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Trust and incentives for 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 regulated by a treaty. To better understand the incentives that allow treaties to emerge, we develop a two-player game theoretic model that couples groundwater behavior and economic incentives to represent the social dilemma of transboundary aquifer cooperation. The game incorporates economic incentives and hydrogeological features and highlights the importance of trust to evaluate the benefits and risks of a treaty. We demonstrate the ability of the game to reproduce key features of cooperation in the Genevese aquifer, which is governed by the longest-running and most collaborative transboundary aquifer treaty on record. We analyze the comparative statics of the game 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 economic 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 results further indicate how two different types of agreements are likely to emerge. Treaties that limit *how much* is being pumped have greater potential when countries have access to an alternative water source, whereas treaties that restrict *where* the aquifer is being exploited 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 often serves as a common-pool resource, where pumping by individual users generates private profits while increasing the pumping costs to all users (Negri, 1989). Absent cooperation or regulation, the ensuing externalities create incentives to over-pump groundwater in a competitive process that has been described as a tragedy of the commons (Gardner et al., 1997). Additionally, the benefits of groundwater withdrawals accrue immediately yet the consequences of groundwater depletion build slowly and are difficult to understand, assess, and monitor (Gleeson and Richter, 2018). Sustainable, equitable, and enforceable groundwater management is therefore essential but often challenging, and groundwater regulation has lagged behind surface water regulation, despite a widespread global dependence on groundwater resources (e.g., Sax, 2002; Water Governance Facility, 2013).

The problem of groundwater management is a growing concern in transboundary basins (Eckstein and Sindico, 2014; Conti, 2014; Rivera and Candela, 2018) due to ongoing groundwater depletion in many of these 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

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groundwater resources, leading to a situation in which transboundary groundwater is severely understudied and under-managed (Eckstein, 2007, 2017; Lee et al., 2018). This situation contrasts with transboundary rivers, which have been studied and regulated more 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 (Burchi, 2018; TFDD, 2016). Only six international transboundary aquifers are currently regulated by a dedicated transboundary treaty (Fig. 1), and only two of them place specific restrictions 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). The Disi/Saq-Ram (hereafter referred to as the Disi) aquifer agreement, signed in 2015, restricts abstraction within a buffer area on either side of the border between Jordan and Saudi Arabia (Müller et al., 2017). The remaining agreements adopt recommendations from the non-binding "Draft Articles on the Law of Transboundary Aquifers" by the United Nations (UNGA, 2008) and "Model Provisions on Transboundary Groundwaters" by the U.N. Economic Commission for Europe (UNECE, 2014). These documents include principles to support equitable and reasonable utilization, an obligation not to cause significant harm, a general obligation to cooperate, and regular exchange of data and information (UNGA, 2013). Although valuable tools to cultivate cooperative relationships and improve transboundary management, these general principles are difficult to assess and enforce. In addition to the six aforementioned treaties specifically focusing on groundwater, we note that some (14%) transboundary surface water agreements include a clause pertaining to groundwater (Giordano et al., 2014), but most (81%) of these conjunctive management treaties contain only limited mentions of groundwater and do not explicitly describe how it should be managed (Lautze et al., 2018).

The dearth of transboundary aquifer agreements has been attributed to a variety of factors including a lack of available policy frameworks (Eckstein, 2017), inadequate technical and institutional capacity (Conti, 2014; Eckstein, 2007; Lee et al., 2018), domestic power structures that oppose regulation (Feitelson, 2006), and legal frameworks or bureaucracy on either side of the border that impede negotiations over transboundary resources at the local level (Sanchez and Eckstein, 2020). Furthermore, attention to transboundary groundwater may be limited due to the gradual rate at which problems arise and the hidden nature of the resource (Movilla Pateiro, 2016; Wijnen et al., 2012). These latter two features of groundwater create regulatory obstacles precisely because groundwater is difficult to monitor and regulations are difficult

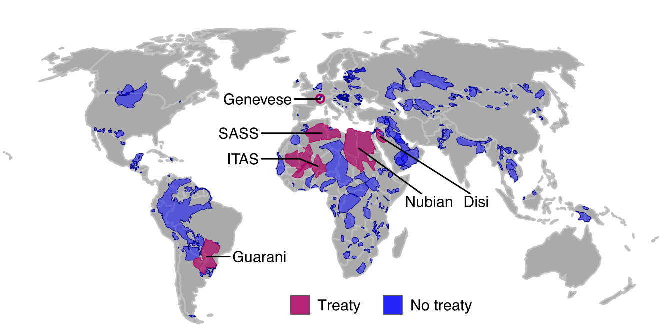

Fig. 1. Global transboundary aquifers (IGRAC and UNESCO-IHP, 2015). Of nearly 600 international transboundary aquifers, only six fall under an international agreement (Burchi, 2018). Of these, only the Genevese and Disi have explicit provisions limiting abstraction. Treaties and Memoranda of Understanding 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 general principles to improve diplomacy and cooperative interactions.

to enforce. In addition, incentives and impediments to cooperation for any particular transboundary aquifer depend on a variety of social and geophysical characteristics that are specific to the aquifer region.

Here, we model incentives for bilateral cooperation through the reduction of pumping-cost externalities (Negri, 1989), which represent a common feature of shared groundwater systems and reflect additional costs of abstraction imposed on transboundary partners. In particular, we develop a game theoretic model that evaluates how incentives to limit or reduce abstractions emerge through the interaction of key economic and hydrogeological features of transboundary aquifer scenarios. The simplicity of the model allows us to abstract from place-specific characteristics of transboundary cooperation to consider, broadly, how geophysical conditions, economic incentives, and mutual trust of transboundary partners interact across transboundary aquifers. As such, we use the results of the model to provide insights and understanding regarding the cooperative management of existing transboundary aquifers. This allows a first-order assessment of the circumstances that might lead to different types of agreements.

