Trust and transboundary groundwater cooperation

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Abstract

International transboundary aquifers provide important water supplies to over 150 countries. Long-term sustainability of these aquifers requires transboundary cooperation and yet only a select few (1%) transboundary aquifers are formally regulated by a treaty. To better understand the drivers and incentives that allow treaties to emerge, we develop a two-player game to model the social dilemma of transboundary aquifer cooperation. The game incorporates socio-economic and hydrogeological features of the system and highlights the importance of trust to evaluate the benefits and risks of any treaty. We validate the game through a case study of the Genevese aquifer, which is governed by the longest-running and most collaborative transboundary aquifer treaty on record. We then focus on the symmetric game between identical players to explore the role of groundwater connectivity, alternative water supply, water demand, and trust on the emergence of transboundary treaties. The solution space highlights how incentives for cooperation are greatest when the value of water is commensurate with the cost of groundwater abstraction. Cooperation requires high trust in situations characterized by water abundance or scarcity. The model further indicates how two different types of agreements are likely to emerge. Treaties that limit abstraction have greater potential when countries have access to an alternative water source, whereas treaties that restrict pumping near the border have greater potential in water-scarce regions with emerging concerns over groundwater depletion. In addition to helping explain the emergence of existing treaties, this framework offers potential to identify aquifers that may be amenable to cooperation.

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Key Points:

- We apply game theory to explore social and hydrological aspects of transboundary aquifer cooperation
- Cooperative behavior depends on trust and whether groundwater abstraction is cost or demand limited
- Both water scarcity and groundwater connectivity increase risk and limit pathways for cooperation

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Abstract

International transboundary aquifers provide important water supplies to over 150 countries. Long-term sustainability of these aquifers requires transboundary cooperation and yet only a select few (1%) transboundary aquifers are formally regulated by a treaty. To better understand the drivers and incentives that allow treaties to emerge, we develop a two-player game to model the social dilemma of transboundary aquifer cooperation. The game incorporates socio-economic and hydrogeological features of the system and highlights the importance of trust to evaluate the benefits and risks of any treaty. We validate the game through a case study of the Genevese aquifer, which is governed by the longest-running and most collaborative transboundary aquifer treaty on record. We then focus on the symmetric game between identical players to explore the role of groundwater connectivity, alternative water supply, water demand, and trust on the emergence of transboundary treaties. The solution space highlights how incentives for cooperation are greatest when the value of water is commensurate with the cost of groundwater abstraction. Cooperation requires high trust in situations characterized by water abundance or scarcity. The model further indicates how two different types of agreements are likely to emerge. Treaties that limit abstraction have greater potential when countries have access to an alternative water source, whereas treaties that restrict pumping near the border have greater potential in water-scarce regions with emerging concerns over groundwater depletion. In addition to helping explain the emergence of existing treaties, this framework offers potential to identify aquifers that may be amenable to cooperation.

1 Introduction

Groundwater is an essential shared resource. It acts as a reservoir that buffers against climate variability and provides water that is often more accessible than the nearest surface water body [*Wijnen et al.*, 2012]. Global water use relies heavily on groundwater, which comprises over 40% of irrigation [*Siebert et al.*, 2010] and 50% of urban water consumption [*Zektser and Everett*, 2004]. The convenience of groundwater, however, belies its susceptibility to overdraft and depletion [*Shah*, 2014; *Wada et al.*, 2010]. Abstraction exceeds recharge in many aquifers, jeopardizing future water supply and often reducing downstream water availability [*Bierkens and Wada*, 2019; *de Graaf et al.*, 2019]. Groundwater is a common-pool resource, where pumping by individual users generates private profits while increasing the pumping costs to all users [*Negri*, 1989]. The ensuing externalities create incentives to over-pump groundwater in what has been described as a tragedy of the commons [*Gardner et al.*, 1997]. The benefits of groundwater withdrawals accrue immediately yet the consequences build slowly and are difficult to understand, assess, and monitor [*Gleeson and Richter*, 2018]. Effective groundwater management is therefore essential but often challenging, and groundwater regulation has lagged behind surface water regulation despite the widespread dependence on groundwater resources [e.g., *Sax*, 2002; *Water Governance Facility*, 2013].

The problem of groundwater management in transboundary aquifers is further compounded by a limited availability of policy frameworks [*Eckstein and Sindico*, 2014; *Conti*, 2014; *Rivera and Candela*, 2018], despite ongoing groundwater depletion in numerous transboundary aquifers [*Wada and Heinrich*, 2013; *Herbert and Döll*, 2019]. Over 150 nations share a transboundary aquifer [*IGRAC and UNESCO-IHP*, 2015] and many of them lack the technical capacity to adequately assess groundwater resources, leading to a situation in which transboundary groundwater is severely understudied and under-managed [*Eckstein*, 2007, 2017]. This situation contrasts with transboundary rivers, which have been studied and regulated intensively [*Wolf*, 2007]. Although many more transboundary aquifers have been discovered [592, *IGRAC and UNESCO-IHP*, 2015] than transboundary rivers [310, *McCracken and Wolf*, 2019], international agreements covering surface waters outnumber agreements covering transboundary aquifers by a factor of 100 to 1 [*TFDD*,

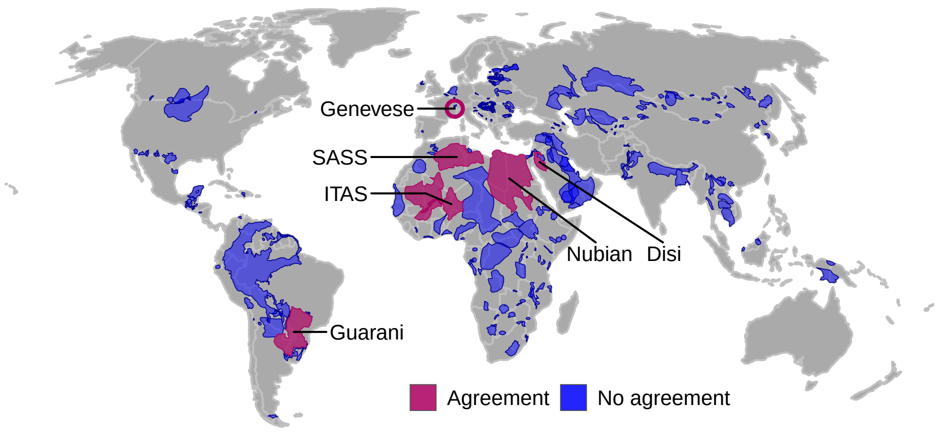

Figure 1. Global transboundary aquifers [*IGRAC and UNESCO-IHP*, 2015]. Of nearly 600 international transboundary aquifers, only six fall under an international agreement [*Burchi*, 2018]. Of these, only the Genevese and Disi have explicit provisions limiting abstraction. Treaties on the Guarani aquifer, the Nubian sandstone aquifer, the Northwestern Sahara Aquifer System (SASS), and the Iullemeden and Taoudeni-Tanezrouft Aquifer System (ITAS) rely on diplomacy and soft-law instruments.

2016; *Burchi*, 2018]. Only six transboundary aquifers are currently regulated by a transboundary treaty (Figure 1), and only two of them place regulations on groundwater use [*Burchi*, 2018]. The Genevese aquifer treaty (originally signed in 1978) regulates artificial groundwater recharge and abstraction by Switzerland and France [*de los Cobos*, 2018], and the Disi aquifer agreement (signed in 2015) restricts abstraction within a buffer area on either side of the border betwen Jordan and Saudi Arabia [*Müller et al.*, 2017]. The remaining agreements rely on soft-law instruments recommended by United Nations guidelines promoting diplomacy and cooperation [*UNGA*, 2008; *UNECE*, 2014], but fall short of explicitly regulating groundwater use.

In this manuscript we model key features of transboundary aquifer scenarios that ultimately incentivize the creation of binding transboundary treaties, and use the results to provide insights and understanding regarding the cooperative management of transboundary aquifers. We focus especially on the Genevese treaty as a case study to validate key aspects of the model dynamics. We use the Disi agreement as a contrasting example, where different incentives and policy produced a fundamentally different agreement than in the Genevese. These differences prompt important questions about each of these scenarios. For instance, the Genevese is mostly used for urban supply whereas the Disi supports urban and agricultural users. While the Genevese reduces incentives to over-pump by explicitly limiting abstraction, the Disi agreement reduces incentives to over-pump by ensuring a minimum distance between water users on either side of the border. We therefore ask, what underlying circumstances led to such distinct policy frameworks in the two treaties? Under which conditions should volume-based or distance-based transboundary aquifer treaties be expected or encouraged? We address these questions by investigating the emergence of transboundary groundwater agreements in the context of social and geophysical characteristics, with an emphasis on the role of trust between countries.

Trust is particularly important in an international context where the objectives of multiple countries may be in opposition, and where complete oversight of water use is impossible given the sovereignty of each actor [*Wolf et al.*, 2005; *Edelenbos and van Meerkerk*, 2015]. Trust building initiatives are essential components of transboundary negotiations over water, particularly in situations where international partners do not have a history of cooperation [*Wolf*, 2010; *Islam and Susskind*, 2013; *Susskind and Islam*, 2012]. Existing transboundary aquifer agreements all include mechanisms intended to build trust between countries, including joint monitoring, information sharing, and increased collaboration [*Burchi*, 2018]. Trust between Swiss and French negotiators played an important role in developing the Genevese treaty [*de Los Cobos*, 2012], and other transboundary surface water agreements have succeeded or failed on the basis of trust [*Biswas*, 2011]. More fundamentally, trust is central to the emergence of collective action to successfully manage common pool resources and avert tragedies of the commons [*Ostrom*, 1990]. Trust helps resolve a basic social dilemma where socially optimal shared outcomes rely on actors forgoing individual gains for the benefit of the group [*Ostrom*, 2003; *McAllister and Taylor*, 2015]. Such individual sacrifice only occurs when actors display a sufficiently high level of trust, defined as the belief that others will reciprocate and comply with any cooperative agreements [*Ostrom*, 2009; *Hardin*, 2001].

We incorporate trust within a model of transboundary aquifer cooperation that captures key socio-economic and hydrogeological features of the coupled human-water system, building on previous work in the Disi aquifer [*Müller et al.*, 2017]. We apply game theory to investigate how economic incentives, hydrogeological constraints, and trust can give rise to formal cooperation over shared groundwater. Game theory has a rich tradition in water resources management to model decision making and conflict resolution within water resource systems [see *Madani*, 2010; *Müller and Levy*, 2019, for extensive reviews]. In this manuscript, we develop a Bayesian game of incomplete information to represent key strategic incentives that underpin transboundary groundwater dynamics (Section 2). The Bayesian nature of the game allows us to formally incorporate trust as the belief of each player that the other player will comply with a cooperative agreement. The game is fully coupled with a groundwater model that determines well drawdown and pumping costs. We validate the game by verifying its ability to qualitatively reproduce the dynamics, narrative, and sequence of events that gave rise to the Genevese aquifer treaty (Section 3). We then analyze the comparative statics of the game by exploring outcomes (i.e. whether there is a treaty and how much groundwater is being used) under a range of economic and hydrogeologic conditions (Section 4). Finally, we reconcile our understanding of the game with existing transboundary aquifer treaties, and use this as a basis to explore a typology of transboundary groundwater institutions (Section 5).

