Economic and Political Equilibrium for a Renewable Natural Resource with International Trade

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Abstract

International resources such as water are typically subject to conflicts as welfare functions perceived by individual countries typically increase monotonically with water. We consider a two-stage equilibrium model where it is possible for countries to share resource out of its self-interest. The first stage solves a trade model to determine economic equilibrium as a function of water allocation. The second stage utilizes the derived welfare functions to identify political equilibrium of a bargaining or game-theoretic problem. The results show that when trade is allowed, welfare functions can be non-monotone in some instances, implying that the level of conflict over water may be reduced or even alleviated.

Key Word: River sharing, Ricardian trade, Non-monotonic welfare, Political equilibrium

JEL Code: D58,F11,Q25

1 Introduction

Water is a critical natural resource for economic activity, and is increasingly scarce due to population and economic growth, and to increasing demand for environmental amenities stemming from water in its natural state. As difficult as water allocation is within countries and other political units, allocation is even more challenging when the water source is international. Wolf et al. (1999) documents that there are "261 international rivers, which cover 45.3 % of the land-surface of the earth (excluding Antarctica)". Of these more than 200 international rivers, 148 flow through two countries, 30 through three countries and the rest through more than three countries (Barrett, 1994a). The nature of international rivers and the scarcity of water intensify the conflicts, and lead to cooperation and river basin management issues. In particular, since no supra-national government exists, international water management carries an even higher burden of cooperative self-interest than might exist in other settings which have governmental allocation channels to oversee joint use of the resource by affected parties.

There is a substantial game-theoretic literature devoted to the design of self-enforcing agreement on water allocation (Ambec and Sprumont, 2002; Ambec and Ehlers, 2008a,b; Ansink and Ruijs, 2008; Ansink, 2009). Cooperative models use coalition formation theory to study the welfare consequences and stability of an international agreement under different circumstances. These include symmetric countries (Carraro and Siniscalo, 1993), asymmetric countries (McGinty, 2007), uncertainty (Na and Shin, 1998; Ulph, 2004; Finus and Pintassilgo, 2012), and issue linkage (Pham-Do, Dinar, and McKinney, 2011). Non-cooperative analyses include Hoel (1992), Barrett (1994b), Bennett et al. (1998), and Ansink (2009). In particular, Ansink (2009) analyses self-enforcing agreements on water allocation based on the outcome of a bargaining game. Carraro and Siniscalo (1998) point out that the structure of the game involving different countries is a chicken game rather than prisoners' dilemma. At least some degree of cooperation exists.

An international water allocation plan needs to be self-enforcing so that the riparian countries are better off under cooperation than non-cooperation, that is cooperation is beneficial for all participants. The construction of such a plan relies on the welfare functions of the riparian countries. The current literature normally assumes a particular welfare function without deriving it from the microeconomic foundations. In particular, Carraro and Siniscalco (1995), Ambec and Sprumont (2002) and others assume the benefit function is strictly increasing and concave, and Ambec and Ehlers (2008b) assume that the agents' benefit function exhibits a satiation point. However monotonic welfare functions may not always be appropriate; for instance, Carraro and Siniscalco (1997) demonstrate a humped-shaped payoff function when environmental issues are linked with R&D cooperation.

As for the stability of an international agreement, even if cooperation is beneficial, it may not be stable as countries have incentives to free ride. Other issues can be linked with the problem of interest to enhance the cooperation. Carraro and Siniscalco (1997) present a model to stabilize an environmental agreement by linking it to an R&D agreement. Barrett (1997) uses trade policy in a partial equilibrium model as a threat in achieving full cooperation to supply a global public good. Bennett, Ragland, and Yolles (1998) connect the river basin management problem to trade to improve upon the unsatisfactory "victim pay" outcome.[1]

This paper analyzes two countries with joint access to an international river and which also can or do participate in international trade. Each country has a representative household and water is the only factor of production. With this setup we consider a two-stage equilibrium model. The first stage solves a trade model to determine economic equilibrium as a function of water allocation between the two countries. The second stage then utilizes the welfare functions from the first-stage analysis to identify political equilibrium formulated as a bargaining or game-theoretic problem. In this setup, the primary question of interest is whether and under what circumstances it is ever self-interest for the two countries to cooperate over the natural resource as opposed to compete for it. The answer will turn out to be yes under some circumstances.