We focus on the role of trust due to the difficulty of monitoring groundwater abstraction and attributing changes in groundwater level to pumping by a particular country. Optimal groundwater abstraction likely requires one or both countries to credibly commit to reduce their pumping. Trust is critical for this to happen, particularly in an international context where the objectives of multiple countries may be in opposition (Wolf et al., 2005), cooperation produces additional risk (Hoffman, 2002), and complete oversight of groundwater abstraction is impractical given the hidden nature of the resource (Albrecht et al., 2017). 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; Susskind and Islam, 2012; Islam and Susskind, 2013). Existing transboundary aquifer agreements all include mechanisms intended to build trust between countries, including joint monitoring, information sharing, and increased collaboration (Edelenbos and van Meerkerk, 2015; 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 (Abbink et al., 2010; Biswas, 2011). Concerns over non-compliance with transboundary agreements have arisen in multiple circumstances including the Mountain aquifer shared by Israel and Palestine (Gvirtzman, 2012; McKee, 2019), the Ganges river shared by India and Bangladesh (Rahman et al., 2019), and the Indus river shared by India and Pakistan (Akhtar, 2010; Qamar et al., 2019). Transboundary trust is shaped not only by inherent beliefs held by one country with respect to another, but also by institutional capacity, historical interactions, ongoing bilateral initiatives, strategic priorities, and cultural narratives (Susskind and Islam, 2012). Often, trust is defined in close relation to the notion of reciprocity, in which an actor may be more willing to sacrifice for the benefit of another if they believe the other actor would do the same (Ostrom, 2003). Although reciprocity may affect the level of trust, we specifically conceptualize trust as the belief of one country that a transboundary partner will seek cooperation and comply with any signed agreement (e.g., see Kydd, 2005).

We incorporate this notion of trust into a model of transboundary aquifer cooperation that captures key economic incentives 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 incentivize formal cooperation over shared groundwater. Although these incentives may influence cooperative outcomes, a variety of factors determine whether or not a treaty is signed in any particular aquifer including domestic politics, diplomatic relations, and institutional capacity (Albrecht et al., 2017). As such, the objective of the model is to facilitate an understanding of cooperation rather than for prediction. Game theory has a rich tradition in international diplomacy (Fearon, 1998; Snidal, 1985) and water resources management (see Madani, 2010; Dinar and Hogarth, 2015; Müller and Levy, 2019, for extensive reviews) to model decision making and conflict resolution. Within that context, our model contributes to two key bodies of literature.

The first literature relates to the representation of aquifer response in game theoretic models of transboundary groundwater. Although a number of game theoretic models have considered cooperation and conflict over transboundary rivers (e.g., Dema, 2014; Eleftheriadou and Mylopoulos, 2008; Khachaturyan and Schoengold, 2019; Motlagh et al., 2017), very few have considered transboundary aquifers. Aside from Müller et al. (Müller et al., 2017), further discussed below, we are only aware of Nakao et al. (Nakao et al., 2002), which simulated transboundary groundwater cooperation along the US-Mexico border, incorporating multiple types of cooperative institutions. Similar to most early games of (non-transboundary) groundwater competition (e.g., Negri, 1989; Gardner et al., 1997; Provencher and Burt, 1993), that study used a single-cell or "bathtub" aquifer model in which pumping yielded homogeneous drawdown throughout the aquifer. Spatially explicit groundwater behavior was incorporated by Brozovíc et al. (Brozović et al., 2010) using the Theis solution for drawdown by pumping wells (Theis, 1935). The spatial behavior of groundwater depletion was further integrated into a groundwater game by Müller et al. (Müller et al., 2017) by formally applying the principle of superposition and using a 2D finite-difference model to account for complex groundwater behavior. We use this framework to model spatial groundwater behavior using the analytical element method (Penny et al., 2020), which allows complex groundwater behavior to be modeled by combining theoretical solutions to any number of individual aquifer elements (e.g., wells, aquifer boundaries, and recharge, see Strack, 2017).

The second literature that this study contributes to relates to the representation of trust in game theoretical models of shared water resources. Several studies focusing on transboundary surface water have modeled how trust can be built through repetitive interactions with incremental benefits (Madani, 2010; Yu et al., 2019; Motlagh et al., 2017). These repeated games describe the ability of players to learn trustworthy behavior based on reciprocal interactions that ultimately improve their respective reputations. Unlike reputation-building games in which trust emerges through repetitive interactions, we focus on the implications of trust in terms of the expected outcomes of transboundary cooperation in a one-shot game. Such a game is representative of transboundary situations where the primary interaction is the development of a formal treaty and where the actions of the other player (e.g., groundwater abstraction) are not directly observable or enforceable. Note that this approach does not require trust to be fixed in time, but rather that trust is exogenously determined at the moment a treaty is considered by each player.

In this manuscript, we develop a Bayesian game of incomplete information to represent key strategic incentives that underpin transboundary groundwater cooperation (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 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 3). We then evaluate the ability of the game to qualitatively reproduce the sequence of events that gave rise to the Genevese aquifer treaty (Section 4.1). 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 cooperation (Section 4.2).