2 Derivation of the transboundary aquifer game

2.1 Utility and groundwater hydrology without cooperation

Consider two players who share an aquifer and must each satisfy a given water demand. Each player can abstract groundwater from the aquifer and also access water from an alternative source, such as surface water or desalinated sea water. The players must therefore determine how much water to supply from each of the two sources to meet demand while minimizing overall costs (Figure 2a). In the absence of cooperation, each player maximizes their individual utility without considering the outcome of the other player. For player i, we formally define this utility as

$$U_i(q_i) = -p_{0i}(Q_i - q_i) - B(d_i)q_i \tag{1}$$

where Q_i is the volumetric water demand that the player must satisfy, $q_i \leq Q_i$ is groundwater abstraction from the shared aquifer, and $Q_i - q_i$ is the quantity supplied from the alternate water source. The parameter p_{0i} represents the unit cost of water from the alternative source, which can also be interpreted as the market value of water (e.g., the cost of purchasing water from another supplier). Lastly, $B(\cdot)$ is the cost of abstraction as a function of groundwater depth, d_i. In confined aquifers, we approximate this cost as $B(d_i) = \beta d_i$, where the proportionality factor β can be interpreted as the cost of energy required to lift a unit of water by a unit length, with units [\$ m^{-3} m^{-1}]. We also define a nonlinear function for $B(d_i)$, to be used in unconfined aquifers, in the Supporting Information (Section S2.1).

In confined aquifers, the groundwater flow equations are linear with respect to hydraulic head [*Strack*, 2017], and the principle of superposition entails that the net effect of pumping by all players can be calculated as the sum of the individual effects of each player [*Brozović et al.*, 2010]. We therefore write the groundwater depth for each player i as

$$d_i = d_{0i} + D_{ii} q_i + D_{ij} q_j \,, \tag{2}$$

where d_{0i} is the undisturbed groundwater depth (i.e., d_i when $q_i = q_j = 0$), and D_{ii} and D_{ij} relate groundwater depth of player i to groundwater abstraction, q_i and q_j, respectively. We similarly define an equation for groundwater depth in unconfined aquifers, which we present in the SI (Section S2.1).

Both abstraction (q_i) and the drawdown relationships (D_{ii} and D_{ij}) remain static for the duration of the game, reflecting the fact that water supplies are often constrained by infrastructure and prior decisions. In the context of the game, this indicates that the decision to abstract q_i puts each player on a path from which they cannot deviate. This assumption is supported by data in the Genevese aquifer, where abstraction for Switzerland and France has been relatively constant since both parties signed the treaty (see Section S2.2), and is also supported by prior analysis in the Disi aquifer [*Müller et al.*, 2017]. The assumption of static drawdown relationships implies that players either assume D_{ii} and D_{ij} depend on the length of the game or that the aquifer has reached steady-state.

The drawdown relationships (D_{ii} and D_{ij}) can be calculated through a variety of methods using numerical models [e.g., *Müller et al.*, 2017] or the analytical element method [e.g., *Penny et al.*, 2020]. In the particular case of a confined, homogeneous, and isotropic aquifer where each player operates a single well, D_{ii} and D_{ij} could be derived analytically from the Thiem solution [*Thiem*, 1906].

Without any form of cooperation, the game is solved by determining the Nash equilibrium in which each player maximizes their own utility, conditional on the other player maximizing theirs. In this case player i abstracts q_i^N, determined through simultaneous optimization of their individual utility as

$$\frac{\partial U_i}{\partial q_i} = 0 \,. \tag{3}$$

Importantly, the groundwater depth of each player depends on the pumping rates of *both* players (Equation 2). Because the cost of abstraction $B(d_i)$ increases with depth, groundwater abstraction by one player leads to a pumping-cost externality which is imposed on the other player [*Negri*, 1989]. In other words, the Nash equilibrium produces a situation where both players over-pump and over-pay for water supply. Players can, however, increase their individual utilities by targeting the socially optimal solution. Doing so requires cooperation.

2.2 Cooperation and trust

Cooperation in the context of the transboundary aquifer game means that players collectively optimize their joint utility so that they both benefit. The socially optimal solution requires either or both players to reduce pumping compared to the Nash equilibrium, thereby reducing groundwater drawdown and the average cost of abstraction (i.e., $B(d_i)$). More precisely, the social optimal can be formalized through a treaty that stipulates abstraction rates of each player in order to maximize the sum of utility of all players. Depending on the economic and hydrogeological characteristics, one player may be required to sacrifice more groundwater abstraction than the other player. For this reason, we allow

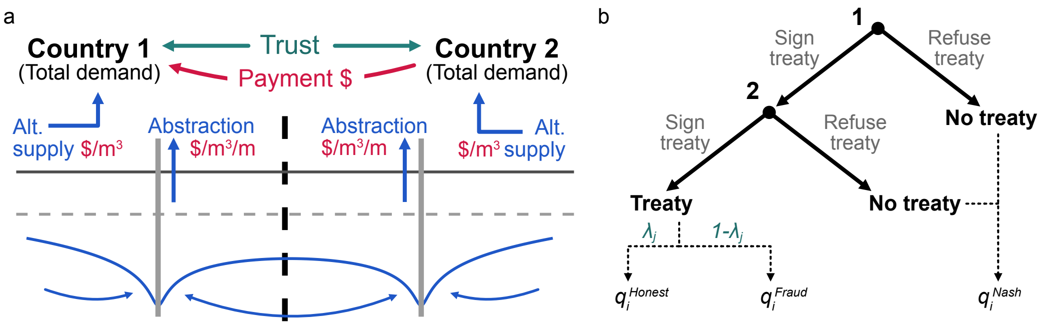

Figure 2. Conceptual model of the transboundary aquifer game, including (a) groundwater and economic model and (b) player decision making and pumping. Both players 1 and 2 must satisfy a total demand, Q_i, through groundwater abstraction (q_i) and an alternative supply, each with associated costs. If either player refuses to sign a treaty, both players pump at the Nash equilibrium q_i^{Nash} (or q_i^N). If both players agree to sign the treaty, Honest players comply with the treaty and pump q_i^{Honest} (or q_i^H), while Frauds maximize their individual utility and pump q_i^{Fraud} (or q_i^F). Each player knows its own type, which is fixed for the entirety of the game. Each player j also has a belief (trust, or $\lambda_j \in [0,1]$) that the other player i is Honest and abstracts q_i^H. Accordingly, this coincides with a belief $(1-\lambda_j)$ that the other player is a Fraud and abstracts q_i^F.

for side payments between players to compensate any differences. We formally define utility for player i under the treaty as

$$U_i(q_i) = -p_{0i}(Q_i - q_i) - B(d_i)q_i - \epsilon_i \pm z, \tag{4}$$

where the new parameter ϵ_i is the cost of signing a treaty (e.g., implementation or monitoring costs), and $z \in (-\infty, \infty)$ represents a payment to player 1 from player 2 to ensure that both players benefit from the treaty, even when one player must sacrifice more groundwater abstraction. Abstraction rates under the optimal treaty, q_i^H, are determined by the joint maximization of utility of both players as

$$\frac{\partial(U_i + U_j)}{\partial q_i} = 0\,. \tag{5}$$

Signing a treaty may appear to be an obvious solution to the pumping-cost externality, but the difficulty of monitoring abstraction (both practical and political) means that neither player can be completely certain that the other player complies with the treaty. Entering into a treaty with a transboundary partner therefore requires trust between countries. We account for trust by assuming that players are either Honest ($t_i = H$) or Fraudulent ($t_i = F$), and that their type is randomly determined. Honest players always comply with any signed treaty and abstract q_i^H (Eq. 5), while Frauds always act in their own self-interest and abstract q_i^F (Eq. 7, below). Each player knows their own type but not the type of the other player. Following standard definitions of trust [see *Hardin*, 2001], we formally incorporate trust into the game as the belief (expressed as the probability $\lambda_i \in [0,1]$) of player i that player j will comply with the treaty, given the possibility that player j could instead disregard the treaty and pump at a higher rate. This stylized form of trust captures the essential belief that others will act in good faith. The expected utility for player i after signing a treaty is then a weighted function of abstraction by both players given as

$$\mathbb{E}[U_i] = \lambda_i U_i\left(q_i, q_j^H\right) + (1-\lambda_i)U_i\left(q_i, q_j^F\right), \tag{6}$$

where the first and second terms on the right-hand side represent the expected utility associated with the other player (j) being Honest or Fraudulent, respectively. This expression can be used to derive the abstraction q_i^F of player i if they are Fraudulent:

$$\frac{\partial}{\partial q_i}\left[\lambda_i U_i\left(q_i^F, q_j^H\right) + (1-\lambda_i)U_i\left(q_i^F, q_j^F\right)\right] = 0\,. \tag{7}$$

In this optimization, player i maximizes their individual utility despite signing a treaty with player j. Just as above, the two terms in the derivative represent the expected utilities arising from the belief of player i that player j will (first term) or will *not* (second term) comply with the treaty.

2.3 Solution to the game

The decision by each player whether or not to sign a treaty requires comparing expected utility under the Nash equilibrium, $U_i(q_i^N, q_j^N)$, with that under the treaty, $U_i(q_i, q_j)$, where utility depends on the types and abstraction rates of both players. Each player prefers that the other player pumps less, and the treaty is appealing because it reduces average pumping of the two players. Any player is therefore inclined to cooperate with an Honest player, who abides by the treaty, but not with a Fraud. Furthermore, because the treaty does not reduce Fraud pumping, players must account for the fact that Frauds are more likely to sign a treaty than Honest players. This feature of the game means that players update their trust in the other player after observing their decision to enter into a treaty.

This transboundary aquifer situation represents a two-stage (or "dynamic") Bayesian game in which players first indicate their desire to sign a treaty, followed by their decisions on abstraction rate, q_i. In dynamic Bayesian games, player strategies must follow a perfect Bayesian equilibrium, meaning that actions at each stage of the game must be sequentially rational given the beliefs of each player, which are updated using Bayes rule given any previous actions [*Gibbons*, 1992].

When the terms of the treaty attract only Fraudulent opponents, an Honest player can anticipate this and refuses to sign. Therefore, a treaty only occurs when both players prefer cooperation regardless of their type, meaning that both $\mathbb{E}[U_i^{Nash}] < \mathbb{E}[U_i^{Fraud}]$ and $\mathbb{E}[U_i^{Nash}] < \mathbb{E}[U_i^{Honest}]$ are satisfied. Because Frauds face fewer restrictions on their pumping, they always benefit equally to or more than Honest players when signing a treaty (i.e., $\mathbb{E}[U_i^{Honest}] \leq \mathbb{E}[U_i^{Fraud}]$). We therefore focus on the conservative case where player i is Honest. In other words, a treaty is signed if

$$\begin{aligned} \mathbb{E}[U_i^{Nash}] &< \mathbb{E}[U_i^{Honest}] \\ U_i(q_i^N, q_i^N) &< \lambda_i U_i(q_i^H, q_j^H) + (1-\lambda_i)U_i(q_i^H, q_j^F)\,. \end{aligned} \tag{8}$$

Evaluating this inequality requires determining pumping in the Nash (no treaty), Honest (treaty), and Fraud (treaty, without compliance) scenarios as described above. The utility functions for both players contain the parameter z, the side payment from player 2 to player 1. Because z can take on any value, players will sign a treaty when they can agree on a value for $z \in (-\infty, \infty)$ such that the inequality in Eq. 8 holds true. We therefore solve Eq. 8 for each player in terms of z and then calculate a minimum acceptable payment for player 1 (z_1) and a maximum allowable payment for player 2 (z_2). If the difference between the two, $\hat{z} = z_1 - z_2$ is greater than zero, the treaty is signed. The variable $\hat{z}$ represents the expected net increase in utility for two Honest players entering into a treaty. We therefore use $\hat{z}$ as a measure of the *utility of the treaty* compared with the Nash equilibrium.