There are two possible spatial configurations of the countries and the river. One might be that the countries are upstream-downstream, or the second is that they might have a joint boundary along the river such as the Rio Grande between Mexico and the United States. Spatial configuration can influence initial property rights and hence influence the starting point in the second-stage political equilibrium analysis. However, the first-stage economic equilibrium analysis considers all possible water allocations, so geometry does not matter here. As a consequence, we do not consider a specific geometry of the system (upstream-downstream or riparian); the spatial configuration does not direclty enter into the analysis, and the analysis is general in this regard.

Conceptually there are at least three motivations for trade between countries (Feenstra, 2004): productivity differences (Ricardian model), primary factor endowments (Hechsler-Ohlin model), or economies of scale (Krugman, 1979). While all of these are relevant to the problem at hand, here we concentrate on the Ricardian case as a reasonable starting point for understanding international natural resource allocation when countries are engaged in trade. For a given technological parameter specification, the trade model is used to calculate world prices for the two goods as dependent on water allocation between the two countries. This is then used to specify country welfare as functions of the water allocation.

The results from the trade model analysis are striking: under some circumstances country welfare can be *declining* in water allocation meaning that countries could potentially gain by giving up some water. This occurs by comparative advantage when the natural resource is necessary for production and productivity differences imply that a good can be produced more effectively elsewhere. Of course, there is a limit to this process as countries have to have sufficient resources to generate exports and income to pay for imported goods/services. While it is intuitive that this phenomenon could occur, it still requires verification given the opposing forces at work, and also this phenomenon does not occur under all circumstances.

The paper next turns to a consideration of political equilibrium; this is where the system geometry may enter by defining an initial property rights allocation. We first consider a bargaining model. The analysis demonstrates that bargaining outcomes are not unique as they depend on the initial water allocation level. In some instances countries might be willing to voluntarily give up water, but not necessarily in other instances, and only up to

[1] The general literature on the design of self-enforcing International Environmental Agreements(IEAs)(Hoel, 1992; Barrett, 1994b; Batabyal, 1996; Na and Shin, 1998; Finus and Pintassilgo, 2012) is also applicable to river basin management.

some point. A discrete-strategy game-theory model is also considered as in previous studies (Bennett et al., 1998). There are two possible water allocation strategies under the control of one country, and autarky/free trade as the two discrete strategies for the other country. Perhaps the main result here is that this may be a limited framework for analysis as the outcome depends on the discrete strategies selected, and in addition it is typically in the self-interest of countries to pursue free trade, so autarchic threats may well lack credibility.

This work contributes to the water allocation literature in several ways. This is a general equilibrium model with trade. A trade model implicitly underlies the game-theoretic models with side payments, and the analysis here allows for the fact that the terms of trade may alter for non-marginal water allocations. This in turn implies that currency and hence side-payment unit values may also alter with water allocation. The main contribution of the paper is the welfare functions. The welfare function properties are derived from the trade model, and, most importantly, the analysis demonstrates that these functions can be non-monotone under some circumstances. This implies that joint allocation of the resource can be self-interest even with no side payments. At the very least, trade reduces the gains from additional water and thus lessens the level of conflict.[2] Finally, while we focus on international river water allocation, clearly the results are applicable to natural resources in general. Examples might be access to a joint groundwater aquifer, a common property resource such as fisheries or forests, or waste assimilative capacity of an environmental resource.

2 Model

We consider an international river basin where there are two countries ($i = 1, 2$) with joint access to the river and which potentially engage in Ricardian trade in produced goods. Annual water flow is W, of which country i takes $W_i = \theta_i W$. The river is assumed to be fully allocated with $\theta_1 + \theta_2 = 1$. There are also two goods, each of which is produced utilizing water with production coefficients specific to each country. Subsequent analysis considers autarky and free trade with exogenous water allocations, social welfare functions and bargaining political equilibrium with endogenous water allocations and trade policy.