2. Theory: Derivation of the transboundary aquifer game

2.1. Utility function and aquifer response

Consider a situation where two groundwater users (i.e., players 1 and 2) share an aquifer and gain some benefit from abstracting water. In order to maximize profits, water use will balance the cost of abstraction with profits generated from water consumption (e.g., through agricultural irrigation). This scenario can be represented for either player i (i.e., $i \in \{1,2\}$) by the equation (see Müller et al., 2017, for application to the Disi aquifer):

$$\max_{q_i \in [0, Q_i]} U_i(q_i, q_j), \quad \text{where } U_i(q_i, q_j) = \alpha_i q_i - \beta d_i(q_i, q_j) q_i. \tag{1}$$

In this equation, q_i $[L^3]$ is the groundwater abstraction volume from the shared aquifer over the considered time horizon, α_i $[\$/L^3]$ is the value of a unit of groundwater (e.g., the profit generated from using the water for irrigation), β [\$ L^{-3} L^{-1}] is the (net present) cost of energy required to lift a unit of water by a unit length, and d_i $[L]$ is the depth of the water table. The constraint Q_i $[L^3]$ represents the abstraction threshold beyond which no marginal revenue is produced. In the context of groundwater use for irrigation, this represents the water volume necessary to fully irrigate all the available cropland during the considered period. Under these conditions, additional pumping from the aquifer would not increase agricultural production, which becomes limited by production factors (e.g., land or labor) other than water. In an urban water supply context, utility can be replaced by:

$$U_i(q_i, q_j) = -\alpha_i(Q_i - q_i) - \beta d_i(q_i, q_j) q_i. \tag{2}$$

Here, Q_i represents the domestic water need that the urban utility needs to satisfy, and α_i now represents the unit cost of water obtained from an alternative source other than the aquifer, with $Q_i - q_i$ the water volume the should be obtained from that alternative source (Fig. 2a). Note that Eqs. 1 and 2 have identical derivatives with respect to q_i, and therefore identical utility-maximizing values of q_i. In both Equations, α_i can be interpreted as the unit value of the aquifer water for player i, either in terms of the associated agricultural output, or in terms of the opportunity cost of not using the water. Furthermore, Q_i portrays the fact that the marginal return of aquifer water drops to zero, once a sufficient quantity of water is obtained.

Importantly, the depth to groundwater for either player is affected by the pumping volumes, q_i and q_j, of *both* players. 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). The average groundwater depth for player i can therefore be written as

$$d_i(q_i, q_j) = d_{0i} + D_{ii} q_i + D_{ij} q_j\,, \tag{3}$$

where d_{0i} is the undisturbed average groundwater depth (i.e., d_i when $q_i = q_j = 0$), and D_{ii} and D_{ij} are aquifer response parameters that relate the groundwater depth of player i to the groundwater abstractions of players i and j (q_i and q_j), respectively. The aquifer response parameters (D_{ii} and D_{ij}) can be estimated through a variety of methods, including finite difference numerical models (e.g., Müller et al., 2017) or the analytical element method (e.g., Penny et al., 2020). In both cases, the model calculates drawdown for player i in response to unit pumping by each player in order to estimate D_{ii} and D_{ij}. The process is repeated for player j to obtain D_{jj} and D_{ji}. 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 Theis solution (e.g., as implemented in Brozović et al., 2010; Madani and Dinar, 2012).

Both abstraction (q_i) and the aquifer response parameters (D_{ii} and D_{ij}) are assumed to be static over the considered time horizon (e.g., the life span of the infrastructure). This reflects the fact that water supplies

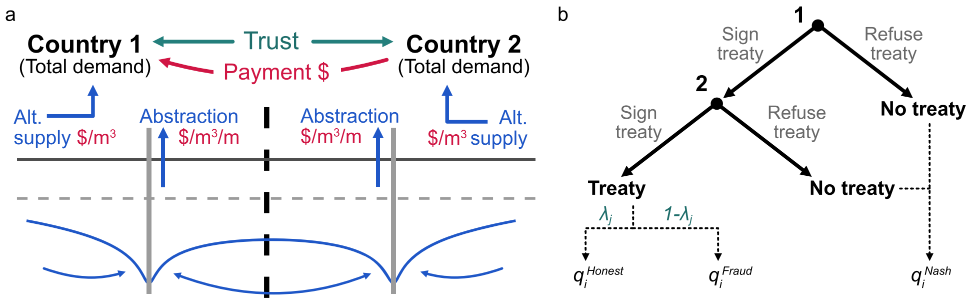

Fig. 2. Conceptual model of the transboundary aquifer game applied to urban water supply, including (a) groundwater and economic model and (b) player decision making and pumping. Both players ($i \in \{1, 2\}$) must satisfy a total demand, Q_i, through groundwater abstraction (q_i) and an alternative supply, each with associated costs. Both players decide simultaneously whether or not to cooperate. 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. The extensive form of the game is presented in Figure S1.

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 will not 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 S2.3), and is also supported by prior analysis in the Disi aquifer (Müller et al., 2017). Note that these two examples are the only known cases of active international groundwater agreements that constrain pumping, which the model seeks to emulate. The assumption of static aquifer response parameters implies that D_{ii} and D_{ij} are obtained by simulating the average drawdown effects of a unit pumping rate imposed for the full duration of the considered time horizon. As such, the parameters of the model can be changed to represent the system across multiple instances in time including, for example, changing abstraction behavior in response to changing demand or climate. The model itself, however, does not assume that players respond dynamically to aquifer conditions. Rather, consistent with the game-theoretical concept of a best-response equilibrium (Gibbons, 1992), the model assumes that each player fully anticipates the other player's response, which they use to determine their optimal course of action prior to the game.

2.2. Non-cooperative equilibrium

Without any form of cooperation, we solve the game by determining the Nash equilibrium in which each player chooses their abstraction to maximize their own utility, conditional on the other player maximizing theirs. In this case the players abstract q_i^N, determined through simultaneous optimization of their individual utility as

$$\begin{cases} \dfrac{\partial U_i(q_i, q_j)}{\partial q_i} = 0 \\ \dfrac{\partial U_j(q_j, q_i)}{\partial q_j} = 0 \end{cases} \tag{4}$$

where $U_i(q_i, q_j)$ and $U_j(q_j, q_i)$ take the functional forms of Eq. 1 or 2, which have identical derivatives. Importantly, the groundwater depth of each player depends on the pumping rates of *both* players (Eq. 3). Because the unit cost of abstraction $\beta \cdot d_i$ 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, but doing so requires cooperation.

