the Ministry of Culture, the Ministry of Economics and Finance, the Ministry of Labor and Employment Promotion. These ministries participate through their respective technical offices or agencies.

Several agencies have been established to regulate and oversee the oil industry. For example, OSINERGMIN and OEFA are two key regulatory bodies. OSINERGMIN was created in 1996 with the mandate to supervise mining, energy and hydrocarbon firms, ensuring they provide safe, reliable, and high-quality service. It is seconded to the Ministry of Energy and Mining (MEM).

OEFA was created in 2008, under the Ministry of Environment, and began its activities in 2010. OEFA is responsible for assessment, supervision and inspection of environmental regulations across different sectors such as mining, energy, fishery, agriculture, solid waste, manufacture, domestic trade. In 2013, Pluspetrol Norte was fined US$8 million for failing to meet the remediation requirements outlined in the Complementary Remediation Plan (OEFA). In 2018, Petroperu, the state-owned company, was fined 49 million soles *(14.5 million US dollars)* for failing to maintain its pipeline, which resulted in several oil spills in 2016. During 2017-2019, OEFA identified 521 infractions across the four oil firms operating in Loreto, with Pluspetrol Norte accounting for 75% of the infractions (OEFA, 2022).

The environmental and social requirements within the oil industry are set forth in the Environmental Protection in the Hydrocarbon Activity Regulation, which norms the managing of environmental impacts of oil extraction and related activities.

Source: Perupetro (1993); Ministerio de Cultura [MINCUL] (2014); OSINERGMIN (2015); OEFA (2023).

Policies and measures related to investment in the extractive industries are aligned with sustainable development objectives in the context of climate change. However, limited monitoring has led to water pollution and conflicts between oil firms and indigenous communities, over several decades (Okamoto & Leifsen, 2012; León & Zuñiga, 2021). According to OEFA, hydrocarbon activities account for 30% of the national infractions, almost on par with the mining sector that is responsible for 32% of the infractions (OEFA, 2023).

Additionally, Defensoría del Pueblo (*Ombudsman*) reported that Loreto is the department with the highest number of conflicts related to oil pollution of water, representing 14% of the total environmental conflicts in the country. Within Loreto, the hydrocarbon sector is responsible for 92% of the conflicts in the region (Defensoría del Pueblo, 2022).

Extractive industries' operations are closely linked to achieving climate policy and sustainable development goals. Peru has enacted a Climate Change Law, which establishes principles and guidelines aimed at promoting sustainable economic growth with low carbon emissions. This law is designed to align incentives with the country's National Determined Contributions (NDCs) under the Paris Agreement (Box 5.2).

Box 5.2: Peru: Climate Change commitments

Peru adhered the Paris Agreement in 2016 and established its Nationally Determined Contributions (NDC). However, political instability and inconsistency between policy goals and their implementation have hindered progress toward meeting these climate goals. The country is committed to reach 208.8 $MtCO_2eq$ as maximum emissions up to 2030, with the potential for a reduction to 179 $MtCO_2eq$ depending on international financial support. The committed goal stands for 30% reduction from the projected *Business as Usual scenario* in 2030 (298.3 $MtCO_2eq$). National, regional and local governments are responsible for designing and implementing instruments to manage the effects of climate change within their respective areas of authority.

In 2018, Peru approved the Climate Change Law (Ley No. 30754, 2018), which incorporates the precautionary principle, and promotes policies and measures to reduce the risks of negative effects of climate change. The law takes a comprehensive approach to climate change, including different perspectives such as river basin management, the role of indigenous communities and traditional knowledge, ecosystem conservation, land use planning, all aimed at reducing emissions and vulnerability to climate change.

In 2021, the Peruvian Ministry of Economics and Finance joined the Coalition of Finance Ministers for the Climate Action, demonstrating Peru's commitment to reduce CO_2 emissions and supporting adaptation measures. The Coalition's program is committed to align policy actions to the Paris Agreement. The Coalition was created in 2018, and currently 96 countries are part of the Coalition.

Sources: Ley No. 30754 (2018); Ministerio de Economía y Finanzas [MEF] (2021); Coalition of Finance Ministers for Climate Action (2024).

5.4. Model set up

The aim of this section is to derive and discuss the conditions under which a strict policy and monitoring provide incentives for green production as well as under which conditions assets can get stranded. We develop a sequential game to examine the interaction between two agents: Government (G) and Firm (F).

The government G moves first and chooses a lenient l or strict s environmental policy. We assume, however that they cannot fully commit to either policy. A strict policy involves setting up institutions equipped with personnel and competences that ease monitoring of

firms, prosecution and punishment of violators of environmental laws and regulations. A strict policy is associated with a cost C_s.

Since the government cannot commit, the firm F cannot be sure whether the government is lenient l or strict s. F forms a belief p that l is chosen. Then F has three options, not to invest, invest and produce brown or green $\{n, b, g\}$. Brown investment yields a normal profit π but pollutes the environment. Green investment avoids pollution but involves additional costs C_g compared to brown investment.

Subsequently, the government can monitor or not. If monitored, a polluting firm will have to bear clean-up costs C_c and pay a fine f. We assume that monitoring costs are lower if a strict policy has been adopted $m_s < m_l$ as institutions that facilitate any enforcement measures are in place. The notation is summarised in Table 5.1. Figure 5.1 shows the game tree.

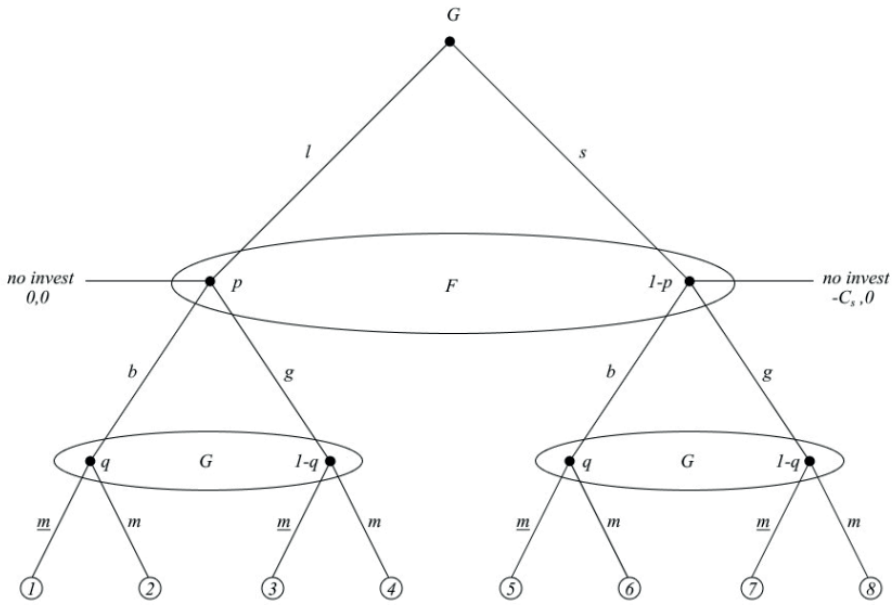


Figure 5.1: The enforcement-pollution game

The agents have different goals. The regulator is concerned about welfare and its budget, attaching a relative weight $\alpha \geq 0$ to the latter.