For simplicity, identical household preferences

$$U_i = c_{i1}^{\alpha} c_{i2}^{1-\alpha} \tag{1}$$

are assumed for both countries. Here U_i is utility and c_{ij} is good j consumption in country i, with the preference parameter satisfying $0 < \alpha < 1$.

The two goods ($j = 1, 2$) are homogeneous across countries, but technologies in the two countries differ. Linear production functions are

$$y_{ij} = \beta_{ij} w_{ij} \tag{2}$$

[2]A further implication is that country welfare functions in a multi-country case with trade will generally depend on all the water allocations, not just the country's own allocation as in the literature. This follows because there are likely differential trading incentives for an individual country with respect to other countries, and this is affected by the water allocation. If there are n countries and water is fully allocated, then the welfare functions can be written as a function of $n - 1$ allocations, leaving a single allocation in the two-country case. This is not pursued here, but could potentially be quite interesting as well as realistic.

where β_{ij} is country i's output coefficient to produce good j, w_{ij} is water allocated to the production of good j in country i, $i \in \{1, 2\}$ and $j \in \{1, 2\}$. Without loss of generality, we assume that

$$\frac{\beta_{12}}{\beta_{11}} < \frac{\beta_{22}}{\beta_{21}} \tag{3}$$

implying that country 1 has a comparative advantage in good 1 and country 2 has a comparative advantage in good 2. This comparative advantage assumption will prevail in the rest of the paper, even if one country has absolute advantage in both goods.

The resource constraint is

$$\sum_{j=1}^{2} w_{ij} \leq W_i \tag{4}$$

for each country. As both utility and production are increasing functions, this constraint will always be binding.

The two countries can choose to stay in autarky and produce both goods to meet the domestic demand, or they can specialize in the good that they have comparative advantage in and trade with each other in order to increase welfare. The question we want to answer is: if the gap between the two countries' productivities is substantially large, would the countries benefit by giving up water and enjoy low-cost goods imported from the other country? Hence, the following sections will derive the welfare functions for each country under both autarky and free trade as a function of the water allocation parameter. Welfare in this context is measured by consumer utility in each country.

3 Autarky

We first consider autarky over the entire range of exogenous water allocations. The subsequent welfare functions will be used later to demonstrate that allowing for free trade can substantially change the nature of individual countries valuation of water allocations. Welfare functions under autarky will also be necessary for the later political equilibrium analysis.

Under autarky, each country maximizes utility subject to the technology and resource constraints with consumption just equal to production $c_{ij} = y_{ij}$. The optimization problem is then

$$\max \ U_i = c_{i1}^{\alpha} c_{i2}^{1-\alpha} \tag{5}$$
$$\text{s.t. } \ c_{ij} = y_{ij} = \beta_{ij} w_{ij} \quad j \in \{1, 2\}$$
$$w_{i1} + w_{i2} = \theta_i W$$