2.3. Cooperation and trust

Cooperation in the context of the transboundary aquifer game means that players collectively optimize their joint utility ($U_i + U_j$), 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., $\beta \cdot d_i$). Social optimal pumping 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, the social optimal may require that one player decreases their groundwater abstraction more than the other player or even that one player increase abstraction. We assume that utility is transferable and allow players to compensate these differences through side payments (see Dinar, 2006, for a review of side payments in transboundary agreements). We formally define utility for player i under the treaty as

$$U_i(q_i, q_j) = \alpha_i q_i - \beta d_i(q_i, q_j) q_i - \epsilon_i + (-1)^i z, \tag{5}$$

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 than the other. Abstraction rates under the optimal treaty, q_i^H, are determined by the joint maximization of utility of both players as

$$\begin{cases} \dfrac{\partial U_i(q_i, q_j) + U_j(q_j, q_i)}{\partial q_i} = 0 \\ \dfrac{\partial U_i(q_i, q_j) + U_j(q_j, q_i)}{\partial q_j} = 0 \end{cases} \tag{6}$$

where, U_i and U_j are both given by either Eqs. 1 or 2, which have identical derivatives.

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. To incorporate trust in the model, we assume that each player is one of two randomly determined types: Honest ($t_i = H$) or Fraudulent ($t_i = F$). Honest players always comply with a signed treaty and abstract q_i^H (Eq. 6), while Frauds always act in their own self-interest and abstract $q_i^F > q_i^H$ (Eq. 8, below). Note that our binary categorization of players does not seek to determine the underlying reasons for complying with the treaty or not, which would depend on a variety of country-specific factors (e.g., strategic goals, capacity to uphold the treaty, and international standing, Kydd, 2005). Each player knows their own type but not the type of the other player. Given this uncertainty, each player has a belief about the other player's type. We incorporate trust into the model as the belief of each player that the other player is Honest and will comply with a signed treaty. Formally, the player i's trust in player j is expressed as the prior probability $\lambda_i \in [0, 1]$ that player j is Honest. This notion of trust is in line with existing literature. In particular trust has been conceptualized as the "the willingness to take risks and the expectation that others will honor particular obligations" (Hoffman, 2002), "a belief that the other side is trustworthy, that is, willing to reciprocate cooperation" (Kydd, 2005), and that trust is context specific, meaning it involves the belief that another actor will carry out a specific action (Hardin, 2001). The expected utility for player i after signing a treaty is then a weighted function of abstraction by both players given as

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

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 (see Fig. 2b). This expression can be used to derive the abstraction q_i^F of player i if they are Fraudulent:

$$\frac{\partial}{\partial q_i}\left[\lambda_i U_i\left(q_i^F, q_j^H\right) + (1 - \lambda_i) U_i\left(q_i^F, q_j^F\right)\right] = 0. \tag{8}$$

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.

The game does not explicitly account for treaty enforcement or impose any sanctions in the case of non-compliance. However, our definition of trust and its implementation in Eq. 7 allow for flexibility in how the trust parameter can be interpreted. For instance, high trust ($\lambda_i \to 1$) could be achieved through reputation and strong diplomatic relations or, alternatively, high trust could be achieved through strong monitoring and enforcement. Low trust ($\lambda_i \to 0$), therefore, would only occur in situations where Frauds can conceal their behavior such that non-compliance is difficult to monitor and enforce.

The model focuses only on treaties that minimize pumping-cost externalities by optimizing volumetric abstractions by each country. This simplifying assumption means that the model cannot directly simulate the emergence of other types of treaties. However, by pointing to *why* a volume-based treaty is likely unfeasible in the considered situations, it provides helpful information to interpret the alternative type of treaty that emerged instead (see Section 4.2).

2.4. 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 Fraudulent one. Furthermore, because the treaty does not reduce Fraudulent pumping, players must account for the fact that Fraudulent players 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, players update their beliefs at each stage according to prior actions of other players (Gibbons, 1992). 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 refuse 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 Fraudulent players 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, in our model, a treaty is signed if and only if:

$$\begin{aligned} \mathbb{E}\left[U_i^{Nash}\right] &< \mathbb{E}\left[U_i^{Honest}\right] \\ U_i\left(q_i^N, q_i^N\right) &< \lambda_i U_i\left(q_i^H, q_j^H\right) + (1 - \lambda_i) U_i\left(q_i^H, q_j^F\right). \end{aligned} \tag{9}$$

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. 9 holds true. We therefore solve Eq. 9 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 ($\widehat{u} = z_1 - z_2$) is greater than zero, the treaty is signed. We therefore use $\widehat{u}$ as a measure of the *utility of the treaty* compared with the Nash equilibrium. This variable represents the expected net increase in utility for two Honest players entering into a treaty, accounting for the fact that each player has uncertainty about the behavior of the other player who may try to cheat. We use this variable as the primary outcome of the game, thereby framing the issue of cooperation from the perspective of Honest players.

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.

3. Results: Comparative statics of the two-player game

The results of the game demonstrate how incentives to cooperate depend on a variety of system characteristics that ultimately dictate whether both players are willing to sign a treaty. As described above (Section 2), 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 model outcomes vary for different combinations of driving parameters (Fig. 3). 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 ($D_{ij}/D_{ii} \in [0, 1]$), the unit value of water (α_i), and trust (λ_i) on the utility of a treaty ($\widehat{u}$). 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. We note that groundwater connectivity will generally increase with greater hydraulic conductivity, a distinct but more common term which represents the ability of porous media to transmit water (Klute, 1965). The remaining parameters, α_i, λ_i, and $\widehat{u}$ are defined above (Section 2).