The firm aims to maximise expected profits. The payoff for each of the eight possible outcomes is reported in Table 5.2 (also see Figure 5.1).

Table 5.1: Notation

Government (G)	Firm (F)
$\{l, s\}$: Strategies: lenient or strict policy $\{m, \underline{m}\}$: Strategy set, monitor or not monitor C_s: Cost of the strict policy e: Environmental damage cost m_s: Monitoring cost under strict policy m_l: Monitoring cost under lenient policy α: weight of government budget vs. welfare. $q \in [0, 1]$: : G's belief that b is played.	$\{n, b, g\}$: Strategies: no, brown or green investment π: normal profit for "brown" production C_c: Clean-up costs C_g: cost of green production f: fine $p \in [0, 1]$: F's belief that l is played.

We adopt the following assumptions.

$C_g < C_c$: green production (avoiding pollution) is better than clean-up.

$C_c < e$: it pays to clean-up.

Consequently, $C_g < e$: green production is cheaper than the environmental cost of pollution.

Table 5.2: Representation as a normal form game specifying the payoffs

		F		
		Not invest	**Brown production**	**Green production**
G	$l, \underline{m}$	0,0	(1)$(\pi - e, \pi)$	(3)$(\pi - C_g, \pi - C_g)$
	l, m	$-m_l, 0$	(2)$(-m_l + \pi - C_c + \alpha f, \pi - C_c - f)$	(4)$(-m_l + \pi - C_g, \pi - C_g)$
	$s, \underline{m}$	$-C_s, 0$	(5) $(-C_s + \pi - e, \pi)$	(7) $(-C_s + \pi - C_g, \pi - C_g)$
	s, m	$-C_s - m_s, 0$	(6)$(-C_s - m_s + \pi - C_c + \alpha f, \pi - C_c - f)$	(8) $(-C_s - m_s + \pi - C_g, \pi - C_g)$

We solve the game backwards and start comparing the government's payoffs with and without monitoring. We do this for the lenient and the strict policy.

Under the lenient policy *l* it is better to monitor if

$q(\pi - e) + (1 - q)(\pi - C_g) \leq q(-m_l + \pi - C_c + \alpha f) + (1 - q)(-m_l + \pi - C_g)$.

Simplifying and solving for m_l we obtain the condition:

$$m_l \leq q(e - C_c + \alpha f). \tag{5.1}$$

Under the strict policy *s*, it is better to monitor if

$$q(\pi - e) + (1 - q)\left(\pi - C_g\right) \leq q(-m_s + \pi - C_c + \alpha f) + (1 - q)(-m_s + \pi - C_g)$$

which simplifies to

$$m_s \leq q(e - C_c + \alpha f). \tag{5.2}$$

Note that the right-hand side of conditions (5.1) and (5.2) for monitoring under lenient and strict policies is the same. Since we assume that environmental damage costs are larger than the clean-up cost, the right-hand side is always positive. It represents the government's expected gain of monitoring, i.e., the welfare gain of clean-up plus a contribution to its budget, weighed with the probability that the firm chooses the polluting investment. If (5.1) holds, then, because $m_s < m_l$, (5.2) will also hold. In this case the government will monitor. For the conditions to hold, however, the belief q of the government that the firm pollutes must be sufficiently high. If that is so, the firm's best response is the clean investment, implying that the government holds a false belief. Our game does not have a pure-strategy equilibrium. We derive its mixed-strategy equilibrium in the Appendix A5.2.

We also show in Appendix A5.2 that monitoring costs are such that the government would monitor if and only if it has adopted the strict policy.

$$m_s \leq q(e - C_c + \alpha f) < m_l. \tag{5.3}$$

In this case the firm chooses brown investment if

$$\pi - C_g \leq p\pi + (1 - p)(\pi - C_c - f).$$

Simplifying gives

$$C_g \geq (1 - p)(C_c + f), \tag{5.4}$$

where p is the firm's belief that the government has adopted a lenient policy l and will not monitor given assumption (3). If belief p is strong enough, the firm adopts the brown investment and expects to be monitored with probability $1 - p$.

As indicated earlier, we derive the mixed-strategy equilibrium in Appendix A5.2. Here we consider out-of-equilibrium play which is likely to occur when players have subjective beliefs and there is no

equilibrium that serves as a focal point. Our game assumes imperfect information and the mixed strategy equilibrium may or may not be played. It is plausible that the government and the firm both hold false beliefs when they make their decisions. Both agents decide based on their respective beliefs q and p.

Uncertainty implies the risk of asset stranding. Assets, the firm's investments, get stranded when the firm adopts brown investment, the government monitors, and the net present value of future oil revenues (NPV(R)), net of the variable cost of production, is insufficient to cover the liabilities for clean-up and the fine. More formally, assets get stranded if,

$$\text{NPV}(R) < C_c - f. \tag{5.5}$$

If beliefs are such that conditions (5.1) or (5.2), and (5.4) hold, i.e., the government monitors and the firm choses brown production, then with sufficiently high fines and clean-up cost the firm will declare bankruptcy and leave its assets stranded.

5.5. Discussion and conclusions

We find that strict environmental policies and monitoring incentivise firms to adopt green production, reducing water pollution. In absence of government commitment to strict regulations, firms choose strategies according to their beliefs about the government´s strategy. If a firm believes the government will enforce a strict policy with credible monitoring, its best response is to engage in green production. However, if the firm expects leniency but the government monitors, the firm faces a fine and will consider to leave its assets stranded.

Monitoring costs vary depending on the type of environmental policy in place. Under a stringent policy, these costs are lower than under a lenient policy due to the presence of institutional infrastructure, personnel, and enforcement resources. In contrast, lenient policy is characterised by fragmented and underfunded monitoring effort, resulting in higher costs (Cohen, 1998). Monitoring thus become a critical component of the environmental policy design which requires not only funding but also consistency and reliability in its application

to help shape firms´ beliefs and decide on the type of production to undertake.

Firms' behaviour is also influenced by the institutional framework. For instance, stringent environmental policy supported by efficient regulatory enforcement practices improves firms' sustainability, reducing environmental infractions and pollution (Gray & Shimshack, 2011; Cheng et al., 2025). Conversely, if the implementation of enforcement mechanisms is delayed, the firms do not have incentive to invest in clean production. For example, if a carbon tax is announced but the implementation is delayed, firms may have an incentive to pollute more before the implementation (Di Maria et al., 2012) . Similarly, delays in monitoring and fines, encourages non-compliance. Moreover, if firms can appeal against the fines, they may exploit legal delays that can last for years. Therefore, firms are incentivised to choose a brown production. However, if fines are extremely high, as described in condition (5) for asset stranding, the financial penalty may force the firm out of business (see Table A5.2, Pluspetrol Norte, 2013).