We present a more formal solution to the game in Section S1, including evaluating player beliefs and combinations of player strategies. Closed-form solutions to the game were obtained using Mathematica and included in an R package containing functions to evaluate the transboundary aquifer game [*Penny*, 2020]. The R package was then used to generate results presented in subsequent sections.

2.4 Demand and the value of water

Before proceeding, we note that the formulation of utility (Equation 1) requiring players to meet a fixed water requirement represents a situation where water demand is perfectly *price-inelastic*. Such a scenario most closely resembles urban water supply, where demand remains relatively stable even as prices fluctuate. In other cases, especially agricultural aquifers with variable irrigation potential, water demand likely depends on the value of water, which could be considered the monetary gains from increasing crop irrigation [*D'Odorico et al.*, 2020]. This caveat needs to be addressed given that we wish to use the game to contextualize existing transboundary agreements, some of which contain considerable agricultural demand.

Fortunately our game can be easily translated to match a game previously developed for the Disi aquifer [*Müller et al.*, 2017], where the aquifer primarily serves agricultural users. In that model, utility in the Nash equilibrium is specified as

$$U_i(q_i) = \alpha_i q_i - \beta d_i q_i \,, \tag{9}$$

where the only difference with Equation 1 is the absence of the demand requirement (Q_i) and the inclusion of the value of water (α_i) instead of the price of the alternative supply (p_{0i}). In this model, there is no alternative source and groundwater use (q_i) depends on the interaction between the value of water and the cost of pumping. In terms of abstraction rates in the Nash and treaty scenarios (for Honest and Fraudulent players), the only difference with the game described above is that abstraction is not limited by a fixed demand. In other words, we can model agricultural aquifers by specifying unlimited Q_i, or practically by setting $Q_i \gg q_i$. This adjustment allows us to extend the game to agricultural aquifers in Section 5.

3 Application to the Genevese aquifer

The Genevese aquifer treaty, signed by Switzerland and France in 1978, offers a useful case study with which to validate the transboundary aquifer game. This treaty is the longest running transboundary aquifer agreement in the world [*Eckstein and Sindico*, 2014] and the only one to explicitly include incentives to limit abstraction rates [*Burchi*, 2018]. Although the stylized formulation of the game cannot fully capture the complex social or hydrogeological characteristics of the Genevese scenario, we use the game to qualitatively reproduce the bilateral dynamics that took place between France and Switzerland in negotiations leading up to the agreement.

The Genevese aquifer runs along the southern border of the Canton of Geneva, Switzerland, with portions of the aquifer extending into France (Figure 3ab). The Arve river, prior to joining the Rhône, recharges the Genevese along the eastern side. The aquifer has a spatial extent of 54 km^2, with 90% of the aquifer lying in Switzerland. The aquifer is overlain by a confining layer, but in most of the aquifer the water table surface is below this layer and we consider the aquifer to be unconfined. This aspect of the scenario is reinforced by the fact that low water levels prior to the agreement caused some wells to fully dry [*de los Cobos*, 2018]. For this reason we use a nonlinear version of the cost function such that the cost of abstraction approaches infinity as the depth of the water table approaches zero. The function for depth (d_i) follows unconfined groundwater equations, where discharge potential replaces hydraulic head. Although similar to the confined version, this accounts for the possibility of the aquifer being fully depleted. Complete details for the unconfined version of the groundwater model are presented in the SI (Section S2.1).

Both Geneva and the surrounding French communities utilize the aquifer for municipal water supply, with Geneva supplementing from Lake Geneva. Although proximity and shared language ensure familiarity between Geneva and the surrounding French communities, trust building was essential to transboundary negotiations in the period leading up to

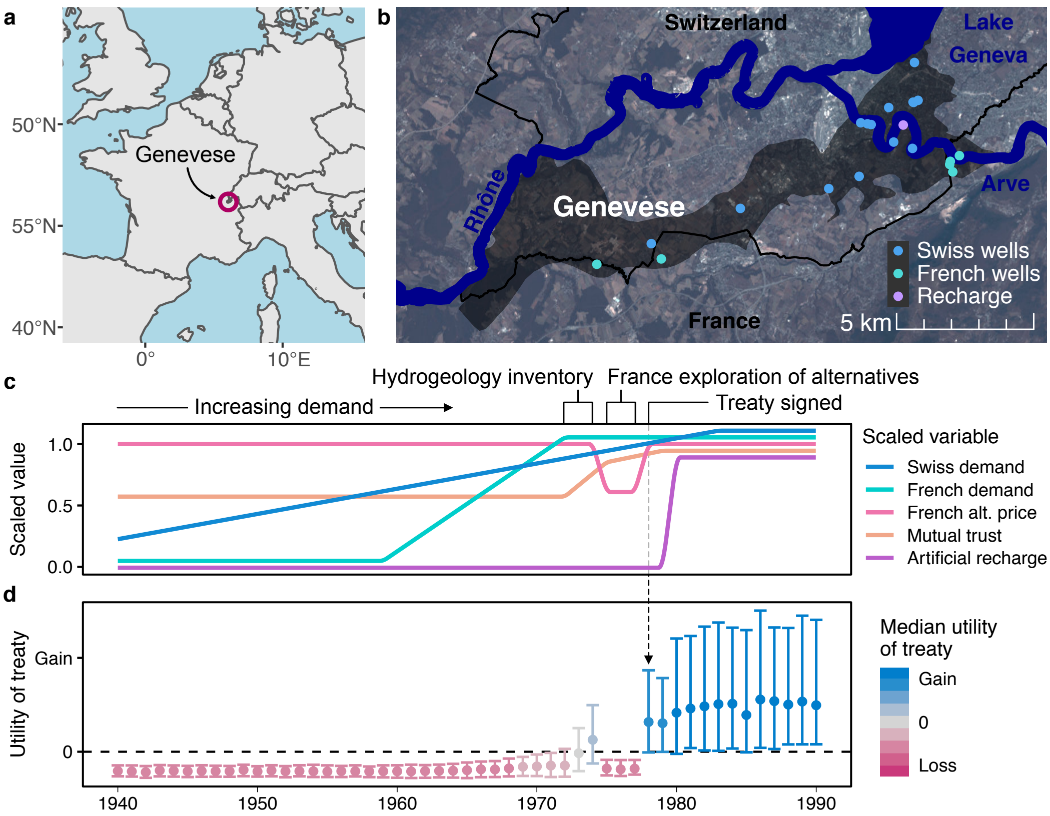

Figure 3. Application of the transboundary game to the Genevese aquifer, including (a) Location of the study site, (b) map of the Genevese aquifer and pumping wells, (c) timeline of events and input parameters to the model, scaled to a maximum value of one, and (d) annual utility of the treaty from Monte Carlo analysis, shown as the median and interquartile range. As shown, the Genevese treaty was signed in 1978.

the treaty. Transboundary collaboration has persisted successfully since the signing of the treaty in 1978. The aquifer is managed by a joint French-Swiss commission (for full disclosure one of the authors, G.D.L.C., is a member of this commission) which ensures both parties adhere to the treaty and that the aquifer maintains sustainable and adequate water levels.

The timeline of events in the Genevese allows us to explore multiple aspects of the transboundary situation. Geneva began utilizing the aquifer for water resources in the 1940s, followed by the French communities in the 1960s (Figure 3c). Water levels began declining in the 1950s and reached a critically low level after France began abstraction, with water levels nearly falling below the level of many wells [*de los Cobos*, 2018]. Both countries jointly decided to investigate the hydrogeophysical properties of the aquifer in 1972 [*de los Cobos*, 2018], while individually beginning to explore alternative water sources. Swiss investigations found that treating water from Lake Geneva would be considerably more expensive than managed aquifer recharge to increase aquifer water levels and allow for additional abstraction [*de los Cobos*, 2015]. In 1975, the French side announced it would not use Genevese water and would instead utilize an alternative source. However, they reversed course three years later and signed the treaty in 1978. Managed aquifer recharge was initiated in 1980, and the treaty has been successfully operational ever since.

We codified this timeline of events into the transboundary aquifer game by varying input parameters to match the timeline (see Figure 3c). Abstraction and recharge data were obtained from *de los Cobos* [2018]. Demand was approximated as a piecewise function comprised of a linear trend that is capped by a maximum demand (Figure 3c, blue). Maximum demand for each country was taken as the maximum reported abstraction over the entire time period. The demand trend was determined via linear regression of abstraction as a function of time, using only the data from years prior to reducing abstraction in the 1960s (see Figure S3). Recharge was set to zero until the recharge facility was commissioned in 1980, after which recharge was fixed to the average annual reported value (Figure 3c, purple). We assumed that recharge would be reduced in the case of no treaty, and we fixed the recharge value in the case of no treaty to be 2% less than in the case of a treaty. We note that this does not affect the signing of a treaty in 1978, only the utility of the treaty beginning in 1980 after the treaty is already signed. The cost of the alternative source (p_{0i}) for both countries was taken as the cost of treating water from Lake Geneva (see Section S2.3 for details). However, during the period in which France announced they would use other water sources (1975–1977), we fixed their alternative price in such a way that it was always cheaper for them to use the alternative source instead of groundwater (Figure 3c, red). We codified $\lambda(t)$ to emulate the relatively high initial level of mutual trust (0.6), and its further gradual increase as both parties worked together to investigate the aquifer and later manage the treaty (Figure 3c, orange). The cost of signing a treaty (ϵ_i) was fixed for the entire period of analysis, with the value determined as a percentage of the utility of a treaty in 1978 (see Section S2.4). The remaining hydrogeological parameters were determined using the analytical element method [*Penny et al.*, 2020] and were also fixed for the entire period of analysis. Note that the original game in Section 2 was adapted to account for specific features of the Genevese agreement including artificial recharge and unconfined aquifer conditions. See see Section S2 for a complete description of these modifications and details on parameterization of this case study.

To ensure that the predicted outcome of the game (i.e., whether or not a treaty was signed) was robust to uncertainty in the parameterization, we conducted a year-by-year Monte Carlo analysis to evaluate uncertainty in the results (results shown in Figure 3d). For each year we randomly sampled all parameters from independent uniform distributions spanning ±20% of their estimated values (see Section S2.4 for full details). Considering all years after 1978, France and Switzerland entered into a treaty in 76.3% of the Monte Carlo simulations. In all years prior to signing the agreement, they sign a treaty in 8.3% of simulations (Figure 3d).