3.1. Groundwater connectivity

Groundwater connectivity affects the interdependence of ground-

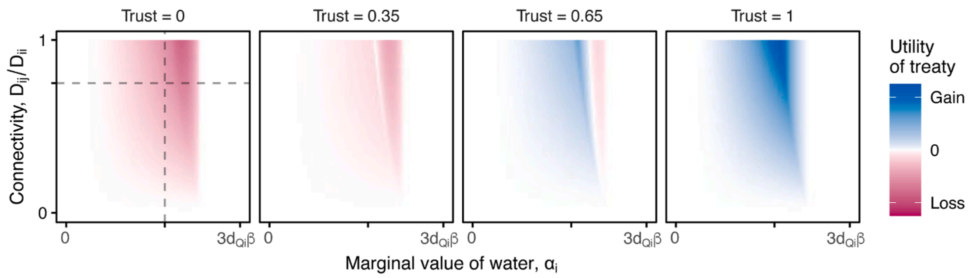

Fig. 3. Variation in the utility of a treaty ($\hat{u}$) in the symmetric game, contingent on groundwater connectivity, marginal value of water, and trust. Utility of the treaty is the utility gained from a treaty relative to the Nash if players are forced to sign the treaty. The benefit of signing a treaty is greatest when connectivity and trust are high while the value of water 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 unit value of water (α_i) that are held constant in Fig. 4. Note that βd_{Qi} represents what the average groundwater pumping costs *would be* if the entirety of demand were sourced from the aquifer (i.e., $\beta d_{Qi} = \beta Q_i(D_{ii} + D_{ij})$).

water resources of both players. All else being held constant, it can be considered the "stakes" of signing a treaty. In the extreme case where the two players are almost entirely disconnected ($D_{ij}/D_{ii} \to 0$), 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. 4a,). Under these conditions, players are ambivalent about signing a treaty (Fig. 4c, 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 (Fig. 4a, green) and the treaty (Fig. 4a, 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 greater reduction in abstraction (for Honest players) which allows Frauds to pump increasingly more when a treaty is signed (Fig. 4a, red).

3.2. Value of water

The utility of a treaty ($\hat{u}$) exhibits a non monotonic relation with the marginal benefit α_i of using aquifer water. As described in Section 2.1, this marginal benefit can be either associated with the value of the goods produced with the water, or with the opportunity costs of not having to rely on an alternative water source to meet a given water need. At the lower extreme ($\alpha_i = 0$), neither player will use the aquifer because no marginal benefit can be generated from the abstracted water. In the context of urban water supply, both players exclusively use an alternative source because it is less expensive than groundwater pumping ($\alpha_i = 0$ means that the alternative water source is free of costs). At the upper extreme ($\alpha_i \to \infty$), both players produce a substantial marginal benefit from the abstracted water and do not wish to compromise their ability to exploit the aquifer. In the context of urban water supply, both players exclusively rely on the shared aquifer because the alternative source is too expensive. In other words, for a sufficiently high value of α_i, both players pump *exactly* their water demand Q_i, regardless of the treaty. Unless some inherent cost arises ($\epsilon_i \neq 0$), in both situations ($\alpha = 0$ and $\alpha \to \infty$), players are ambivalent about signing a treaty which will be either useless ($\alpha = 0$, no-one uses the aquifer) or toothless ($\alpha \to \infty$: no-one will agree to restrict their consumption).

Just as abstraction at the extremes obeys clear rules, abstraction throughout the domain of α_i follows predictable behavior which can be separated into clearly defined "zones", as shown in Fig. 4b. As just argued, when the marginal benefit of using the aquifer is lower than the cost of abstracting groundwater from the undisturbed water table depth (i.e., $\alpha_i < \beta d_{0i}$), neither player has incentive to exploit the shared aquifer (*i. No abstraction zone* in Fig. 4b). As the marginal benefit of pumping (α_i) increases past the threshold βd_{0i}, players start using the aquifer and pumping rates increase linearly with α_i. Reliance on the aquifer increases as the marginal benefit of pumping increases. The incentives to over-pump (given by the difference between Honest and Nash abstraction rates in Fig. 4b) increase, as do the risks of signing a treaty (difference between the Honest and Fraud abstraction rates in Fig. 4b). In this zone, abstraction is cost-limited meaning that players consider trade-offs between the cost of groundwater and the marginal benefits of abstraction α_i (*ii. Cost-limited zone* in Fig. 4b). If α_i is sufficiently high, the Fraudulent player will use the aquifer to the full extent of their capacity and pump Q_i. In an urban water supply context, they would rely entirely on the aquifer to meet their water need Q_i (*iii. Demand limited – Fraud*). At this point, increasing values of α_i will increase reliance on the aquifer in the absence of treaty (Nash, in green on Fig 4b), but will *not* increase incentives to cheat (Fraud, in red on Fig 4b). 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. 4d). For even higher values of α_i, the Nash equilibrium pumping rate reaches the threshold Q_i (*iv. Demand limited – Nash*), where 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 α_i all players consume Q_i regardless of the treaty, equivalent to the extreme case of $\alpha_i \to \infty$ described above (*v. Abstraction only*).

The progressive decoupling of abstraction with the marginal benefit of pumping in zones (iii-v) occurs due to the pumping threshold Q_i, beyond which the marginal benefit of increasing consumption vanishes. For urban users, this threshold represents the total water need that needs to be satisfied. For agricultural users, this threshold is represented by the transition from water to another constraining factor (e.g., land or labor) that limits agricultural production. In situations where this transition does not occur for reasonable values of q_i (e.g., in desert aquifers where labor and land are not constrained), Q_i does not have an effect on pumping decisions, and solution space becomes restricted to zones (i) and (ii) (see Fig. 4). 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.