The case of Loreto provides a concrete real-world example. Prior to 1993, in absence of environmental regulations the firms engage in brown production. The National Assessment and Environmental Agency (OEFA) was created in 2008 but began activities in 2010. In 2013. OEFA fined Pluspetrol Norte 8 million dollars for non-compliance with environmental regulations and the firm declared bankruptcy and exited lot 8. Other firms also withdrew from contracts due to conflicts, leaving behind oil infrastructure (see Table A5.2). In contrast, the only firm still operating in the region has complied with environmental regulations and fostered community engagement through job opportunities and revenue sharing. This strategy aligns with existing literature indicating that firms are more likely to engage in clean production when green production cost reduces or associated benefits increase (Tietenberg, 1996).

The Loreto case illustrates that under a lenient policy with some degree of monitoring, firms may still face asset stranding due to penalties for water pollution. In this region, oil operations ceased in three lots due to conflicts and financial constraints (see Table A5.2) with some lots still inactive for more than five years.

Water-related conflict is another factor of stranded assets. Future research could extend the model incorporating the community as a third agent who receives benefits from a clean environment. Including the cost of conflicts in both, the firm's profit function and the social welfare function could enhance our understanding of how stringent environmental policies provide appropriate incentives. Chapter 4 presents the interaction between a firm and a community affected by water pollution. Private agreements such as side payments are shown to mitigate conflicts.

In the analysis of our model we allow out-of-equilibrium play of the game. Imperfect information can lead to misaligned beliefs and agent's may fail to coordinate their actions (Kreps, 1989). Our enforcement-pollution model attempts to capture agents' interactions, particularly the risk of asset stranding when the clean-up cost and fines exceed the net present value of revenues, under a strict policy.

Our model also suggests a potential link between environmental policy design and the winners' curse. Uncertainty implies that firms form subjective beliefs. The most "optimistic" firm is likely to overvalue the expected profits, to underestimate the risks, and to make the winning bid for the licence. This underscores the need to explore how the government and the institutional design may exacerbate winners' curse problem. Allocating resources to firms who take high risks may undermine both public and private goals. Future research can more formally establish the link between bidding for licences and stranded assets.

Additionally, our framework could be extended by explicitly incorporate the expected profit loss from stranded assets into the firm's profit function (Hansen, 2022), and integrating this into the welfare function. Such analysis would shed more light on the government's trade-off between strengthening environmental policy and avoiding capital loss when firms exit and assets get stranded.

In conclusion, we find that stringent policies combined with credible enforcement, promote green production and reduce the risk of asset stranding. This conclusion is aligned with previous literature that points out the role of stringent policy favouring green production (Gray & Shimshack, 2011; Cheng et al., 2025). However, we shed light on the strategic behaviour between agents under uncertainty and role of the

agents' beliefs. If firms incorrectly believe the government will act leniently, when in fact it enforces strict regulations, they may be exposed to significant penalties and the risk of asset stranding. A stringent environmental policy on its own may well be insufficient. It is as important to build up a reputation that policies will be enforced. As long as the government cannot commit, firms have little incentives to invest in a safe and clean environment.

Appendices

Appendix A5.1: Tables

Table A5.1: Oil production (in 1000 barrels)

Year	Peru Production	North Amazon Oil production	Pluspetrol Lot 8	Perenco Lot 67	Petrotal Lot 95	Pluspetrol / Frontera Energy Lot 192
2013	22956	8961	3483	14	6	5407
2014	25296	10070	3489	1846	0	4735
2015	21173	6834	2806	555	0	3473
2016	14773	2148	1601	132	0	415
2017	15900	3520	2132	0	0	1388
2018	17837	5006	2058	135	170	2642
2019	19339	6073	1611	505	1499	2459
2020	14522	3382	594	247	2065	476
2021	14013	3746	0	517	3229	0
2022	14796	4774	0	367	4407	0

Source: INEI (2023a).

Table A5.2: Loreto: Oil lots and firms

Lot	Firm	Contract span	Key characteristics
8	Petroperu	1971-1996	
	Pluspetrol Norte	1996-2024	Pluspetrol Norte declared bankruptcy after been fined 8 million dollars by OEFA for not complying with the remediation activities, according to the firm's Environmental Remediation Plan. The Lot was withdrawn in 2021.
	Upland-Petroperu	2024-2028 (still no production)	Signed a four-year temporary contract
192	Occidental Petroleum (OXY)	1971-2000	The lot is near to 25 indigenous communities of different indigenous groups such as Quechua, Achuar, Kichwa in the river basins Corrientes, Pastaza and Tigre. The previous consultation process was developed during 2018-2021.
	Pluspetrol Norte	2000-2015	
	Frontera Energy (before Pacific Stratus)	2015-2020	
	Petroperu	2020-2024	
	Altamesa Energy Peru-Petroperu	2024-2053 (as yet no production)	In 2023, Pluspetrol got a US$ 70 million fine by OEFA. There has been no production since 2020. Altamesa laid off all employees in Loreto in February 2025. Operations were suspended due to financial problems. Altamesa withdrew the contract and left debts which were assumed by the State national oil firm partner (Petroperu).
95	Perupetro-Harken del Peru	2005-2041	
		2011-2041	
	Gran Tierra Energy Peru	2018-2041 (production since 2018)	Conflicts during 2020 and 2022. In 2023, a Social Fund was created by the firm and included as part of the Contract between the State and the firm. There have been no conflicts since 2023.
	Petrotal		

67	Advantage Resources International Barrett Resources Perenco	1995-2031 1997-2009 2009-2031 (production since 2013)	Overlapping with Pucacuro Protected Area and with an Indigenous Reserve which is a new protected area. In 2024, Perenco withdrew the contract due to overlapping property rights and the creation of a new protected area.
39	Barret Resources Repsol Burlington Reliance Exploration and Production PetroVietnam Exploration and Production Repsol – Perenco	1999-2039 2001-2039 2005-2039 2009-2039 2012 2013	In 2010 and 2012, the Ethic Council of the Norwegian Government Pension Fund recommended, to exclude Repsol and Reliance Exploration and Production, both firms from the Fund. The Fund states that oil operations where indigenous communities without contact live are opposed to the ethical principles of the Fund. In 2014, the recommendation was revoked after Repsol informed the firm sold its share on the joint venture and there was no operation in the lot.
64	Talisman Petroperu Geopark-Petroperu Petroperu	2009-2013 2013-2016 2016-2021 2021-	Talisman withdrew the contract because of conflicts and financial constraints. Geopark withdrew the contract because of conflicts.
121	Subandean E&P	2009-2010	Construction of 1240 km of seismic line.
129	Burlington Gran Tierra Energy Peru	2013	Withdrawn contract
117	Petrobras		Withdrew the contract due to conflicts and financial constraints.

Adapted from: Perupetro (2010); Claps (2013); Council on Ethics (2014); León & Zuñiga (2021).