The results demonstrate that the game accurately associates the emergence of an agreement with the set of conditions (demand, costs, and trust) that prevailed in 1978 (Figure 3d), when the Genevese aquifer treaty was actually signed. In the early period (1940–1965), there is no need for a treaty because only Switzerland is utilizing the aquifer for water supply. As French demand for abstraction increases (1965–1972), the treaty would have required that Switzerland limit its pumping to maximize joint utility. For the set of parameter values that prevail during that period, the game predicts that France is willing to pay for this reduction by Switzerland, but Switzerland demands more than France is willing to pay. In the following period (1973–1974), both parties nearly enter into an agreement. But France envisions supplying water from its alternative source (1975-1978) meaning that its (perceived) costs of *not* using the Genevese aquifer decrease, making a treaty with Switzerland less attractive. In 1978, France reverts to greater reliance on the shared aquifer, represented in the game as a higher cost of the alternative water source. This change by France, combined with managed aquifer recharge by Switzerland and increasing trust on both sides due to joint investigation efforts, makes the treaty a desirable solution for both parties after 1978. Finally, the completion of the artificial recharge facility in 1980 further increases the utility of cooperation between both sides.

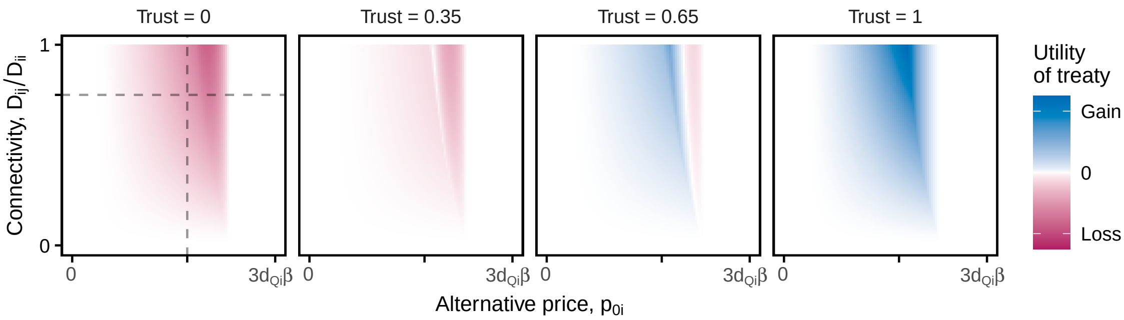

Figure 4. Variation in the utility of a treaty ($\hat{z}$) in the symmetric game, contingent on groundwater connectivity, price of alternative supply, and trust. Utility of the treaty is the utility gained from a treaty relative to the Nash if players are forced to sign the treaty. The benefit of signing a treaty is greatest when connectivity and trust are high while the alternative supply is not too low or too high. The transects in the left subpanel (and middle axis ticks in other subpanels) indicate the levels of groundwater connectivity (D_{ij}/D_{ii}) and alternative price (p_{0i}) that are held constant in Figure 5. Note that d_{Qi} represents what the average groundwater pumping costs *would be* if the entirety of demand were sourced from the aquifer (i.e., $d_{Qi} = \beta Q_i(D_{ii} + D_{ij})$.

4 Comparative statics of the two-player game

The game incorporates a variety of dynamics that ultimately dictate whether both players are willing to cooperate and sign a treaty. The decision of each player to cooperate depends on the expected utilities associated with signing (or not signing) the treaty, given their beliefs on the type (Honest or Fraud) and actions of the other player. We proceed to analyze the comparative statics of the game by considering how outcomes vary for different combinations of driving parameters (Figure 4). To simplify this task, we analyze the symmetric game where all parameters are equivalent for each of the two players. We especially focus on the interactive effects of groundwater connectivity ($D_{ij}/D_{ii} \in [0, 1)$), alternative price (p_{0i}), and trust (λ_i) on the utility of a treaty ($\hat{z}$). Groundwater connectivity represents the rate at which players reduce the water level of the other player relative to the rate at which they reduce their own water level. The remaining parameters, p_{0i}, λ_i, and $\hat{z}$ are defined above (Section 2).

4.1 Groundwater connectivity

Groundwater connectivity affects the interdependence of groundwater resources of both players. For a given alternative price, it can be considered the "stakes" of signing a treaty. In the extreme case where the two players are almost entirely disconnected ($D_{ij}/D_{ii} = 0$), neither player affects the abstraction costs of the other player, there is no pumping-cost externality, and equilibrium pumping rates are exactly identical with and without treaty (Fig 5a). Under these conditions, players are ambivalent about signing a treaty (Fig 5c, white), and would only develop a preference if there exists some cost ($\epsilon_i \neq 0$) associated with the treaty. In other words, the stakes of the treaty are low.

At the upper extreme of connectivity ($D_{ii}/D_{ij} \to 1$), pumping by one player creates equivalent drawdown for both players [i.e., a single-cell or bathtub model, *Brozović et al.*, 2006]. Between these extremes, increasing connectivity leads to an increasing pumping-cost externality, and the benefits and risks of a treaty both increase monotonically. The difference in abstraction between the Nash equilibrium (Figure 5a, green) and the treaty (Figure 5a, blue) represents the pumping-cost externality that arises from individual utility maximization. The risk of signing a treaty also increases with connectivity due to the

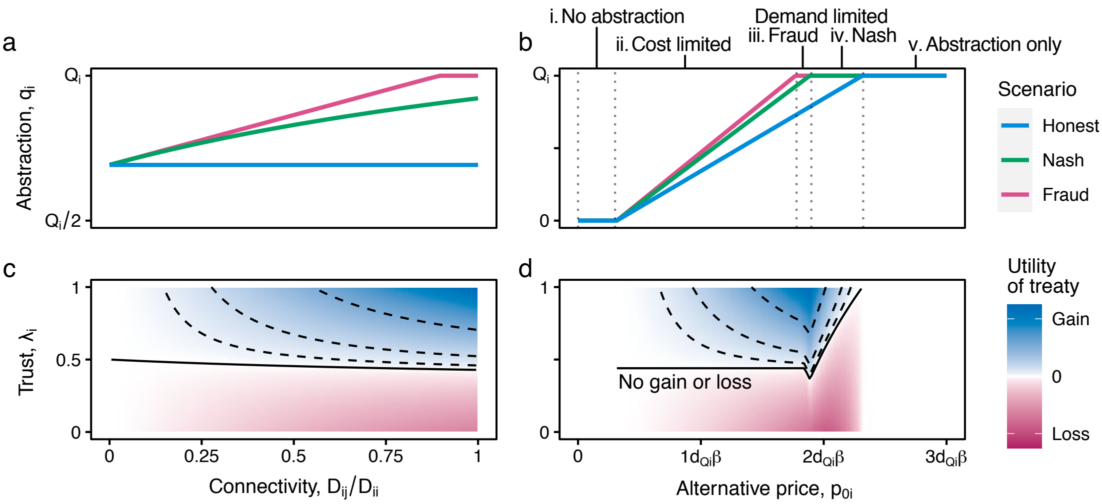

Figure 5. Effect of connectivity, alternative price, and trust on dynamics of the symmetric game, including (a-b) pumping and (c-d) utility. In the connectivity plots (left), both alternative price and the sum $D_{ii} + D_{ij}$ are held constant. Keeping $D_{ii} + D_{ij}$ constant means that drawdown depends only on abstraction (q_i), not on connectivity. As connectivity increases, the benefits and risks of a treaty also increase, raising the stakes of a treaty (c). In the alternative price plots (right), connectivity is held constant and the five zones of the game are shown in (b). For low and high values of p_{0i}, pumping rates under the Nash equilibrium are equal to pumping rates for Honest and Fraud players. Between these extremes, pumping rates increase linearly with alternative price from 0 to total demand (Q_i). Fraud pumping (red) is shown only for complete trust ($\lambda_i = 1$), but note that it approaches pumping in the Nash equilibrium (green) as $\lambda_i \rightarrow 0$. Players are ambivalent about a treaty along the solid line representing no gain or loss, meaning that trust must be above the line for a treaty to occur. The dashed contours represent the trust needed to sign a treaty in situations where there is a cost associated with signing, with the three lines being separated by a half-log increase in utility (i.e., upper dashed line represents 10x the utility of the lower dashed line).

greater reduction in abstraction (for Honest players) which allows Frauds to pump increasingly more when a treaty is signed (Figure 5a, red).

4.2 Alternative price

The utility of a treaty ($\hat{z}$) exhibits a non monotonic relation with the cost of the alternative source. At the lower extreme ($p_{0i} = 0$), both players exclusively use the alternative source because it is less expensive than groundwater pumping (it is free). At the upper extreme ($p_{0i} \rightarrow \infty$), both players exclusively pump groundwater because the alternative source is too expensive and both players pump *exactly* their water demand Q_i regardless of the treaty. In both situations, players are ambivalent about signing a treaty unless some inherent cost arises ($\epsilon_i \neq 0$). Just as abstraction at the extremes obeys clear rules, abstraction throughout the domain of alternative price follows predictable behavior which can be separated into clearly defined "zones", delineated in Figure 5b.

When alternative price is lower than the cost of abstracting groundwater from the undisturbed water table depth (i.e., $p_{0i} < \beta d_{0i}$), neither player has incentive to pump groundwater and all water is supplied from the alternative source (*i. No abstraction zone* in Figure 5b). As the price of the alternative source increases past the threshold βd_{0i}, players start using the aquifer and pumping rates increase linearly with the price of the alternative source. Reliance on the aquifer increases as the price of the alternative source increases. The incentives to over-pump (given by the difference between Honest and Nash abstraction rates in Fig. 5b) increase, as do the risks of signing a treaty (difference between the Honest and Fraud abstraction rates in Fig. 5b). In this zone, abstraction is cost-limited meaning that players consider trade-offs between the cost of groundwater and the alternative source (*ii. Cost-limited zone* in Figure 5b). If the price of the alternative water source is sufficiently high, the Fraud will abstract Q_i and rely entirely on the aquifer to meet demand (*iii. Demand limited – Fraud*). At this point, increasing values of p_{0i} will increase reliance on the aquifer in the absence of treaty (Nash, in green on Fig 5b), but will *not* increase incentives to cheat (Fraud, in red on Fig 5b). The aggregate effect is that the benefits of a treaty continue to increase while the risks decrease (visible as a dip in the utility contour lines in Fig. 5d). For even higher values of p_{0i}, the Nash equilibrium pumping rate reaches the total demand Q_i (*iv. Demand limited – Nash*). Here the difference between pumping rates with and without a treaty diminishes and a treaty loses its ability to reduce abstraction. For sufficiently high values of p_{0i} all players consume Q_i regardless of the treaty, equivalent to the extreme case of $p_{0i} \rightarrow \infty$ described above (*v. Abstraction only*).

The decoupling of abstraction with alternative price in zone (v) occurs because each player must supply a fixed demand Q_i, meaning that demand is perfectly price-inelastic. Such a scenario is representative of urban consumption. However, as described in Section 2.4, demand for agricultural users is likely to be price-elastic. Elastic demand can be simulated by ensuring that $Q_i \gg q_i$, so that agricultural aquifers are constrained to the *(i) No abstraction zone* and *(ii) Cost limited zone* (see Figure 5). In this case, zone (i) indicates that the value of water is small enough that no groundwater is worth pumping. In zone (ii), abstraction increases linearly with the value of water.