3.3. Trust

Trust plays an important role in model scenarios 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, which we define 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 Fig. 5 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 the marginal benefit of pumping α_i 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 (Fig. 5a). Moving into the *(iii) Demand limited (Fraud)* zone, the benefits of a treaty increase while the risks of a treaty reduce (Fig. 5b). The decreasing risk arises because Fraud abstraction (q_i^F) is limited by demand (Q_i) and approaches abstraction in the Nash as α_i increases (see Fig 4 b). In the *(iv) Demand limited (Nash)* zone, the benefits and risks both decrease, but the benefits decrease more rapidly than the risks (Fig. 5c). For this reason, the trust required to sign a treaty increases dramatically at the upper end of this zone (Fig. 4d). 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 require the lowest level of trust. In zone (iv), a treaty can be achieved but requires a higher level of trust, particularly near zone (v).

4. Discussion

4.1. Is the model realistic?

The Genevese aquifer treaty, signed by Switzerland and France in 1978, offers a useful case study with which to assess cooperative outcomes in 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 relations 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 (Fig. 6ab). The timeline of events in the Genevese (Fig. 6c) 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. Water levels began declining in the 1960 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 since (de los Cobos, 2018).

We codified this timeline of events into the transboundary aquifer game by varying input parameters within Monte Carlo simulations to capture both uncertainty and nonstationarity in the input variables (see Section S2). In order to capture specific features of the Genevese aquifer, we modified the game (described in Section 2) to account for unconfined behavior and aquifer recharge (see Section S2.1). The model indicates that a treaty was more likely than not in 1974, then unlikely while France pursued inexpensive alternatives, and again likely in 1978 (when the treaty was actually signed). The model results (presented in Figure S2) offer confidence that the transboundary aquifer game adequately captures key features of the treaty negotiation.

4.2. A typology of transboundary groundwater cooperation

The transboundary aquifer game provides a basis for identifying classes of transboundary groundwater agreements that seek to reduce pumping-cost externalities by restricting pumping rates by one or both countries. Indeed, by reconciling existing treaties with the model, a typology of transboundary groundwater cooperation emerges that provides clearer distinctions between the agreements that have been signed. The typology includes treaties that (1) explicitly regulate abstraction volumes (the Genevese), (2) explicitly restrict abstraction within a buffer region near the border (the Disi), and (3) rely on general principles to promote cooperation and collaboration. Fig. 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 and represents the marginal benefits of pumping water from the shared aquifer. Again, these marginal benefits can be either interpreted as the marginal revenue associated with the goods produced with the abstracted water (agriculture) or the marginal opportunity cost associated with obtaining that water from an alternative source (urban water supply).

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 Fig. 7). The motivation for cooperation therefore arose from the desire to preserve groundwater supplies in the aquifer and ensure access for both Switzerland and France (de los Cobos, 2018). Given the small size of the aquifer and the close proximity of wells on either side of the border, the only available option to ensure groundwater sustainability was to reduce abstraction. The model demonstrates that 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 4.1). 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 an inexpensive alternative source of water. In other words, both players were satisfied with the status quo 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). Similar to the Genevese, both sides were concerned about declining water table levels and were confronted with the development of new water supply infrastructure. In the case of the Disi, however, groundwater depletion was driven primarily by domestic abstraction on either side of the border, and not by mutual depletion (Müller et al., 2017). This allowed the Disi agreement to emerge, which places no limits on the quantity of groundwater abstraction but restricts abstraction near the shared border. The effect of the Disi approach is that pumping by either player has little effect on water levels of the other player because of the large distance between wells on either side of the border (Müller et al., 2017). 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 unappealing. Additionally, the model indicates that trust, as defined in the model, has little effect on the expected outcomes when connectivity is low because of the minimal effect each player has on the other player's well drawdown. The treaty reframes groundwater depletion as a domestic issue because either side does not deplete their groundwater more quickly than they might have if the aquifer was not internationally shared. Furthermore, limiting connectivity reduces the stakes of the treaty and could facilitate higher trust between countries by lowering risks and rewards (see Poteete et al., 2010; Hoffman, 2002). More generally, a high marginal revenue of water α, combined with a low demand threshold Q, indicates situations where both parties are heavily reliant on the aquifer, either to produce a high value output or because any alternative source of water would be prohibitively expensive. Under these conditions, use of the