Appendix A5.2: The mixed-strategy equilibrium of the enforcement-pollution game

The strategy set of the government is $\{s, l\}$ at its first decision node and $\{m, \underline{m}\}$, at its second. The firm's strategy set is $\{b, g\}$; see Figure 5.1 for the game tree and Table 5.2 for the payoffs. We assume for the monitoring costs $0 < m_s < m_l \leq e - C_c + \alpha f$. The latter weak inequality guarantees that monitoring can be worthwhile under the lenient policy. Implementing the strict policy s at cost C_s is only a relevant option if monitoring costs can saved compared to a lenient policy. Therefore, we also assume

$$(m_l - m_s) \geq C_s \quad \Leftrightarrow \quad m_l \geq C_s + m_s.$$

The government's best response to F playing b is to monitor, but the firm's best response to monitoring is g. If g is played the government's best response is to not monitor, but the firm's best response to not monitoring is b. So we do not have a pure-strategy equilibrium. For a mixed strategy equilibrium agents must be indifferent between any of their pure strategies.

Consider the government's belief q that the firm plays b. Then we cannot have $m_l < q(e - C_c + \alpha f)$, since the government would always monitor given such belief and we have seen that this cannot be an equilibrium. Similarly, we cannot have $q(e - C_c + \alpha f) < m_s$ as, in this case, the government would never monitor. Therefore condition (5.3) follows.

$$m_s \leq q(e - C_c + \alpha f) < m_l. \tag{5.3}$$

The condition says that the government would always monitor when it has chosen s and never monitor when it has chosen l.

We can now calculate the equilibrium belief for which G is indifferent between s or l, a condition for the mixed strategy equilibrium. For the equilibrium belief it must hold that

$$q^*(\pi - e) + (1 - q^*)(\pi - C_g) = q^*(-C_s - m_s + \pi - C_c + \alpha f) + (1 - q^*)(-C_s - m_s + \pi - C_g).$$

This simplifies to

$$q^* = \frac{C_s + m_s}{e - C_c + \alpha f}.$$

Similarly for the firm's equilibrium belief p^* that the government chooses the lenient policy, we must have that the firm is indifferent between b or g. This is the case if

$$p^*\pi + (1-p^*)(\pi - C_c - f) = p^*\big(\pi - C_g\big) + (1-p^*)(\pi - C_g).$$

This simplifies to

$$(1-p^*)(C_c + f) \geq C_g.$$

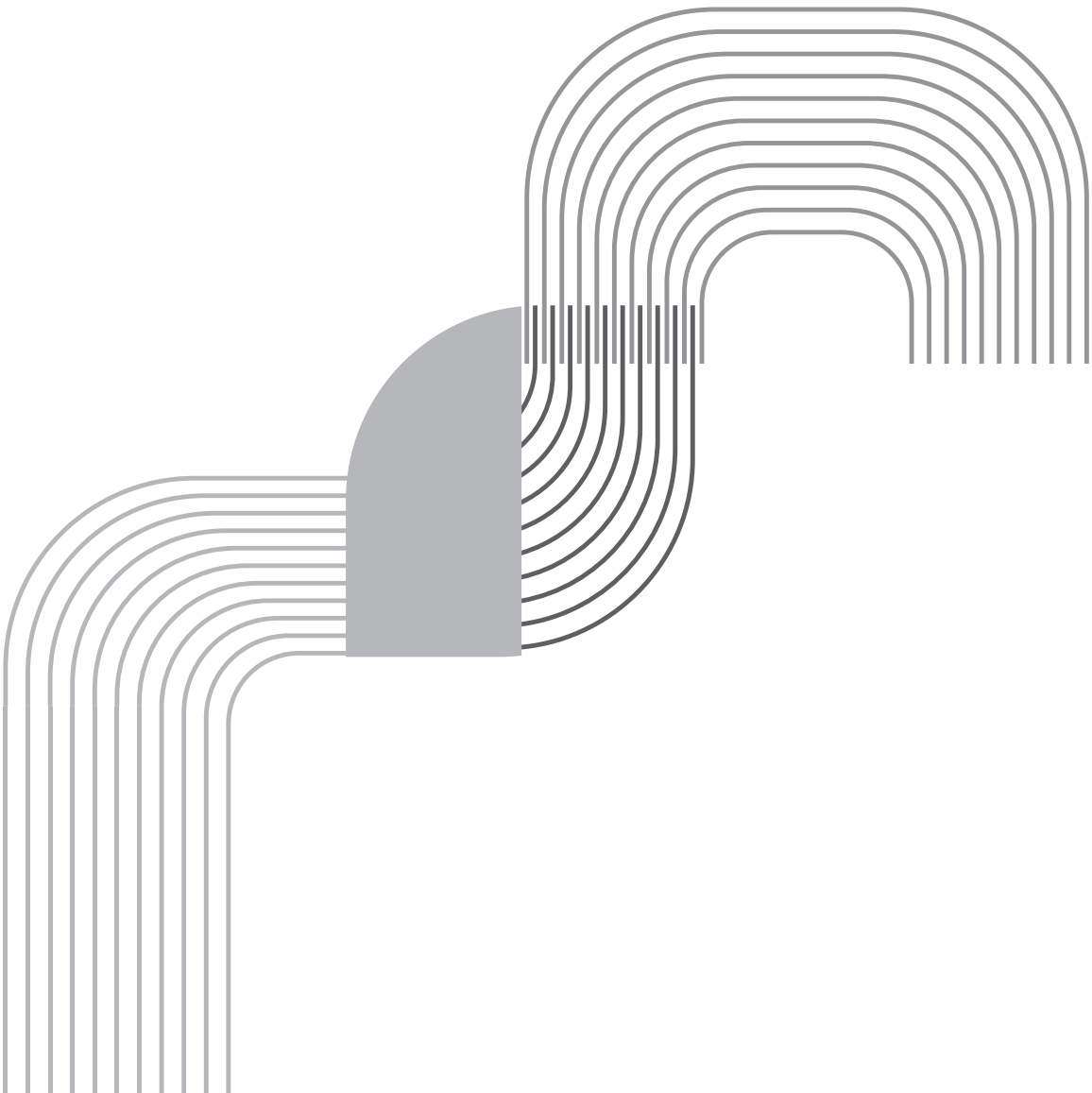
Hence,

$$p^* = \frac{C_c - C_g}{C_c + f}.$$

The unique mixed-strategy Nash equilibrium is G's play of (l, s) with probabilities $(p^*, 1-p^*)$ and F's play (b, g) with probabilities $(q^*, 1-q^*)$. In the equilibrium agents must have correct believes.

Chapter 6

General Discussion and Conclusion



6.1. Synthesis

6.1.1. Key Findings

This thesis addresses water allocation and water pollution in the context of water scarcity, conflicts and weak governance in shared river basins. It investigates (i) how scarce water can be allocated based on rules, (ii) how joint infrastructure investments can mitigate scarcity and conflicts, (iii) how water pollution can be mitigated using side payments, and (iv) through stringent environmental policies.