4.3 Trust

Trust plays an important role in situations where players could benefit from a treaty but risk being cheated by a Fraud. The importance of trust depends on the relative risks and benefits of a treaty for each of the two players. We define these factors relative to the Nash (no treaty) scenario. More precisely, the benefit of a treaty is the difference in utility between the Nash and treaty scenarios for two Honest players, given by $U_i(q_i^H, q_j^H) - U_i(q_i^N, q_j^N)$. The risk of a treaty is the difference between not signing a treaty and being cheated by a Fraud, given by $U_i(q_i^N, q_j^N) - U_i(q_i^H, q_j^F)$. Note that these are the absolute benefits and risks of a treaty, unweighted by trust. Benefits and risks are plotted against each other in Figure 6 for each of the five zones as a percentage of utility in the Nash equilibrium. We note that with high trust, Frauds become emboldened and abstract greater quantities because they are more certain that they are cheating an Honest player. With lower trust, the absolute risk would reduce but the *expected* risk (i.e., weighted by $1 - \lambda$) would increase.

The risks and benefits of a treaty are zero in the *(i) No abstraction* and *(v) Abstraction only* zones, because abstractions rates are equivalent in the treaty and no treaty scenarios. As alternative price increases in the *(ii) Cost limited* zone, the benefits and risks increase at proportional rates, meaning that the trust required for a treaty remains constant (Figure 6a). Moving into the *(iii) Demand limited (Fraud)* zone, the benefits of a treaty increase while the risks of a treaty reduce (Figure 6b). The decreasing risk arises because Fraud abstraction (q_i^F) is limited by demand (Q_i) and approaches abstraction in the Nash as alternative price increases (see Fig 5b). In the *(iv) Demand limited (Nash)* zone, the benefits and risks both decrease, but the benefits decrease more rapidly than the risks (Figure 6c). For this reason, the trust required to sign a treaty increases dramatically at the upper end of this zone (Figure 5d). These results demonstrate that a treaty can be signed across any of the zones, but that zones (ii) and (iii) are most favorable because they re-

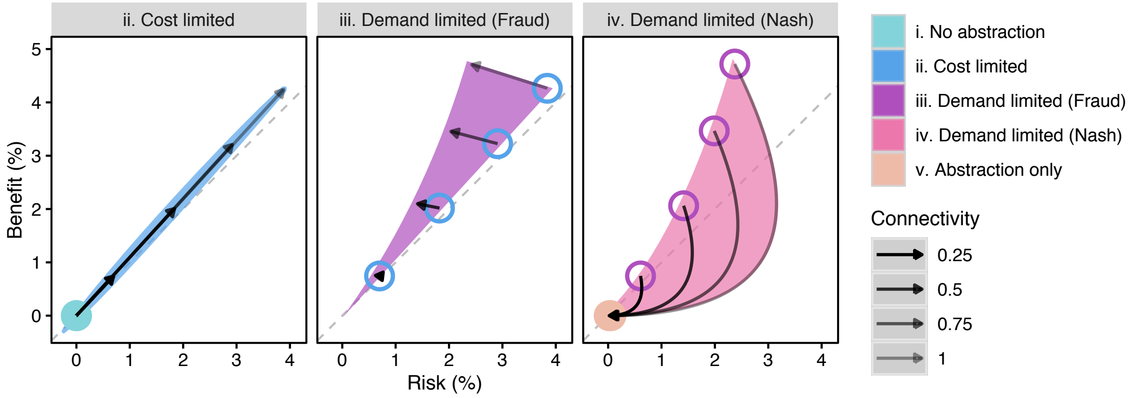

Figure 6. Benefits and risks of signing a treaty for zones (ii–iv), with moderately high trust ($\lambda_i = 0.65$). Colors indicate the zones, with circles indicating the adjacent zone. Each arrow represents the change in benefits and risks for constant connectivity as alternative price increases across the zone. Following the arrow is analogous to moving left-to-right in Figure 5b. The relative benefits and risks of a treaty indicate the level of trust needed to sign a treaty, with a lower benefit-to-risk ratio requiring higher trust (see Section 4.3). Generally, the *Demand limited (Nash)* zone requires the highest trust.

quire the lowest level of trust. In zone (iv), a treaty can be achieved but requires a higher level of trust, particularly near zone (v).

5 A typology of transboundary groundwater cooperation

The transboundary aquifer game provides a basis for developing a typology of transboundary groundwater cooperation. We classify existing treaties as those that (1) explicitly regulate abstraction volumes (the Genevese), (2) explicitly restrict abstraction within designated zones (the Disi), and (3) rely on soft-law instruments to promote cooperation and collaboration. Figure 7 illustrates the general mapping of these agreements onto the transboundary aquifer game under different values of Q_i. The horizontal axis is identical across all three panels, with the exception that panel c highlights agricultural aquifers by presenting the axis as the value of water (α_i) instead of alternative price (p_{0i}). We note that the two concepts are equivalent (see Section 2.4).

The Genevese treaty was signed in the context of increasing demand for water and depleting groundwater resources to the extent that some wells had dried (i.e., shifting from panel a to b in Figure 7). In the context of the game, the situation was favorable for cooperation given the joint depletion of groundwater, availability of alternative supply, and high trust between countries. Nevertheless, negotiations were difficult at times and nearly fell through (Section 3). Even as demand increased, the incentive to cooperate was insufficient to sign a treaty until both sides realized that continued abstraction would result in runaway costs, aquifer depletion, and that neither player had a readily available alternative source of water. In other words, both players were satisfied with the status quo Nash equilibrium until it became untenable.

The Disi agreement was signed in the context of increasing groundwater use by Saudi Arabia and Jordan, and the construction of the Disi pipeline that conveys water from the aquifer to the largest city in Jordan (Amman). The agreement places no limits on the quantity of groundwater abstraction but restricts abstraction near the shared border, with the effect of limiting groundwater connectivity between countries [*Müller et al.*, 2017]. Such an agreement was possible because the treaty was signed prior to mu-

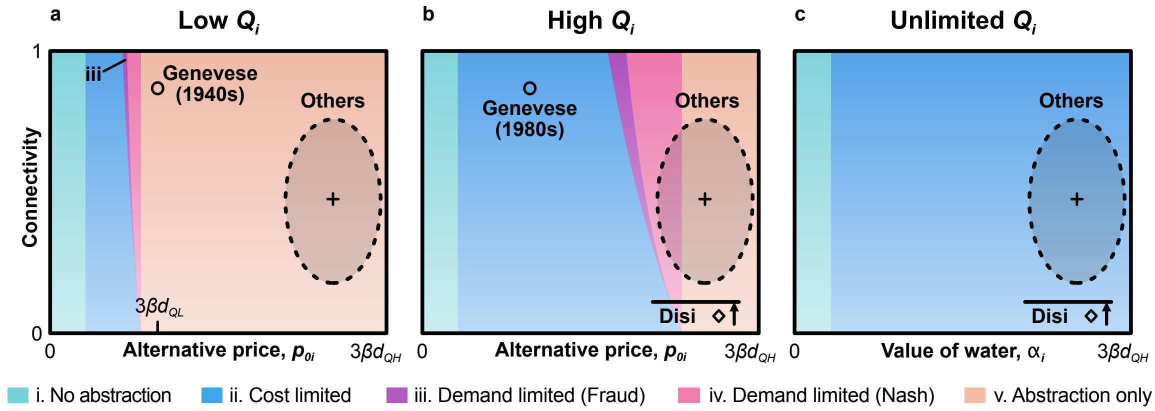

Figure 7. Transboundary aquifer dynamics and relation to existing treaties. (a) When Q_i is low, demand is generally sourced entirely from the aquifer (zone v), unless alternative price is also low (other zones). (b) When Q_i is high, demand is likely to be achieved through a combination of groundwater and the alternative source (zones ii–iv) unless alternative price is also high (zone v). (c) Agricultural aquifers can be represented by specifying unlimited Q_i, in which case demand depends on the value of water (α_i) and is sourced entirely from groundwater. Connectivity represents the interdependence of groundwater supply, while the the horizontal axis can be considered a metric of surface water scarcity, both for alternative price and the value of water. Transition through the five zones can occur either through increasing costs (p_{0i} or α_i) or through increasing demand, as in the case of the Genevese. Note that both the vertical and horizontal axes are identical to the axes in Figure 4, and that d_{QL} and d_{QH} correspond to Low Q_i and High Q_i, respectively.

tual depletion of water resources. The essential achievement of this approach is to avoid pumping-cost externalities without the need for a treaty to *reduce* abstraction, which would be politically sensitive. The treaty reframes groundwater depletion as a domestic issue because either side can only deplete their own groundwater, not that of the other player. Furthermore, limiting connectivity reduces the stakes of the treaty and could facilitate higher trust between countries by lowering risks and rewards [e.g., see *Poteete et al.*, 2010].

The remaining agreements lack any regulation of groundwater abstraction, but rather build a foundation for cooperation by establishing best practices, aquifer assessment and monitoring initiatives, "do no harm" principles to limit overdraft and pollution, and a diplomatic framework for resolving disputes [*Burchi*, 2018]. With the exception of the Guarani, these aquifers are situated in arid regions where alternative water sources are expensive. Depending on the aquifer and the scale of interest (e.g. local versus national), these aquifers also exhibit a range of connectivity. We therefore place these foundation treaties on the right side of Figure 7, while acknowledging that they could be situated in a range of scenarios or zones.

These findings collectively demonstrate that multiple classes of hard-law instruments are available to prevent tragedies of the commons in transboundary aquifers, but that each one requires particular circumstances to be met. For instance, limiting abstraction is a viable option in the *Cost limited zone (ii)* with the reasonable availability of an alternative water source, but may be politically challenging in the *Demand limited (Nash) (iv)* and *Abstraction only (v)* zones, which require exceptionally high trust. In zones (iv and v), limiting connectivity is a reasonable approach to reduce transboundary externalities provided connectivity is low to begin with. Otherwise, agreements that rely on soft-law instruments are more tractable. Lastly, high p_{0i} and α indicate situations with water scarcity, meaning that limiting abstraction in water-scarce regions will be difficult unless demand is elastic (as in Figure 7c). Limiting connectivity in such situations may be the most viable option.

Generally, groundwater use tends to expand and increase over time. This means that connectivity is likely to increase, as groundwater-depleted areas expand, and the stakes of cooperation will escalate. It could also mean that some aquifers transition to zones (ii) and (iii) from zones (iv) and (v), creating both challenges and opportunities for cooperation. The intensification of groundwater use and interdependence means that transboundary cooperation will become increasingly important.

6 Conclusions

Transboundary aquifers provide critical water supplies around the world but have received little attention from the broader research community. To help close this gap, we develop a game theoretic model to explore the relationship between socio-economic and hydrogeological characteristics of transboundary aquifer cooperation, with an emphasis on the role of trust. We validate the ability of the game to reproduce basic features of transboundary aquifer cooperation using the Genevese aquifer as a case study, where the treaty is signed after demand and trust increase and only when alternative price is high enough to merit Swiss and French investment in the aquifer. Furthermore, cooperation is strengthened by the implementation of artificial groundwater recharge, which benefits both Switzerland and France.