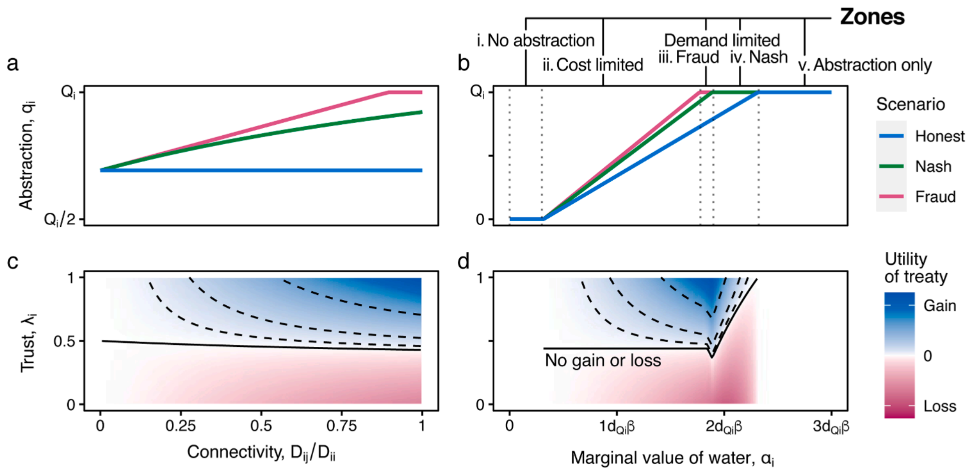

Fig. 4. Effect of connectivity, marginal value of water, and trust on outcomes of the symmetric game, including (a-b) pumping, q_i, and (c-d) utility, $\hat{u}$. In the connectivity plots (left), both the marginal value of water and the sum $D_{ii} + D_{ij}$ are held constant. Keeping $D_{ii} + D_{ij}$ 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 marginal value of water plots (right), connectivity is held constant and the five zones of the game are shown in (b). For low and high values of α_i, pumping rates under the Nash equilibrium are equal to pumping rates for Honest and Fraud players. Between these extremes, pumping rates increase linearly with marginal value 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 $\lambda_i \to 0$. 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 (c) and (d) 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). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

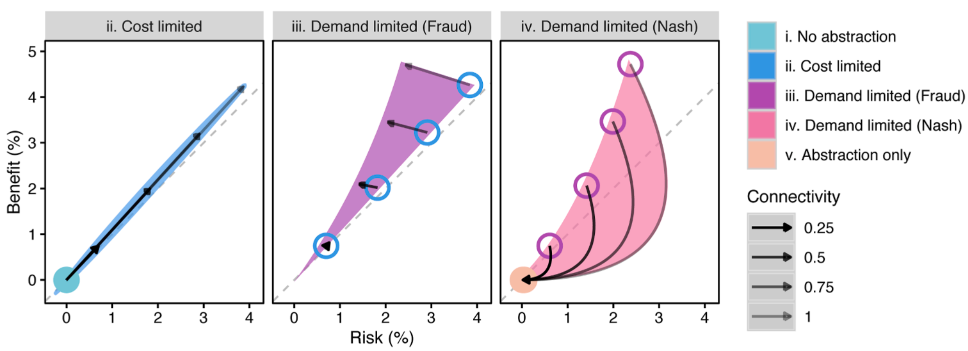

Fig. 5. Benefits and risks of signing a treaty for zones (ii–iv), with moderately high trust ($\lambda_i = 0.65$). Colors indicate the zones, with circles indicating the adjacent zone. Each arrow represents the change in benefits and risks associated with a treaty for constant connectivity as the marginal benefit of pumping from the aquifer increases across the zone. Following the arrow is analogous to moving left-to-right in Fig. 4b. 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 3.3). Generally, the *Demand limited (Nash)* zone requires the highest trust. Note that zones are defined in Section 3.2 and Fig. 4b.

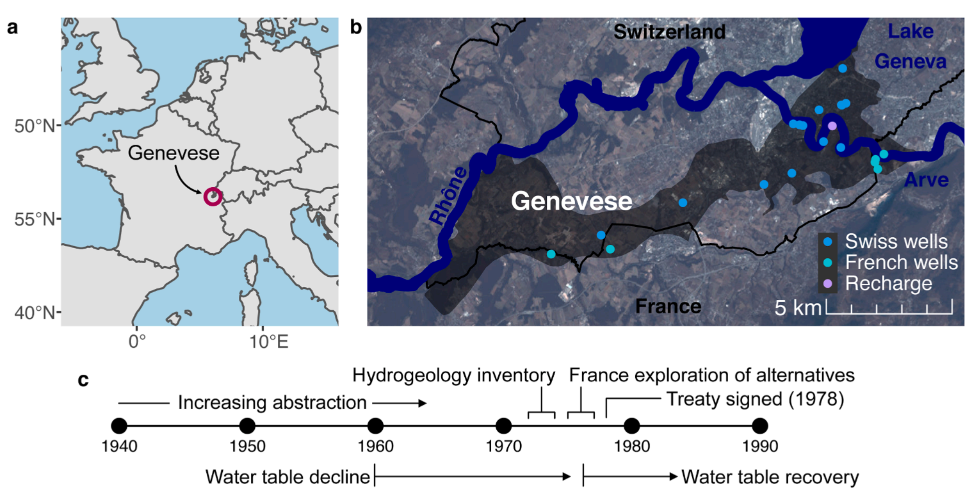

Fig. 6. The Genevese aquifer and treaty timeline. (a) Location, (b) map of the Genevese aquifer and pumping wells, and (c) timeline of events. As shown, the Genevese treaty was signed in 1978.

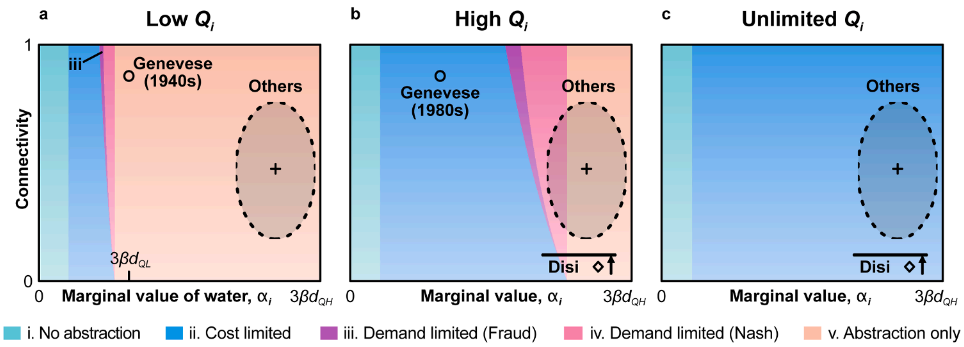

Fig. 7. Transboundary aquifer zones and relation to existing treaties. (a) When Q_i is low, urban water demand is generally sourced entirely from the aquifer (zone v), unless the cost of an alternative water source is also low (other zones). (b) When Q_i is high, a water supply utility will likely meet their water demand through a combination of groundwater from the shared aquifer and water from the alternative source (zones ii–iv), unless the cost of the alternative water source is too high (zone v). (c) In an extreme case of unlimited Q_i (e.g., agricultural water use in a desert aquifer with unlimited labor and land), water use is determined by the value of water (α_i) and is sourced entirely from groundwater. Connectivity represents the interdependence of groundwater supply, while the horizontal axis can be considered a metric of surface water scarcity. Transition through the five zones can occur either through increasing costs (α_i) or through increasing demand threshold (Q_i), as in the case of the Genevese. Note that both the vertical and horizontal axes are identical to the axes in Fig. 3, and that d_{QL} and d_{QH} correspond to the depth of the water table at pumping rates equivalent to Low Q_i and High Q_i, respectively.