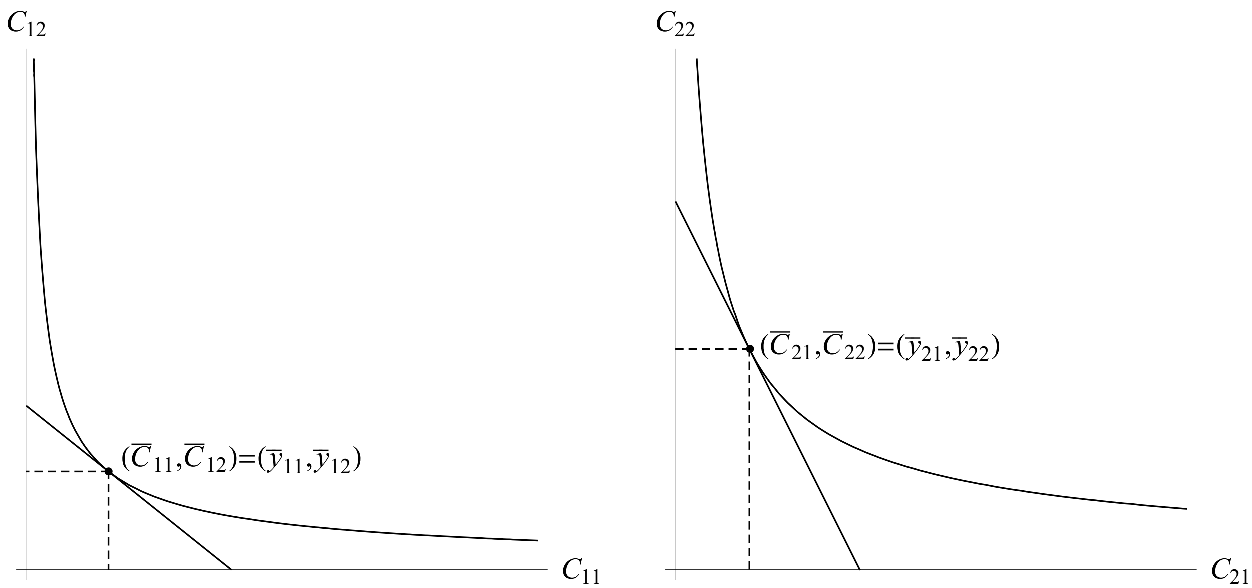
for country $i \in \{1, 2\}$ and given the allocation parameter θ_i.

The utility maximization problem is illustrated in Figure 1. Solving this problem gives consumptions and outputs:

$$\bar{c}_{i1} = \bar{y}_{i1} = \alpha \beta_{i1} \theta_i W \tag{6}$$

$$\bar{c}_{i2} = \bar{y}_{i2} = (1 - \alpha) \beta_{i2} \theta_i W \tag{7}$$

Figure 1: Utility Maximization Under Autarky



(a) Country 1 **(b)** Country 2

Figures generated with parameter values $\alpha = 0.4$, $\beta_{11} = 5$,$\beta_{12} = 4$,$\beta_{21} = 3$,$\beta_{22} = 6$.

for $i \in \{1, 2\}$. Substituting the optimal consumption levels into the utility function gives the maximized utility for country i under autarky.

$$U_i^A = (\alpha\beta_{i1})^\alpha((1-\alpha)\beta_{i2})^{1-\alpha}\theta_i W \tag{8}$$

Autarky prices ratio is just the slope of the production possibility frontier in Figure 1. Hence, autarky relative prices are

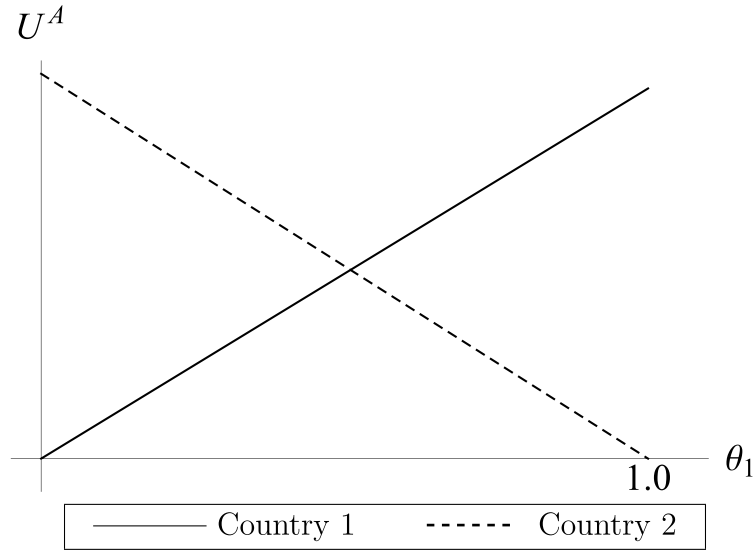
$$\bar{p}_{i1}/\bar{p}_{i2} = \beta_{i2}/\beta_{i1} \tag{9}$$

Furthermore, as illustrated in Figure 2, autarky implies that both countries' welfare functions are linear and monotonically increasing in the water allocation parameter, θ_i . Both countries would be better off as they get more water to produce more goods that are only consumed domestically. Neither country would voluntarily concede to less water without any other conditions, hence, conflict arises.