We simplify analysis of the dynamics of the game by focusing on the symmetric game, with two identical players, and by organizing the solution space into zones where abstraction is either cost limited or demand limited. In demand-limited scenarios, the alternative source is expensive and cooperation requires high levels of trust between players. In cost-limited scenarios, players offset groundwater abstraction with an alternative water source and cooperation requires lower trust. Transboundary aquifers with high connectivity in water-scarce regions (i.e., demand limited) will require the highest trust and ingenuity to execute. The delineation of cooperation into distinct zones combined with a typology of treaties presents an opportunity to broadly identify aquifers that would be amenable to cooperation or those that risk escalating into crises over transboundary water resources.

These findings help explain why only two transboundary aquifer treaties exist that contain hard-law instruments to regulate groundwater abstraction. Of the six existing transboundary aquifer treaties, only one (the Genevese) can be considered a cost-limited scenario with high groundwater connectivity and a readily available alternative source. The remaining transboundary aquifers exhibit lower connectivity and more expensive alternative water sources (four of the remaining transboundary treaties are in arid climates).

These findings provide a theoretical basis for the best practices described in the United Nations “Law of transboundary aquifers” [*UNGA*, 2008] and “Model provisions on transboundary groundwaters” [*UNECE*, 2014]. As suggested in these resolutions, the most effective approaches will initiate aquifer investigations and collaborative activities between countries early in the development of the aquifer before overdraft occurs. Initial efforts should include understanding aquifer properties and exploring alternative supply options to supplement groundwater. These actions can improve management decisions and build trust between countries, in addition to increasing opportunities for cooperation to limit the transboundary consequences of groundwater withdrawal.

Data availability

The R package for the transboundary aquifer game is archived on Zenodo [*Penny*, 2020], which also contains the timeseries of parameters to evaluate the Genevese case study from 1940 to 1990. The code is also available as an R package on Github (github.com/gopalpenny/genevoisgame). Data on global transboundary aquifers is available upon request from IGRAC.

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Supporting Information for "Trust and transboundary groundwater cooperation"

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Contents

1 Transboundary aquifer game

1.1 Extensive form of the game

In the transboundary aquifer game, two players must decide whether or not to cooperate to preserve a shared resource, contingent on the benefit and risks of cooperation. In the case a treaty is signed, Honest player abstract at levels agreed upon in the treaty, while Frauds pump at a rate that maximizes their individual utility, introducing the possibility of betrayal and requiring trust between players. Each player seeks to satisfy total water demand, Q_i, at the lowest cost. The game proceeds as follows (Fig. S1):

1. Nature randomly determines the type of players 1 and 2 ($t_i,\ \ i \in \{1,2\}$), where Honest players comply with any signed treaty (H, with probability $P(t_i = H) = \lambda_j$) while Frauds disregard the the treaty and maximize individual utility (F, $P(t_i = F) = 1 - \lambda_j$). Each player knows their own type and and although they do not know the type of the other player, they have a belief about the type of the other player given by the probabilities $P(t_j = H) = \lambda_i$ and $P(t_j = F) = 1 - \lambda_i$. The structure of the game is common knowledge.

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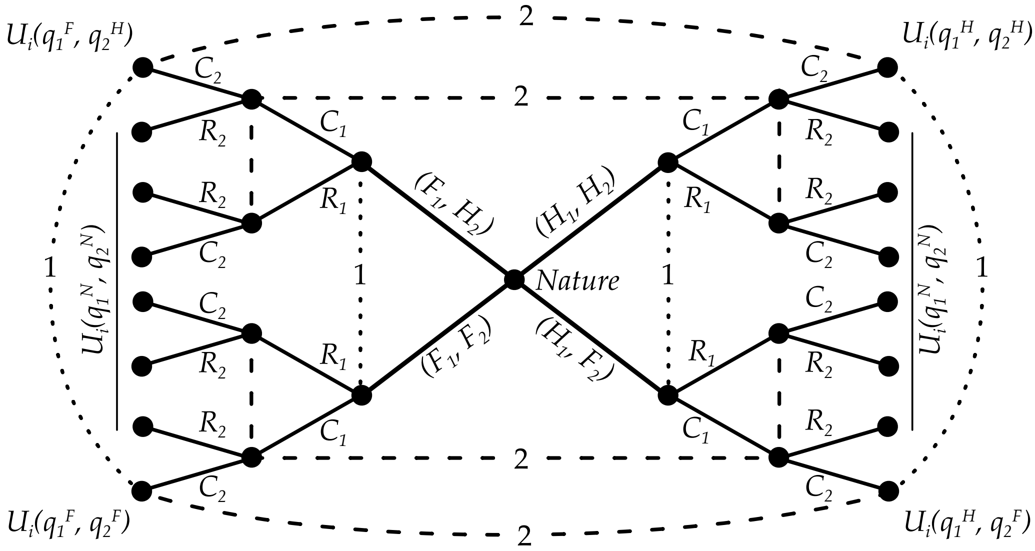

Figure S1. Extensive form of the trust game showing potential strategies for players 1 and 2. Payouts and beliefs are explained within the text.

2. Both players simultaneously choose whether to sign the treaty (C_i) or refuse to sign the treaty (R_i).
3. If both players cooperate (C_1, C_2) they sign the treaty ($\Omega = 1$). Otherwise, the treaty is not signed ($\Omega = 0$).

   (a) Although players could theoretically sign a wide range of treaties, we assume the only feasible treaty assigns pumping in such a way to maximize the joint utility of two honest players. Additionally a treaty allows a payment z from player 2 to player 1.

   (b) If there is no treaty, there is no exchange of fees ($z = 0$), and groundwater abstraction is determined by the subgame Nash equilibrium under no treaty ($q_1 = q_1^N, q_2 = q_2^N$).

4. Utility for each player is given by $U_1(q_1, q_2)$ and $U_2(q_1, q_2)$, as described below.

In addition to the two plays by nature $(t_1, t_2) \in \{H, F\}^2$, the action space for the two players is:

$$(a_1, a_2, q_1, q_2) \in \{C_1, R_1\} \times \{C_2, R_2\} \times [0, Q_1] \times [0, Q_2]$$

In solving the game, we are interested whether there exists a side payment z where cooperation is appealing for both players. To evaluate this possibility, we define utility and abstraction (Section S1.2) and test potential strategies (Section S1.3).

1.2 Payouts and abstraction rates

Utility for each player is given by:

$$U_i(q_1, q_2) = -p_{0i}(Q_i - q_i) - B(d_i)q_i - \epsilon_i \cdot \Omega \pm z \cdot \Omega \tag{1}$$

where q_i is the water abstracted by country i, p_{0i} is the unit cost of water from some alternative water source, Q_i is the total water requirement, $B(\cdot)$ is the unit cost of pumping groundwater from depth d_i, ϵ_i accounts for costs of signing the treaty, z is the payment from player 2 to player 1 per the agreement, and Ω is a binary variable that (if true) indicates that a treaty is signed.

1.2.1 Nash equilibrium (no treaty)

If either player refuses to cooperate, the treaty is not signed ($\Omega = 0$), there are no side payments ($z = 0$) and players pump q_1^N and q_2^N, which are the pumping rates determined by the Nash equilibrium. Utility is individually maximized by the two players, and abstraction is determined by solving

$$\frac{\partial U_1(q_1^N, q_2^N)}{\partial q_1^N} = 0, \quad \frac{\partial U_2(q_1^N, q_2^N)}{\partial q_2^N} = 0. \tag{2}$$

1.2.2 Joint maximum (treaty)

A signed treaty ($\Omega = 1$) stipulates abstraction rates of two honest players, q_1^H and q_2^H. These rates are determined by maximizing the joint utility of both players by solving:

$$\frac{\partial\left[U_1(q_1^H, q_2^H) + U_2(q_1^H, q_2^H)\right]}{\partial q_1^H} = 0, \quad \frac{\partial\left[U_1(q_1^H, q_2^H) + U_2(q_1^H, q_2^H)\right]}{\partial q_2^H} = 0 \tag{3}$$

1.2.3 Abstraction by a Fraud

If the treaty is signed and either player is a Fraud, that player will choose to forgo the treaty allocation and maximize their own utility by abstracting q_i^F. In doing so, they must account for the possibility that the other player is also a Fraud. The expected utility of a Fraud is therefore is given by:

$$\mathbb{E}[U_1(q_1^F, q_2)] = \lambda_1 U_1(q_1^F, q_2^H) + (1-\lambda_1) U_1(q_1^F, q_2^F) \tag{4}$$

$$\mathbb{E}[U_2(q_1, q_2^F)] = \lambda_2 U_2(q_1^H, q_2^F) + (1-\lambda_2) U_2(q_1^F, q_2^F)\,. \tag{5}$$

Because neither player is certain of the type of the other player, abstraction by each Fraud player (q_1^F, q_2^F) must be solved by maximizing the expected utility of both Fraud players simultaneously:

$$\frac{\partial}{\partial q_1^F}\left[\lambda_1 U_1(q_1^F, q_2^H) + (1-\lambda_1) U_1(q_1^F, q_2^F)\right] = 0 \tag{6}$$

$$\frac{\partial}{\partial q_2^F}\left[\lambda_2 U_2(q_1^H, q_2^F) + (1-\lambda_2) U_2(q_1^F, q_2^F)\right] = 0\,, \tag{7}$$

while noting that abstraction under the treaty must already be known.

Strictly speaking, trust in the equations above should be the probability that the other player is a Fraud conditional on the knowledge that the treaty has been signed. We denote this *a posteriori* probability λ_i', and we use this to solve the game in Section 1.3 using Bayes rule, finding that in the case that a treaty is signed, we always obtain $\lambda_i' = \lambda_i$, such that the two are interchangeable in the equations for abstraction and utility (see Section S1.3).

1.3 Potential strategies

Here we evaluate potential strategies (s_i) for each of the players, which includes a choice of action $(a_i \in \{C_i, R_i\})$ for each of their potential types $(t_i \in H_i, F_i)$. The strategy for player i can therefore be represented as $(a_i|_{H_i}, a_i|_{F_i})$. A strategy is a perfect Bayesian equilibrium strategy (s_i^*) for player i if it results in the maximum expected utility U_i, given the sequentially rational decisions of the other player. In this section, we are interested in identifying which combination of strategies, $\{s_i, s_j\}$, are perfect Bayesian equilibrium strategies and yield a signed treaty between the players. To do this we evaluate combinations of strategies and whether or not they fall on the equilibrium path.

In the case that a treaty is signed $(a_i = C_i, a_j = C_j)$, each player can update their belief that the other player is Honest. This belief of player i depends on the strategy of player j and is determined by Bayes rule $\lambda_i' = P(H_j|C_j) = P(C_j|H_j)\frac{P(H_j)}{P(C_j)}$, noting that $P(H_j) = \lambda_i$.

1.3.1 Both players pool on cooperation

We begin by considering the strategy combination in which both players pool on cooperation, meaning that they cooperate regardless of their type: $\{(C_1, C_1), (C_2, C_2)\}$. Our objective is to determine whether (and under what conditions) this combination of strategies results in a perfect Bayesian equilibrium. We start by considering the perspective of player 1 under the assumption that player 2 has decided to pool on cooperation.

