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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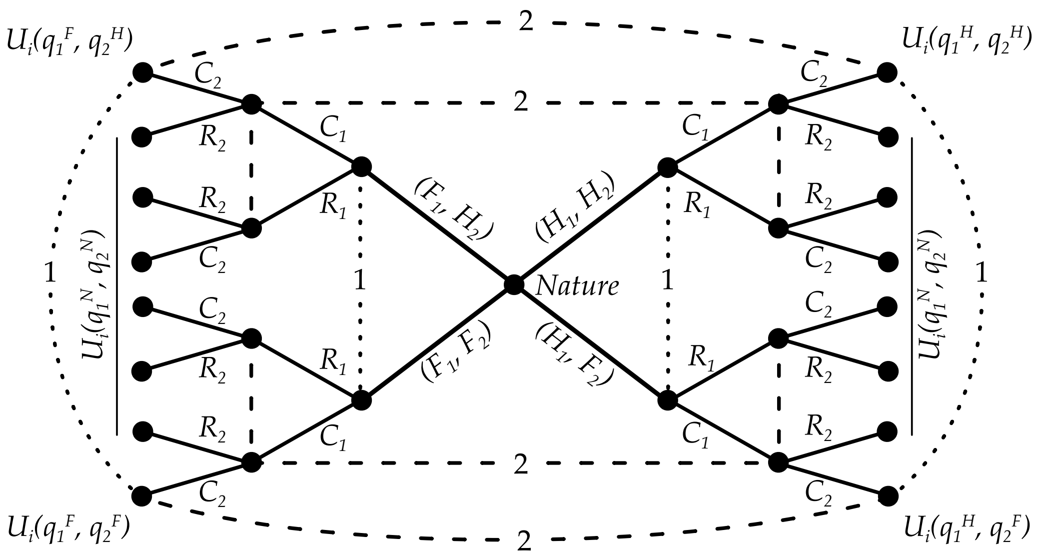

Figure S1. Extensive form of the trust game showing potential strategies for players 1 and 2. Payouts and beliefs are explained within the text.

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].

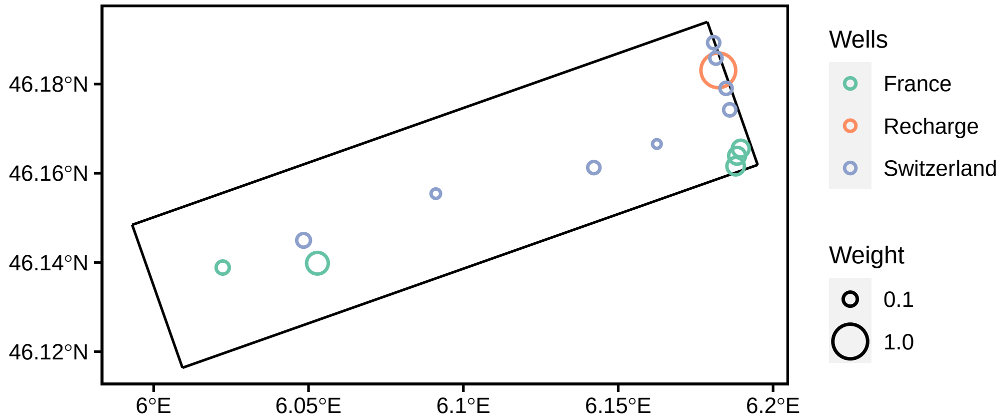

Figure S2. Idealized representation of the Genevese aquifer used for modeling drawdown relationships.

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

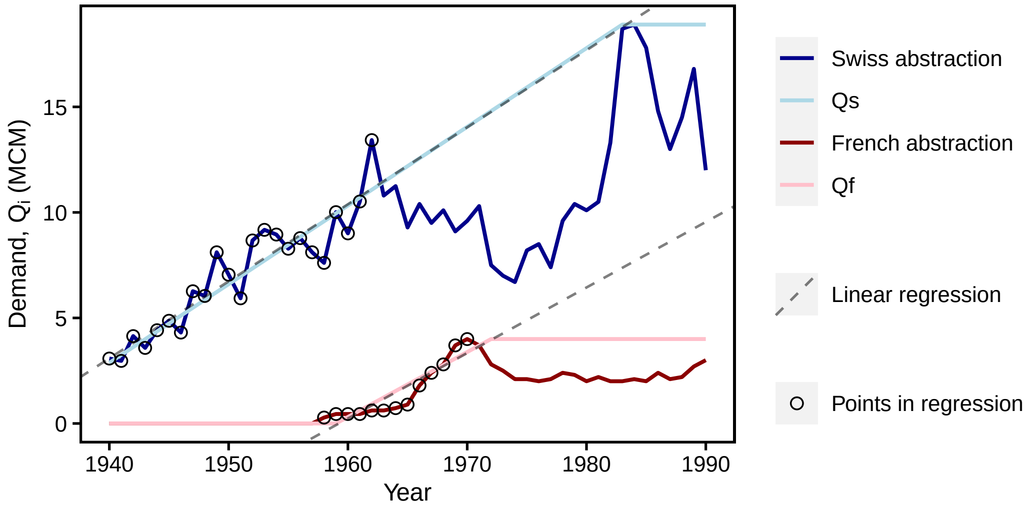

Figure S3. For both Switzerland and France, Q_i was determined from abstraction timeseries. The rising limb was determined from linear regression of the circled points. Increasing demand continues until reaching a maximum, determined by the maximum abstraction of each country over the timeseries. The 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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