shared aquifer becomes inelastic to its own cost, providing little room for either party to restrict their abstraction (as in Fig. 7c). Limiting connectivity in such situations, as was done in the Disi-Saq/Ram aquifer, may be the most viable option.

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, where annual abstractions represent a small fraction (<3%) of annual recharge and the primary concerns include vulnerability to contamination in unconfined zones of the aquifer and long-term declining water storage in portions of the confined aquifer with slow recharge (Sindico et al., 2018), all other agreements concern aquifers 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 treaties on the right side of Fig. 7, while acknowledging that they could be situated in a range of scenarios or zones.

It is important to note that the model developed in this study focuses on a specific type of agreement that limits water abstraction volumes in order to maximize the joint utility of the users. Consequently, the model does *not* directly evaluate the feasibility of any other types of agreement. Instead, the model can be used to identify likely reasons *why* a volume-based agreement did not emerge and can help us interpret the type of agreement that did emerge. For instance, the Nubian Sandstone Aquifer System (NSAS) agreement provides for a mechanism for information sharing and joint hydrogeologic modeling efforts. Modeling results suggest that, although drawdown near pumping centers can be substantial, transboundary drawdown is likely minimal, even in regions where pumping centers are located near national borders (Voss and Soliman, 2014). This places the NSAS aquifer in the low connectivity region at the very bottom of Fig. 7. However, the model also outlines the risk of oasis loss and associated environmental impacts due to dropping water tables (Voss and Soliman, 2014). Among other benefits, information sharing associated with the agreement improves modelling accuracy to allow countries to monitor and mitigate these (domestic) issues (Government of Egypt, Government of Libya, Government of Chad, Government of Sudan 2013). In the case of the Iullemeden Taoudeni-Tanezrouft Aquifer System (ITAS), water levels have been affected by expanding agriculture into low rainfall area and land use changes in the recharge zone over the past decades. These effects will be exacerbated by a predicted decrease in precipitation and increase in evaporation associated with climate change in the Sahel region. These changing conditions might alter the location of the ITAS in parameter space in Fig. 7 with substantial associated uncertainty. The Memorandum of Understanding provides for a consultation mechanism for information gathering, information exchange and decision making for sustainable water resource management of the aquifer (Eckstein and Dodo (2012)). In the case of the Northwestern Sahara Aquifer System (commonly referred to by its French acronym, SASS), locally high transboundary connectivity and extreme water scarcity (Sahara and Sahel Observatory, 2003) place the aquifer in the upper right corner of Fig. 7, where a volume-base agreement is unlikely. Instead, the riparian countries have created a consultative mechanism that includes a permanent technical committee tasked with information sharing and managing a joint aquifer model. This process allowed regions with high vulnerability or high exploitation potential to be mapped to possibly optimize the spatial location of exploitation regions (Sahara and Sahel Observatory, 2003).

These findings collectively demonstrate that multiple classes of regulatory frameworks are available to limit groundwater abstraction and prevent pumping-cost externalities in transboundary aquifers, but that each one requires particular circumstances to be met. In particular, the zones relate connectivity and value of water with plausible treaty outcomes. 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 general principles to promote cooperation are more tractable.

Lastly, 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.

5. Conclusions

Transboundary aquifers provide critical water supplies around the world but have received relatively little attention from the broader research community given the importance of the resource. To help close this gap, we develop a game theoretic model to explore the relationship between economic incentives and hydrogeological characteristics of transboundary aquifer cooperation, with an emphasis on the role of trust. By focusing on the pumping-cost externality between two players that seek to minimize the cost of their water supply, our analysis pertains to aquifer scenarios where two countries share a single border and cooperation entails reducing (or limiting) the pumping-cost externality. Other scenarios with additional players (e.g., aquifers shared by three or more countries), different cooperative objectives (i.e., other than the pumping-cost externality), or more complicated groundwater configurations (e.g., a confined aquifer recharged by surface water in another country) may yield different outcomes. Future work should also consider additional externalities related to groundwater abstraction including subsidence, ecosystem degradation, and water quality.

Despite its limitations, the model demonstrates how interactions among groundwater connectivity, water demand, and the economic value of water shape transboundary pumping-cost externalities. The typology encapsulates these principles by relating model outcomes with existing transboundary cooperative frameworks that seek to limit pumping-cost externalities by (1) regulating abstraction volumes (i.e., the Genevese), (2) restricting abstraction near the border (i.e., the Disi), or (3) developing cooperative frameworks for learning about the aquifer and building trust. Given the theoretical foundation of the model, we posit that these drivers transcend the unique features of these aquifers and likely affect economic incentives for transboundary aquifer cooperation more generally. Furthermore, in combination with the model, the typology of treaties presents an opportunity to broadly identify aquifers that might be amenable to cooperation or those that risk escalating into crises over transboundary water resources.

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.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary material

Supplementary material associated with this article can be found, in the online version, at 10.1016/j.advwatres.2021.104019

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