If player 1 plays C_1, the expectation of her utility under a treaty is given by:

$$\mathbb{E}[U_1(q_1, q_2)] = \begin{cases} \lambda_1' U_1(q_1^H, q_2^H) + (1 - \lambda_1') U_1(q_1^H, q_2^F), & t_1 = H \\ \lambda_1' U_1(q_1^F, q_2^H) + (1 - \lambda_1') U_1(q_1^F, q_2^F), & t_1 = F \end{cases} \tag{8}$$

If player 1 were to play R_1, her utility would be $U_1(q_1^N, q_2^N)$, and she will only play C_1 if $U_1(q_1, q_2 \mid C_1) > U_1(q_1^N, q_2^N)$. The fact that player 2 pools on cooperation entails that $P(C_2 \mid H_2) = P(C_2 \mid F_2) = 1$ and, applying Bayes formula, $\lambda_1' = \lambda_1$. Rearranging the terms and substituting $\lambda_1' = \lambda_1$ we see that cooperation is an equilibrium strategy for player 1 if the following requirements (m_{CC}) for each type are true:

$$m_{CC1,H} : P(C_1 \mid H_1) \Leftrightarrow \left[\lambda_1' U_1(q_1^H, q_2^H) + (1 - \lambda_1') U_1(q_1^H, q_2^F) \overset{?}{>} U_1(q_1^N, q_2^N)\right] \tag{9}$$

$$\Leftrightarrow \left[\lambda_1 \overset{?}{>} \frac{U_1(q_1^N, q_2^N) - U_1(q_1^H, q_2^F)}{U_1(q_1^H, q_2^H) - U_1(q_1^H, q_2^F)}\right] \tag{10}$$

$$m_{CC1,F} : P(C_1 \mid F_1) \Leftrightarrow \left[\lambda_1' U_1(q_1^F, q_2^H) + (1 - \lambda_1') U_1(q_1^F, q_2^F) \overset{?}{>} U_1(q_1^N, q_2^N)\right] \tag{11}$$

$$\Leftrightarrow \left[\lambda_1 \overset{?}{>} \frac{U_1(q_1^N, q_2^N) - U_1(q_1^F, q_2^F)}{U_1(q_1^F, q_2^H) - U_1(q_1^F, q_2^F)}\right] \tag{12}$$

We now consider the perspective of player 2. If player 2 plays C_2, the expectation of his utility under a treaty is given by:

$$\mathbb{E}[U_2(q_1, q_2)] = \begin{cases} \lambda_2' U_2(q_1^H, q_2^H) + (1 - \lambda_2') U_2(q_1^F, q_2^H), & t_2 = H \\ \lambda_2' U_2(q_1^H, q_2^F) + (1 - \lambda_2') U_2(q_1^F, q_2^F), & t_2 = F \end{cases} \tag{13}$$

If player 2 were to play R_2, his utility would be $U_2(q_1^N, q_2^N)$, and player 2 will only play C_2 if $U_2(q_1, q_2 \mid C_2) > U_2(q_1^N, q_2^N)$. Rearranging the terms and substituting $\lambda_2' = \lambda_2$

we see that player 2 cooperates if the following requirements (m_{CC}) are true:

$$m_{CC2,H} : P(C_2 \mid H_2) \Leftrightarrow \left[\lambda_2' U_2(q_1^H, q_2^H) + (1 - \lambda_2') U_2(q_1^F, q_2^H) \overset{?}{>} U_2(q_1^N, q_2^N)\right] \tag{14}$$

$$\Leftrightarrow \left[\lambda_2 \overset{?}{>} \frac{U_2(q_1^N, q_2^N) - U_2(q_1^F, q_2^H)}{U_2(q_1^H, q_2^H) - U_2(q_1^F, q_2^H)}\right] \tag{15}$$

$$m_{CC2,F} : P(C_2 \mid F_2) \Leftrightarrow \left[\lambda_2' U_2(q_1^H, q_2^F) + (1 - \lambda_2') U_2(q_1^F, q_2^F) \overset{?}{>} U_2(q_1^N, q_2^N)\right] \tag{16}$$

$$\Leftrightarrow \left[\lambda_2 \overset{?}{>} \frac{U_2(q_1^N, q_2^N) - U_2(q_1^F, q_2^F)}{U_2(q_1^H, q_2^F) - U_2(q_1^F, q_2^F)}\right] \tag{17}$$

The first requirement $m_{CC2,H}$ is more restrictive and if it is true, $m_{CC2,F}$ will always be true. The same can be said for $m_{CC1,H}$ and $m_{CC1,F}$, respectively. Therefore, both players pooling on cooperation is an equilibrium strategy provided $m_{CC1,H}$ and $m_{CC2,H}$ are true.

1.3.2 Player 1 pools on cooperation, player 2 separates by type

In this case, player 1 pools on cooperation and player 2 chooses an action based on the disposition of his type, meaning that Honest players are inclined to cooperate while Frauds are inclined to refuse cooperation. The combination of strategies is $\{(C_1, C_1), (C_2, R_2)\}$. To test if this strategy is on the equilibrium path, we evaluate whether or not there are situations in which either player would want to change their strategy.

We consider the perspective of player 2. Because player 1 always cooperates, we can substitute $\lambda_2' = \lambda_2$, similar to the case above. If player 2 is Honest and changes his play to R_2, his utility will be $U_2(q_1^N, q_2^N)$. If player 2 is a Fraud and changes his play to C_2, his utility will be $\lambda_2' U_2(q_1^H, q_2^F) + (1 - \lambda_2') U_2(q_1^F, q_2^F)$. Therefore, the following two requirements must be met:

$$m_{CT2,H} : P(C_2 \mid H_2) \Leftrightarrow \left[\lambda_2' U_2(q_1^H, q_2^H) + (1 - \lambda_2') U_2(q_1^F, q_2^H) \overset{?}{>} U_2(q_1^N, q_2^N)\right] \tag{18}$$

$$\Leftrightarrow \left[\lambda_2 \overset{?}{>} \frac{U_2(q_1^N, q_2^N) - U_2(q_1^F, q_2^H)}{U_2(q_1^H, q_2^H) - U_2(q_1^F, q_2^H)}\right] \tag{19}$$

$$m_{CT2,F} : P(R_2 \mid F_2) \Leftrightarrow \left[U_2(q_1^N, q_2^N) \overset{?}{>} \lambda_2' U_2(q_1^H, q_2^F) + (1 - \lambda_2') U_2(q_1^F, q_2^F)\right] \tag{20}$$

$$\Leftrightarrow \left[\lambda_2 \overset{?}{<} \frac{U_2(q_1^N, q_2^N) - U_2(q_1^F, q_2^F)}{U_2(q_1^H, q_2^F) - U_2(q_1^F, q_2^F)}\right] \tag{21}$$

In order to evaluate when $m_{CT2,H}$ and $m_{CT2,F}$ are both true, we re-arrange the inequalities and recombine as follows:

$$\lambda_2 U_2(q_1^H, q_2^F) + (1 - \lambda_2) U_2(q_1^F, q_2^F) < U_2(q_1^N, q_2^N) < \lambda_2 U_2(q_1^H, q_2^H) + (1 - \lambda_2') U_2(q_1^F, q_2^H) \quad (22)$$

$$0 < \lambda_2 \left[U_2(q_1^H, q_2^H) - U_2(q_1^H, q_2^F) \right] + (1 - \lambda_2) \left[U_2(q_1^F, q_2^H) - U_2(q_1^F, q_2^F \right] \quad (23)$$

Both terms on the right hand side of Eq. 23 will never be positive because $U_2(q_1^H, q_2^H) \leq U_2(q_1^H, q_2^F)$ and $U_2(q_1^F, q_2^H) \leq U_2(q_1^F, q_2^F)$, meaning that the inequality will never hold true. In other words, $m_{CT2,H}$ and $m_{CT2,F}$ cannot be true simultaneously, and the combined strategies $\{(C_1, C_1), (C_2, R_2)\}$ is not a perfect Bayesian equilibrium strategy.

This result can be understood intuitively when considering that the utility of player 2 will increase if he is a Fraud, which always seeks to maximize his expected utility and take advantage of player 1 through the agreement. There is a trivial case in which this strategy is a perfect Bayesian equilibrium when the trust of player 1 is zero, but we ignore these trivial cases which can be accounted for using other strategies.

1.3.3 Player 1 pools on cooperation, player 2 separates for exploitation

In this case, player 1 pools on cooperation and player 2 chooses a strategy based on a cynical world view in which Honest players are distrustful and Frauds wish to exploit the other player $(C_1, C_1), (R_1, C_1)$. This combined strategy is never a perfect Bayesian equilibrium, which could be shown using formal mathematical arguments as presented above. However, the result can also be obtained by reasoning through the options of both players.

If both sides were to sign a treaty, player 1 would know that she has entered into an agreement with a Fraud. There is never a reason to enter into an agreement with a Fraud, who will always disregard the treaty allocation and maximize his own utility. In other words, if player 1 suspects that player 2 might play this strategy, she should always refuse a treaty. This combined strategy is never on the equilibrium path for player 1 and cannot be considered a perfect Bayesian equilibrium.

1.3.4 Summary of strategies

So far we have shown that pooling on cooperation (C_i, C_i) makes sense for both players under certain circumstances. We have further shown that (C_i, R_i) never makes sense for player i, and that player j would never want to cooperate with an opponent whose strategy is (R_i, C_i). The final strategy of pooling on refusal (R_i, R_i) can be on the equilibrium path but is unimportant in terms of the game because it never leads to a treaty.

Therefore, a treaty only emerges when both players pool on cooperation, requiring that $m_{CC1,H}$ and $m_{CC2,H}$ are satisfied. Any remaining strategies that fall on the equilibrium path result in no treaty, in which case the solution is represented by the Nash equilibrium.

2 Genevese case study

2.1 Modifications to the game

The Genevese scenario required modifications to the game to account for additional aspects of the case study that were important to signing the treaty. First, we added terms to the utility and depth functions to account for the fact that the treaty was signed with the intention that Switzerland build an artificial recharge facility to maintain aquifer water levels. Second, we converted the relationship between abstraction and drawdown from confined behavior to unconfined behavior, to account for the fact that the aquifer is mostly unconfined and could be significantly depleted. Finally, we adjusted the cost function to reflect the increasing cost of pumping in a depleting aquifer.

The new utility equation is written as

$$U_i(q_1, q_2) = -p_{0i}(Q_i - q_i) - B(d_i)q_i - c_{0ri} - c_{ri}r_M(\Omega) - \epsilon_i \cdot \Omega \pm z \cdot \Omega, \tag{24}$$

where c_{0ri} is the fixed construction cost for a recharge facility, c_{ri} is the unit cost of recharge, r_M volumetric the rate of aquifer recharge contingent on a treaty, and the remaining terms are identical to Eq. 1. Because France does not directly pay for recharge, $c_{0rf} = c_{rf} = 0$.