These questions are associated with the following approaches: (i) the development of a unified model framework for the joint allocation of surface water and groundwater, (ii) the analysis of joint infrastructure investments to increase gains from water sharing and to reduce conflicts, (iii) the analysis of water pollution and conflict resolution through side payments, and (iv) the analysis of the role of environmental standards and their enforcement for the risk of asset stranding. The analyses are based on game-theoretic models to capture the strategic interaction among agents.

Water allocation rules and hydro-economic integration are key to the efficient and equitable outcomes of water allocation (Chapter 2)

Water allocation in drylands becomes challenging in an upstream-downstream setting where two water sources, surface water and groundwater, are hydrologically linked through recharge. The recharge rate indicates the proportion of surface water that infiltrates and replenishes the aquifer. Irrigation is the main water use in such regions and agricultural producers hold claims on both sources. Some producers use surface water and others use groundwater, depending on crop type and production scale. For instance, agri-export producers rely primarily on groundwater, while small and medium-scale producers serving domestic markets rely primarily on surface water.

Recharge generates heterogeneous feasibility constraints across agents, introducing complexities that are not present in classical water sharing models (Ambec & Sprumont, 2002; Ansink & Weikard, 2012). Using sharing rules, Chapter 2 addresses the efficiency-equity trade-off in a unified framework that integrates surface water and groundwater.

This is done using a hydro-economic model that captures the essential physical and economic properties of upstream-downstream interdependence for agricultural producers with different crop patterns and water-use portfolios.

A cooperative game is developed to analyse water scarcity where the agents located along the river have claims that exceed water availability. I propose two water sharing rules which consider the water sources as one interconnected system. These are: the Proportional Rule and Upstream Priority to Surface Water. The Proportional Rule (P) is appropriate when surface water availability is low and provides for an equitable distribution according to claims. The Upstream Priority to Surface Water rule (U) generates efficiency by serving surface water claims first. In this situation the upstream surface water users can get their full claim, but some downstream water users do not receive water. Giving priority to upstream water users reduces water loss when claims to groundwater are small.

The model is applied to the Ica valley, a Peruvian arid area. Calibration results are consistent with the literature that applies sharing rules to water sharing problems (Goetz et al., 2008; Flores-Swagrzak et al., 2020). Our findings show that surface water allocation affects recharge and groundwater availability. Rule P improves recharge and facilitates serving groundwater claims, favouring equity, serving equally surface water and groundwater claims, but potentially leading to water loss. Conversely, Rule U serves surface water claims sequentially, starting with the most upstream user. This rule favours efficiency limiting water loss but implements an unequal distribution. The model demonstrates that when groundwater is more scarce than surface water, recharge becomes critical as well as the flow variability. Therefore, monitoring both is necessary, in particular in the context of climate change. However, effective monitoring requires updated and reliable data. Integrated data systems have administrative and financial costs that must be assessed ex ante to ensure efficient, credible and enforceable implementation of rules.

Cooperative agreements and joint infrastructure investments improve water use efficiency and mitigate conflicts (Chapter 3)

Changes to the Institutional framework triggered by investments and technological innovations can enhance water-use efficiency and

mitigate conflicts in shared river basins. Using an axiomatic approach, I apply the Nash Bargaining Solution (NBS) and the Kalai-Smorodinsky solution (K-S) to demonstrate that a binding agreement for joint infrastructure investments can improve water allocation and welfare, favouring cooperation in a bi-regional river basin, compared to conflict in the *status quo*.

I study the Ica river basin where the agents involved are upstream indigenous communities and downstream agricultural producers. The cooperative solutions capture the efficiency-equity trade-off associated with water redistribution and benefit-sharing. Through joint investments, upstream communities can have water during the dry season, improving alpaca productivity and income in the highlands, while downstream agricultural producers benefit from mitigated conflicts and improved aquifer recharge.

The model differs from the standard bargaining models in the river sharing literature (Atwi & Chóliz, 2011; Houba et al., 2013; Degefu et al., 2017) by explicitly modelling infrastructure investments as determinants of the bargaining set. Investments shifting out the frontier of the bargaining set as well as the disagreement point. The disagreement point is the pay-off each player receives if there is no agreement. The case study shows the economic and social asymmetries between the agents, resulting in divergent fallback positions. Downstream firms have the financial and political capacity to lobby the Government or seek for alternative water markets, while upstream communities depend mainly only on subsistence-based activities.

The findings show that infrastructure investments allow to increase benefits to upstream and downstream agents, compared to a situation without it. The investments increase water availability in both regions. In the upstream region productivity of alpaca raising can be improved through all-year-round water availability that improves rangelands. The downstream region benefits from improved aquifer recharge that makes water available for additional irrigated farmland. Additionally, the shift of the disagreement point reflects communities´ vulnerability reduction to water scarcity. Therefore, joint infrastructure investments change the strategic bargaining positions, which is different from facing water allocation and investments as separate policy domains.

These investments are feasible because of changes in the institutional framework that allows a joint management of water and soils.

The case of the Ica river highlights institutional conditions that facilitate conflict resolution through (i) a change in the political and institutional water framework, (ii) the political will of regional authorities, (iii) effective stakeholders participation, and (iv) international cooperation to strengthen technical capacities. Therefore, institutional change triggered by investments and new technology can improve water use efficiency, mitigate conflicts and enhance cooperation in a context of water scarcity.

Side payments and credible threats incentivise firms to invest in environmental effort and avoid pollution (Chapter 4)

Side payments can solve oil pollution conflicts when the threat to lose them is credible. They are especially relevant in situations of weak governance and asymmetric power relations. Traditionally, oil pollution has been analysed as a problem of negative externalities (Heinz et al., 2007; A. Bebbington, 2011; Yusta-García et al., 2017). This chapter extends the analysis by modelling a sequential game with perfect information between a firm and a community. Side payments are conditioned on non-attack and are embedded within a binding agreement linked to the firm's operating license.

The model shows that side payments can incentivise the firm to invest in environmental effort to avoid pollution and simultaneously incentivise the community to refrain from violence. The magnitude of the side payment is critical. Without it, a firm may find profitable to pollute, while the community attacks to obtain compensation if it exceeds the cost of attack. With side payments, attacks would result in the loss of these payments. Thus, sufficiently high side payments can lead to peace.

Stringent environmental policy contributes to clean production under uncertainty and asset stranding (Chapter 5)

Governments pursue cleaner production, yet weak enforcement often enables firms to pollute if they believe that sanctions will not be applied. When policy shifts toward stringency, firms who previously believed in lenient enforcement may face penalties severe enough to render their assets stranded. A sequential game with imperfect

information is developed, to derive conditions under which the government monitors and the firm either complies or pollutes.

Monitoring is optimal when expected benefits (e.g. welfare gains from pollution control and revenues from fines) exceed monitoring costs. Because of imperfect information agents' beliefs may be true or not and the game may unfold out of equilibrium. Asset stranding occurs when expected future revenues net of variable costs are insufficient to cover environmental liabilities and fines.