4 Free Trade

Now suppose the two countries engage in free trade. We want to see if free trade will give countries some leverage in negotiating the water allocation. Would the gains from free trade let the countries give up some water out of its self-interest? First, we derive the free trade welfare as a function of θ_1. The free trade equilibrium has three cases (Feenstra, 2004). The most general case is that the two countries each specializes in the good that they have comparative advantage in. The other two cases arise when one country is relatively large

Figure 2: Welfare Functions Under Autarky



compared to the other. In those cases, if the two countries still specialize in one good, then production in the small country would not be able to meet the demand of both countries. The large country has to produce both goods while the small country still specializes in the good that it has comparative advantage in. Hence the world relative price would be the autarky relative price in the large country.

In general, the free trade utility maximization problem for country i is

$$\max \ U_i = c_{i1}^{\alpha} c_{i2}^{1-\alpha} \tag{10}$$

$$\text{s.t. } \tilde{p}_1 c_{i1} + \tilde{p}_2 c_{i2} = \tilde{p}_1 y_{i1} + \tilde{p}_2 y_{i2}$$
$$y_{ij} = \beta_{ij} w_{ij}$$
$$w_{i1} + w_{i2} = \theta_i W$$

where $\tilde{p}_j$ is the free trade equilibrium world price for commodity j, which clears the world market for good j: $y_{1j} + y_{2j} = c_{1j} + c_{2j}$.

4.1 Intermediate water allocation

Here we consider an intermediate water allocation such that the world equilibrium price ratio $\tilde{p}_1/\tilde{p}_2$ falls between autarky prices

$$\beta_{12}/\beta_{11} = \bar{p}_{11}/\bar{p}_{12} < \tilde{p}_1/\tilde{p}_2 < \bar{p}_{21}/\bar{p}_{22} = \beta_{22}/\beta_{21} \tag{11}$$

with the parametric condition for this to occur to be derived later. Country 1 then specializes in good 1

$$y_{11}^* = \beta_{11}\theta_1 W, \quad y_{12}^* = 0 \tag{12}$$

while Country 2 specializes in good 2

$$y_{21}^* = 0, \quad y_{22}^* = \beta_{22}(1-\theta_1)W \tag{13}$$

implying that each country uses all the water assigned to it to produce the good in which it has a comparative advantage.

Each country solves the consumer optimization problem (10), resulting in the optimal consumption levels

$$c_{11}^* = \alpha\beta_{11}\theta_1 W, \quad c_{12}^* = \frac{\tilde{p}_1}{\tilde{p}_2}\beta_{11}(1-\alpha)\theta_1 W \tag{14}$$

$$c_{21}^* = \frac{\tilde{p}_2}{\tilde{p}_1}\beta_{22}\alpha(1-\theta_1)W, \quad c_{22}^* = (1-\alpha)\beta_{22}(1-\theta_1)W \tag{15}$$