We also modify the equation for drawdown to incorporate a term for recharge and to represent unconfined groundwater dynamics. In unconfined aquifers, abstraction is related linearly with discharge potential, ϕ_i, which is equivalent to the square of the thickness of the water table. For this reason, it is more convenient to express cost and drawdown in terms of the saturated thickness of the water table, h_i, so that depth is $d_i = d_{Bi} - h_i$ where d_{Bi} is the depth of the bottom of the aquifer. The discharge potential is then given as

$$\phi_i = h_i^2 = h_{0i}^2 - \Phi_{ii}q_i - \Phi_{ij}q_j + \Phi_{ir}r_M, \tag{25}$$

where h_{0i} is the undisturbed saturated thickness of the water table accounting for steady-state recharge and discharge, and the coefficients relate discharge potential for player i

with abstraction by country i (Φ_{ii}), abstraction by country j (Φ_{ij}), and managed recharge (Φ_{ir}).

Increasing costs as the aquifer depletes must be considered when accounting for player strategies in a resource-limited aquifer. To do so, we utilize an exponential function such that the cost approaches infinity as the water table thickness approaches zero. This function is weighted so that abstraction cost is $B_{nl}(d_i) \approx \beta d_i$ (similar to the confined case) when the depth of the water table is small. As depth increases, the exponential is given more weight. After applying the variable substitution $d_i = d_{Bi} - h_i$, we write the cost function for unconfined aquifers as

$$B_{nl}(h_i) = \beta\Big[d_{Bi}(1-l)(\ln d_{Bi} - \ln h_i) + l(d_{Bi} - h_i)\Big]. \tag{26}$$

This function is continuous over the domain $h_i > 0$ and adheres to our requirements that $\lim_{h_i \to 0} B_{nl} = \infty$ and the cost of pumping is zero if the water table is at the land surface. Pumping is nearly linear as the water table approaches the surface ($h_i \to d_{Bi}$), with a slope of $-\beta$, the same as the linear specification for confined aquifers. The free parameter $l \in [0, 1)$ controls the relative weighting between the linear and nonlinear portions of the curve.

2.2 Groundwater model

Our modeling sought to broadly reproduce the circumstances of the Genevese aquifer leading up to and after the signing of the treaty in 1978. Doing so required fully parameterizing the utility and depth functions for the unconfined aquifer as shown above (Equations 24, 25, and 26). We note that the full time series of parameters used to generate Figure 3 in the manuscript is available online [*Penny*, 2020].

We generated hydrological parameters using data provided by the Geological survey of the Canton of Geneva (GESDEC), including groundwater elevation and abstraction and raster files containing elevation for the land surface and aquifer boundaries. We calculated depth to the bottom of the aquifer as the average land surface elevation minus the average elevation of the bottom of the aquifer. We calculated the undisturbed water table depth (d_{0i}) as the average surface elevation minus average water table elevation prior to 1960. Although this data is proprietary, all inputs to the transboundary aquifer game utilized in this study are included in *Penny* [2020, available online].

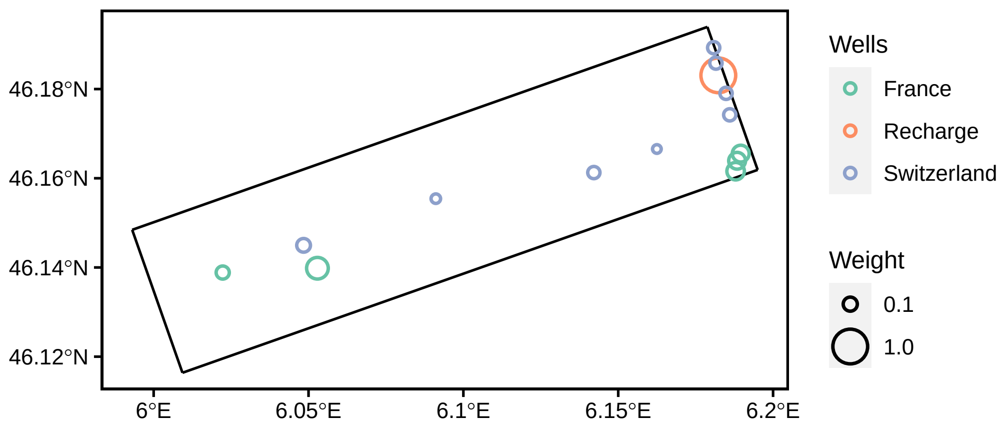

Figure S2. Idealized representation of the Genevese aquifer used for modeling drawdown relationships.

The drawdown relationships, Φ_{ii}, Φ_{ij}, and Φ_{ir} were modeled using the analytical element method and the R package anem [*Penny et al.*, 2020]. We manually idealized the aquifer boundaries to fit a rectangle and shifted placement of pumping wells to ensure similar location with respect to the aquifer boundaries. We weighted abstraction in each well by the relative rates of abstraction in each of the wells using data provided by GESDEC. The idealized aquifer is shown in Figure S2. Because demand in the aquifer exceeded recharge, we modeled the Arve river as a constant-flow boundary which recharged 7.5 million cubic meters (MCM) of water to the aquifer each year [*de los Cobos*, 2018]. Fluxes through the remaining aquier boundaries are low, and in the model we set them to no-flow boundaries. The R package anem contains a function called `get_drawdown_relationships` which applies the analytical element method to directly calculate the relationships Φ_{ix}. The function requires that each well is parameterized by a well diameter and radius of influence. We used well diameters supplied by GESDEC, and estimated the radius of influence of each well using the approximation by *Aravin and Numerov* [1953] with a total elapsed time of pumping of 25 years [*Fileccia*, 2015]. We supplied the wells and aquifer parameters to the `get_drawdown_relationships` function, and used it to obtain final values for the drawdown relationships.

We approximated demand using a linear regression to capture increasing demand which was then capped at a maximum value, determined as maximum abstraction over the period of analysis (see Figure S3). In reality demand continued to increase [Geneva currently obtains 90% of its water supply from lake Geneva, *SIG*, 2020] but, because the

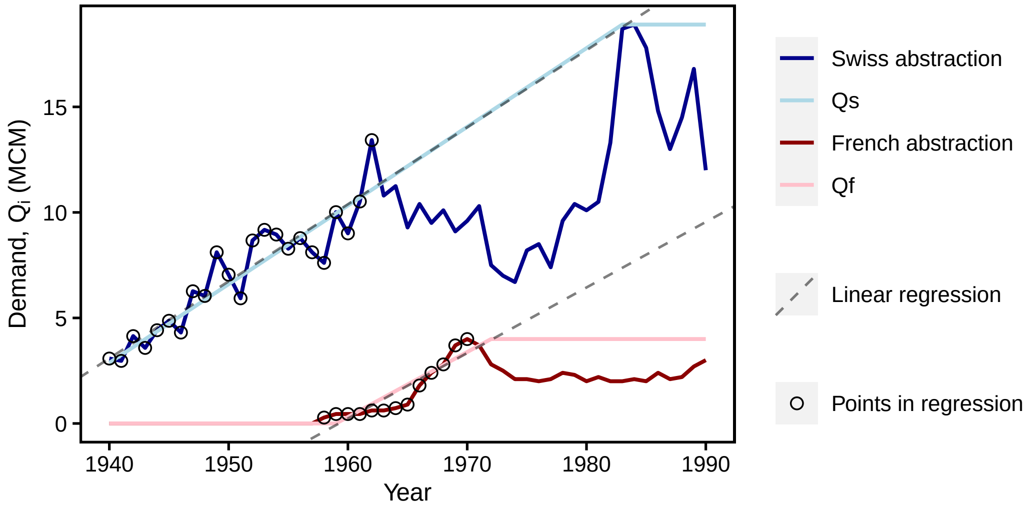

Figure S3. For both Switzerland and France, Q_i was determined from abstraction timeseries. The rising limb was determined from linear regression of the circled points. Increasing demand continues until reaching a maximum, determined by the maximum abstraction of each country over the timeseries. The units are million cubic meters (MCM) per year.

abstraction shifted to a cost-limited situation, additional abstraction beyond these values had no bearing on the treaty as it was satisfied by alternative sources.

Lastly, recharge was fixed at 8.2 MCM per year, representing the average recharge to the aquifer since the recharge facility was commissioned in 1980. We assume that if no treaty was signed, that Switzerland would likely reduce the amount of annual recharge. We fixed this reduction to 2% of the total recharge (i.e., 0.082 MCM). However, we note that greater reductions in the absence of a treaty would be possible and would further incentivize each side to sign a treaty (in other words, 2% serves as a conservative estimate). As noted in the main text, this 2% difference begins with the initiation of recharge in 1980 and therefore does not affect the decision to cooperate in 1978. Instead, it demonstrates the additional value of shared recharge after 1980.

2.3 Economic parameters

The remaining parameters pertain to the economic cost of water supply and recharge. These include alternative price (p_{0i}), the cost of abstraction (β), and the fixed and variable costs of recharge (c_{0rs} and c_{rs}, respectively).

Alternative price was determined by assuming water could be treated from lake Geneva using ultrafiltration, which is common in the region. The energy intensity of ultrafiltration is approximately 0.1 kWh m^{-3}, which itself represents about 30% of overall costs [*Lipp et al.*, 1998]. This results in water supply costs of 0.067 CHF m^{-3}, assuming a cost of 0.2 CHF kWh^{-1} for electricity [*Federal Electricity Commission ElCom*, 2020], which gives a rough approximation of electricity prices in Geneva. This yields a cost of 67,000 CHF MCM^{-1} for the alternative source.

The cost of abstraction was determined as the cost of energy to lift 1 m^3 of water by 1 m. The energy to lift groundwater is 9.81 kJ m^{-3} m^{-1}. Converting to kWh and assuming a pumping efficiency of 60%, this translates to an energy efficiency of 0.0045417 kWh m^{-3} m^{-1}, or 908.33 CHF MCM^{-1} m^{-1}. We round up to obtain an abstraction cost of 910 CHF MCM^{-1} m^{-1}.

The cost of recharge was determined via numbers provided by *de los Cobos* [2018], including the unit cost of recharge under two scenarios. In the first scenario with a total recharge rate of 20 MCM, the average unit cost of recharge is 0.07 CHF m^{-3}. In the second scenario with a total recharge rate of 10 MCM, the average unit cost of recharge is 0.12 CHF m^{-3}. Linear combination of these scenarios yields a fixed cost for the recharge facility of $c_{0rs} = 1 \times 10^7$ CHF and a variable cost of $c_{rs} = 2 \times 10^4$ CHF MCM^{-1}.

2.4 Sensitivity analysis

The parameter values described above contain uncertainty. To ensure that the model results were robust to parameter uncertainty, we conducted a year-by-year Monte Carlo analysis (N = 1,000 each year), varying each parameter by 20%. In other words in the Monte Carlo analysis, each parameter was sampled 1,000 times each year from a uniform random distribution spanning the mean value plus or minus 20%. The only variables that were not sampled from a ±20% range were trust, which was clipped to the range $\lambda_i \in [0, 1]$, transaction costs, which were were sampled from $\epsilon_i \in [0, 620]$ representing 0–75% of the utility of the treaty ($\hat{z}$) without transaction costs in 1978, the shape parameter on abstraction costs, which was sampled from $l \in [0.2, 0.8]$, and the reduction in recharge in the case of no treaty, which was sampled from the range $[0, 0.05]$. The results of this year-by-year sensitivity analysis are presented in the main text. Overall, when only considering the time period 1978-1990 (N = 13,000), we note that a treaty was signed in 76.3% of the simulations.

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