The model emphasizes that consistent monitoring is essential for shaping firms' beliefs and ensuring policy credibility. Moreover, a reliable enforcement system (financial, institutional, and human resources), is critical to achieve policy goals.

In light on the research findings, the models show that solving water conflicts depends on institutional designs that shape agents' behaviour by changing incentives, pay-offs and outside options, determining trade-offs between efficiency and equity. The analysis identifies key cross-cutting issues such as the dilemma between efficiency and equity. The thesis demonstrates that, despite asymmetries between the agents, it is feasible to achieve a water conflict resolution if it includes equity. Additionally, a flexible institutional arrangement supported by credible threats and enforcement mechanisms can sustain cooperative equilibria and mitigate opportunistic behaviour. However, evaluating the performance and impacts of mechanisms such as allocation rules, infrastructure investments, side payments require access to open data. Open data strengthen commitment and trust among agents, particularly in environments characterised by significant economic and social asymmetries, enhancing transparency and accountability. Moreover, integrating information systems in the domains of climate, hydrology, production systems and health at the local and regional level entails non-negligible costs. These costs must be incorporated when choosing an institutional design to ensure feasible, reliable and efficient integrated data systems.

6.1.2. General Remarks

Understanding agents' behaviour is essential for improving welfare and mitigating conflicts within river basins. An integration of game theory and institutional economics offers an appropriate framework

for analysing strategic behaviour in contexts characterised by water scarcity, weak governance, asymmetric economic structures and limited enforcement. The thesis contributes to interpreting real-world water conflicts through a solid and consistent theoretical framework to offer solutions by identifying the incentives that guide agents' decisions.

The models developed in this thesis demonstrate that institutional design is a critical determinant of agents' behaviour. Stringent and credible environmental policy and enforcement foster clean production, reduce conflicts and enhance welfare; even in the presence of economic, social and cultural asymmetries. Reliable and consistent institutions build stability in both cooperative and non-cooperative settings.

The cases from Ica, Huancavelica and Loreto reveal common patterns in water-related conflicts: (i) weak enforcement leads to water misallocation or pollution, generating negative externalities and conflicts; (ii) incentives for the local community to attack polluting firms depend on opportunity costs and expected compensation; (iii) asymmetric information and economic, social and cultural differences hamper conflict resolution.

Institutional design provides a framework for agents' decision making, and align coordination among national, regional, local authorities. Water institutions composed of formal and informal, macro and micro rules (Saleth & Dinar, 2008) shape not only water outcomes but also broader institutional and sectoral performance.

The findings demonstrate that a coherent and credible institutional framework is necessary to alleviate water scarcity, support economic activities, reduce conflicts and protect vulnerable ecosystems such as drylands, highlands and rainforests. Game theory, as a formal tool of institutional analysis, provides a rigorous bridge between scientific analysis and policy design, integrating sharing rules, bargaining models, and sequential games to enhance equitable water allocation and management

6.2. Policy Implications

Water allocation and pollution challenges exacerbate water scarcity and intensify conflicts which are further magnified by the adverse effects of climate change. These challenges undermine welfare, hinder economic performance, and degrade environmental conditions. Effective policy design must strengthen coordination between national and subnational authorities, and align environmental policy goals with implementation capacity. Drawing on the Peruvian cases analysed in this thesis, three broad sets of policy implications emerge: (i) stringent policy and enforcement can improve water allocation and foster clean production (Chapters 2, 3 and 5); (ii) side payments can enhance welfare and mitigate conflicts, when weak governance prevails (Chapter 3 and 4); (iii) improved information provision reduces uncertainty, shapes expectations, and supports conflict mitigation (Chapters 3-5). These insights offer practical lessons for developing economies.

(i) Stringent policy and enforcement can lead to improve water allocation and clean production.

Institutional design provides incentives and may lead to conflict or cooperation. An environmental policy can be strict or lenient. A strict environmental policy and enforcement can lead to efficient water allocation and reduce pollution. However, the lack of government's enforcement capacity make the agents' believe that they can pollute and get away with it.

A strict environmental policy needs monitoring, which requires consistency and reliability in its application to help shape firms' beliefs and guide their decisions on the environmental measures taken. Monitoring has costs but also is a condition for achieving policy goals (Chapter 5). Monitoring under a strict environmental policy would have lower costs because financial resources are allocated as part of a strategy to provide institutional infrastructure, technical personnel and enforcement resources for achieving the policy goals. Conversely, under a lenient policy monitoring would have higher costs because the monitoring effort is fragmented, inconsistently applied and underfunded. Therefore, monitoring can lead to improve firms' sustainability, reducing environmental infractions, pollution and conflicts.

Stringent policy and enforcement are critical in water allocation in a river sharing problem, too. Water allocation needs to rely on rules in order to set property rights, acknowledging water users' claims and the trade-off between efficiency and equity, when two water sources are related (Chapter 2). The hydro-economic model shows the role of recharge when two water sources (surface water and groundwater) are related and shared by agricultural producers located upstream and downstream in an arid area. The model shows that surface water allocation affects groundwater availability. Hence, monitoring hydrological variables and recharge become critical because recharge is vulnerable to flow variability.

Institutional changes can facilitate the upstream-downstream relationship improving water availability, welfare and conflict mitigation. Political will and stakeholders' participation are critical for conflict resolution. A lesson learned is that national government intervention for investments need to be coordinated with subnational governments and local stakeholders to avoid conflicts.

(ii) Side payments can improve welfare and mitigate conflicts when weak governance prevails

Side payments facilitate conflict resolution. The thesis illustrates that this mechanism works in water allocation and pollution solutions (Chapters 3 and 4), improving welfare. The institutional changes that allow bi-regional management, provide the conditions for side payments. In this case, downstream water users would be willing to pay upstream water users since the former have a higher marginal value than the latter. Therefore, side payments facilitate water transfer to downstream, improving water allocation and increasing the social welfare in the river basin.

Side payments can solve conflicts between firms and local populations that are due to water pollution. A side payment, which includes a credible threat in an institutional agreement, can mitigate negative externalities and facilitate stable and peaceful outcomes, despite weak governance prevails (Chapter 4).

Stakeholders' participation is necessary for understanding the nature, the purpose and the benefits of the side payment. Side payments may

change the game and become a mechanism for solving a conflict, improving welfare and enhancing cooperation.

(iii) Information provision to stakeholders can reduce uncertainty and mitigate conflicts

Under uncertainty agents respond according to their beliefs. A history of lack of trust and commitment creates adverse conditions for solving conflicts (Chapters 3, 4 and 5). Lack of information may trigger conflicts, particularly when agents have economic, social and cultural asymmetries (Chapters 3 and 4).

Lack of information about agents' behaviour leads to decisions based on beliefs. Agents decide according their beliefs about the strategy of the other agent (Chapter 5). However, if the firm believes that a lenient policy would be implemented and the government decides a strict policy then the firm will be fined and may go out of business and face asset stranding.

Information is useful for agents' decision making. A reliable, updated and open access data system has administrative and financial costs. However, lack of information leads to decisions under uncertainty which can generate inefficient outcomes, such as limiting conflict resolution.

A general policy implication is that transparency, allocation mechanisms and credible enforcement can turn conflicts into cooperation opportunities to manage water scarcity and conflicts.

6.3. Contribution to the Literature

This thesis contributes to the literature on water economics by integrating game theory and institutional economics to tackle problems of water scarcity, pollution and conflicts applying cooperative and non-cooperative games, providing solutions to conflicts and stable outcomes. Game theory gives a solid framework for a better understanding of agents' behaviour in strategic interaction.

6.3.1. Contributions to models on water sharing

Water allocation is analysed extending the water sharing framework which has been extensively applied to address transboundary river

conflicts (Ambec & Sprumont, 2002; Ansink & Weikard, 2012; Atwi & Chóliz, 2011; Degefu et al., 2017). On the one hand, there is an extensive literature that has used a utility or welfare framework, while here we focus only on the resource availability and resource allocation. This thesis extends the water sharing problem considering two related water sources (surface water and groundwater) with claims for both water resources (Chapter 2). The hydro-economic model highlights the role of recharge which connects these two water sources, shedding light how surface water allocation influences groundwater availability within an upstream-downstream interdependence. The model is inspired by (Yang et al., 2025) who analyse the allocation of pollution rights to agents located along a river. We highlight the role of recharge which connects these two water sources. Another contribution is adjusting sharing rules to this more complex setting. Two rules are proposed, Proportional Rule and Upstream Priority to Surface Water, that can guide the interdependent water allocation. This analytical framework shows, from a static perspective, the role of the recharge rate and of water flow. This is a first attempt, to apply the hydro-economic model in an arid area under different situations of water flow, with the purpose of demonstrating that rules are necessary, and the criteria to select them depends on water availability, rate of recharge, claims and water users' location.

The cooperative game models are extended, using the Nash Bargaining Solution and the Kalai-Smorodinsky solution for water allocation (Mehrparvar et al., 2016) and the sharing of gains from cooperation. The mentioned solutions are applied in the situation where the bargaining set is expanded due to infrastructure investments (Chapter 3). Both solutions show welfare improvements compared to the *status quo.* The *status quo* leads to conflicts, while sharing gains associated to investments leads to an improved water allocation, mitigates conflicts and increases welfare.

6.3.2. Contributions to models on oil pollution of water resources and conflicts

The thesis explores oil pollution of water resources and related conflicts, extending the role of side payments, including punishment. This mechanism is useful for conflict resolution, under certain conditions, mainly when weak governance prevails (Chapter 4). A

novelty is to highlight the potential link between conflicts and asset stranding. This connection is relevant to understand the conditions under which the community has incentives to attack or not and the firm to pollute or not. I acknowledge that stranded assets have been studied associated to climate change effects, increasing environmental regulations that can lead to asset stranding (Dinar, 2006; Kimbrough & Sheremeta, 2013; Caldecott et al., 2021).

Oil pollution and conflicts indirectly suggest weak governance with limited enforcement of law generating incentives to attack, which can affect the communities' livelihoods and the industry's economic performance.

6.4. Limitations and Future Research

This thesis examines how strategic behaviour by agents can lead to water misallocation or pollution and finds the conditions and solutions that can improve water management, solving conflicts and improving welfare. I acknowledge model simplifications such as their static structure, limited empirical calibration, but without missing the main variables for the analysis.

Further research can address dynamic modelling under climate change impacts, behavioural experiments and agent-based approaches to capture adaptative decision making linked to institutional changes. Dynamic models are useful to analyse seasonality of river flow. River flow variability affects water allocation, which is exacerbated by the adverse effects of climate change. To this extent, infrastructure investments to reduce vulnerability can be analysed as benefit sharing or cost sharing games. It is particularly relevant when water sources are related and river flow affects groundwater availability. Exploring the role of investments or side payments in a dynamic setting can capture recharge improvements over time such that the infiltration rate becomes endogenous in the model of Chapter 2. However, this setting is analytically involved and data demanding which hampers applicability.

On water pollution, further research can extend the game with additional agents. For instance, the model of oil pollution conflicts between a firm and a community can be refined. The State can

facilitate building trust between the agents by monitoring the community's benefits from side payments. Moreover, the model of oil pollution and stranded assets (Chapter 5), can include the community as an additional agent bearing the risk of pollution and conflicts. Additionally, a preceding stage of game can be included for a better understanding of the bidding process, where the bidders make an assessment of the resource value. If the bid is higher than the expected value of the resource, there would be a risk of asset stranding if a bidder with limited financial resources cannot comply with environmental regulations due higher production costs. As a result, the risk of pollution can lead to conflicts and also to asset stranding.

6.5. Concluding Remarks

This thesis demonstrates that water scarcity and pollution conflicts, can be transformed into opportunities for enhancing welfare and cooperation when they are analysed with game theory and institutional economics approaches. The research highlights the agents' strategic interaction by integrating theoretical modelling with real-world cases in Peru. It shows that when agents' behaviour is guided by credible institutions and cooperative mechanisms, water scarcity can be transformed into a welfare sharing.

Credible institutions and enforcement are critical to align incentives leading to efficient water allocation and controlling water pollution. Effective enforcement can facilitate the achievement of economic, social and environmental policy goals by mitigating conflicts and enhancing cooperation.

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Summary

Water scarcity is a long-standing worldwide concern that requires deeper attention. It is an increasing global challenge which threatens economic development, environmental stability and social cohesion. Water resources are shared by multiple users, including households and industry, and exhibit variability in time and space, which is exacerbated by climate change. Additionally, rising pollution affects water scarcity, limiting freshwater for competing users. These pressures can lead to conflicts affecting welfare. Although Latin America suffers little from water stress on a continental scale (UN-Water, 2024), this is different for particular countries and regions across Latin America. While in Mexico water stress is 45.6%, in Brazil it is 1.5% (UN-Water, 2024). In Latin America, water-related conflicts have increased, becoming the fourth region worldwide with more water conflicts in 2023 (Pacific Institute, 2024).

The overarching objective of this thesis is to contribute analyses and solutions to real-world water conflicts by examining the strategic behaviour of the agents under water scarcity and weak governance. This thesis focuses on water allocation and water pollution in Peru. Peru is a relevant country for study in this domain, because its increasing water stress, raising from 5.6% in 2015 to 7.2% in 2021 (UN Water, 2024), water pollution and conflicts under weak governance. Peru's heterogenous geography, including coastal areas, highlands and extensive rainforest, shows a mismatch between freshwater availability and the spatial distribution of population and economic activities. Moreover, Peru is among the countries most vulnerable to climate change, where 56% of the glacier area has melted during the last six decades (INAIGEM, 2023).

The thesis addresses four research questions:

1. How can water resources be allocated to surface water and groundwater users when allocation and availability are interdependent? This question addresses an equity-efficiency trade off. (Chapter 2)

2. How can infrastructure investments be designed to solve conflicts and improve welfare? This question explores the potential of investments to transform a conflict into a win-win situation. (Chapter 3)
3. To what extent can side payments mitigate negative externalities and facilitate stable and peaceful outcomes with improved welfare, when weak governance prevails? This question studies conflicts when law enforcement is weak or absent. (Chapter 4)
4. How can a stringent environmental policy and enforcement incentivise clean production and how does it affect the risk of asset stranding? Addressing this question sheds more light on government's (lack of) incentives to enforce the law. (Chapter 5)

To answer these questions, we use case studies and micro-economic modelling, applying game theory. The cases provide information on agents, their preferences, and their choice options which are the elements to analyse strategic interaction and the role of the institutional framework. The models capture the mechanisms underlying conflictive situations. Although the models are inspired by specific cases, they are general enough to apply to other locations or industries.

The methodological approach for each research question is as follows:

Water allocation and hydro-economic integration (Chapter 2). A cooperative game theory model of sharing emission rights in a river setting (Yang et al., 2025) is modified and extended to analyse the allocation of surface water and groundwater in an integrated way, where groundwater recharge has a critical role. We develop a unified hydro-economic model where water users have claims to both water sources at their location, extending the sequential river sharing literature (Ambec & Sprumont, 2002b; Ansink & Weikard, 2012b). Two allocation rules are proposed: the Proportional Rule (P) and a rule that gives Upstream Priority to Surface Water (U). The model is applied to the Ica valley. The calibration results are consistent with the literature that applies water sharing rules. The findings demonstrate that surface water allocation affects recharge and groundwater availability. Rule P favours recharge and facilitates serving groundwater claims,

promoting equity, but leading to water loss. Conversely, Rule U serves surface water claims sequentially, starting from most upstream user. This rule promotes efficiency, limiting water loss but leads to an unequitable distribution. The model demonstrates that when groundwater is more scarce than surface water, recharge becomes critical.

Cooperative agreements and joint infrastructure investments (Chapter 3). To analyse a conflictive water sharing problem, we use a cooperative game approach in an upstream-downstream setting and include joint infrastructure investments to assess its contribution to welfare and cooperation improvements. The agents are two regions characterised by economic, social and cultural asymmetries. A bargaining framework is applied, using the Nash Bargaining Solution (NBS) and the Kalai-Smorodinsky solution (K-S). Both solutions demonstrate that a binding agreement on joint infrastructure investments can improve water allocation and welfare, enhancing cooperation. The cooperative solutions capture the efficiency-equity trade-off associated with water redistribution and benefit-sharing.

Oil pollution conflicts, side payments and pacification (Chapter 4). A sequential game is developed to analyse the strategic interaction between a firm and a community in presence of oil pollution externalities. The model derives the conditions under which side payments and compensations schemes can deter community retaliation and avoid violent conflict, while influencing the firm's environmental effort decision in the presence of penalties and threats. The magnitude of the side payment is critical. Without side payments, the firm may find profitable to pollute, while the community attacks to achieve compensations. With side payments, the community's incentives to attack are attenuated such that side payments support peace.

Oil pollution and stranded assets (Chapter 5). A sequential game with incomplete information is used to model the strategic interaction between the government and a firm under uncertainty. The chapter addresses the role of agents' beliefs in shaping agents' strategies. Based on beliefs about the other player's strategy, each agent chooses his action. We derive conditions for assets getting stranded, explaining the government's incentives to monitor or not and the firms' decisions to

produce clean or not. The model emphasizes that consistent monitoring is essential for shaping firms' beliefs and ensuring policy credibility. Moreover, a reliable enforcement system demands human, institutional and financial resources to achieve policy goals.

The Peruvian case studies provide insights for modelling water-related conflicts, to understand the strategic interaction between agents under weak governance. The thesis proposes solutions aimed, on the one hand, to improve water allocation based on allocation rules and joint infrastructure investments. On the other hand, to mitigate pollution based on side payments with a credible threat. The role of stringent policy and enforcement is critical to support a coherent and credible institutional design. This can provide incentives to agents' alignment to policy goals which can alleviate water scarcity, support economic activities, reduce conflicts, and protect vulnerable ecosystems. As a result, welfare and cooperation can be enhanced.

This thesis contributes to the water economics literature by integrating game theory and institutional economics. The microeconomic models capture the agents' decision-making that responds to the incentives generated by the governance system. The thesis extends on previous literature. In case of water sharing problem, by analysing water allocation of two interdependent water sources, including recharge, and proposing allocation rules, as it was explained previously. The bargaining problem is extended by including joint infrastructure investments. These extensions help to have a better understanding of the allocation problem and find solutions to improve water allocation and mitigate conflicts. In case of water pollution, the extension is on side payments, including a credible threat to solve conflicts.

A general policy implication is that transparency, well-designed allocation mechanisms, and credible enforcement can turn conflicts into opportunities for cooperation to manage water scarcity and conflicts. Water allocation failures and pollution undermine welfare, hinder economic performance, and degrade environmental conditions. Effective policy design requires strengthening coordination between national and subnational authorities and aligning environmental policy goals with enforcement capacity.

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Zoila del Rosario Gómez Gamarra
Wageningen School of Social Sciences (WASS)
Completed Training and Supervision Plan



Name of the learning activity	Department/Institute	Year	ECTS*
A) Project related competences			
A1 Managing a research project			
WASS PhD Introduction	WASS	2016	1
PhD Research proposal	WUR	2016	6
Scientific Writing	Wageninegn in'to Languages	2018	1.8
'Gestión de los Recursos Naturales' (*Natural Resources Management*)	Conference: Retos del desarrollo en el Perú (*Challenges for Peru development*) Universidad del Pacífico/Research Center-Latin American Centre Oxford University, Lima, Peru	2018	0.5
'Políticas públicas, bosques y valoración económica' (*Policy, forests and economic valuation*)	Workshop: Deforestación y conexiones con el bienestar *(Deforestation and welfare connections).* Universidad del Pacifico-Department of Economics and Research Center, Lima, Peru	2024	0.5
A2 Integrating research in the corresponding discipline			
Research Methodology	WASS	2016	4
Cost-Benefit Analysis, ENR 33306	WUR	2017	6
B) General research related competences			
B1 Placing research in a broader scientific context			
Coordination and participation in Citylab project	Universidad del Pacífico & Erasmus+. Lima , Peru	2016-2018	6
B2 Placing research in a societal context			
Organizing International Summer School: Spatial analysis, land use and environment	Universidad del Pacifico & Nova School of Business and Economics, Lima, Peru	2020	3
Writing a book chapter: Gestión de los Recursos naturales: retos al 2030" (Natural Resources Management: Challenges to 2030)	Portocarrero & Vergara (2019) eds. Aproximaciones al Perú de hoy desde las Ciencias Sociales, Lima, Peru	2019	1
C) Career related competences/personal development			
C1 Employing transferable skills in different domains/careers			
Teaching and supervising students	Universidad del Pacífico, Lima, Peru		4
Total			**33.8**

*One credit according to ECTS is on average equivalent to 28 hours of study load

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