Market clearing for the first good is

$$y_{11}^* = c_{11}^* + c_{21}^* \tag{16}$$

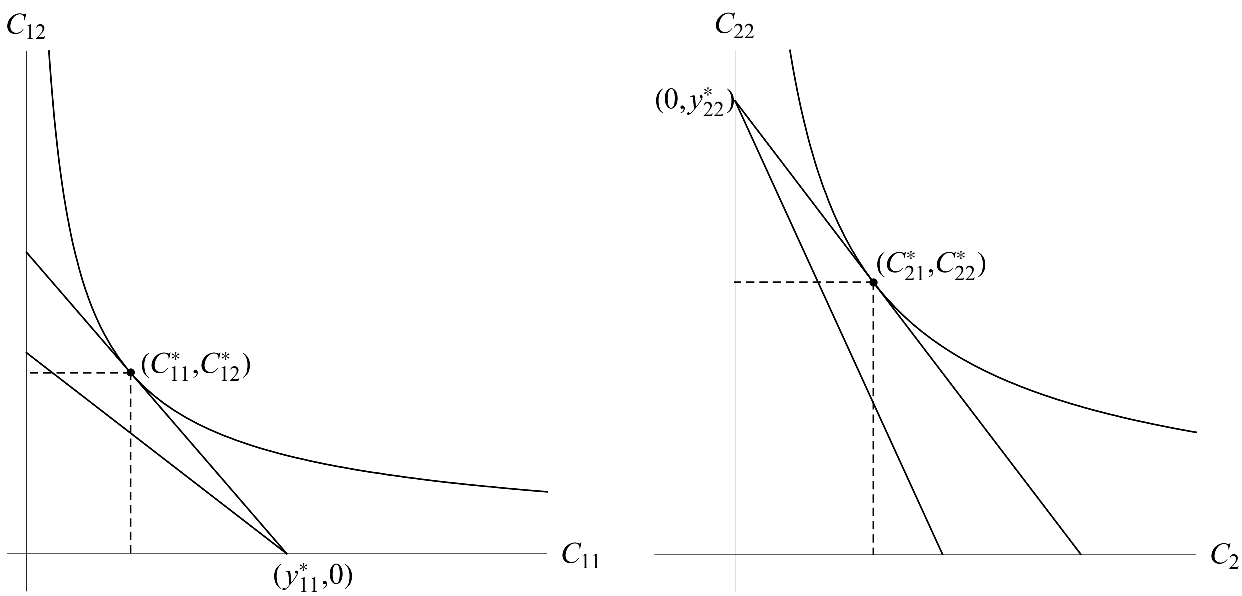
with market clearing for good 2 implied by Walras Law. This yields

$$\frac{\tilde{p}_1}{\tilde{p}_2} = \frac{\beta_{22}\alpha(1-\theta_1)}{\beta_{11}(1-\alpha)\theta_1} \tag{17}$$

as the world equilibrium price ratio in this particular case.

Figure 3 illustrates the free trade equilibrium for the two countries. Country 1 specializes in good 1, exports $(y_{11}^* - c_{11}^*)$ of good 1 to country 2 and imports (c_{12}^*) of good 2 from country 2. Country 2 specializes in good 2, exports $(y_{22}^* - c_{22}^*)$ of good 2 and imports (c_{21}^*) of good 1. This is the standard free trade case.

Figure 3: Utility Maximization Under Free Trade: Case 1



(a) Country 1 **(b)** Country 2

Case 1: Intermediate water allocation between two countries($\theta_1 = 0.4$). Figures generated with parameter values $\alpha = 0.4$, $\beta_{11} = 5$, $\beta_{12} = 4$, $\beta_{21} = 3$, $\beta_{22} = 6$.

As previously noted, for this case to occur the world equilibrium price must be bounded by the autarky prices. Substituting (17) into (11) yields

$$\frac{\beta_{12}}{\beta_{11}} < \frac{\beta_{22}\alpha(1-\theta_1)}{\beta_{11}(1-\alpha)\theta_1} < \frac{\beta_{22}}{\beta_{21}} \tag{18}$$

and solving for θ_1 gives

$$\frac{\alpha\beta_{21}}{\alpha\beta_{21}+(1-\alpha)\beta_{11}} < \theta_1 < \frac{\alpha\beta_{22}}{\alpha\beta_{22}+(1-\alpha)\beta_{12}} \tag{19}$$

as the parametric condition for this free trade pattern. This requires that the water allocation θ_1 must not be too large, in which instance production of country 2 could not meet the world demand, nor can it be too small, implying that production of country 1 would be insufficient to meet world demand for good 1.

Under these conditions, we can substitute the world equilibrium price ratio (17) into the optimal consumption equations (14-15), and then optimal consumption into the utility functions (1) to find the country welfare functions. This yields

$$(U_1^{FT})_1 = (\beta_{11}\theta_1)^{\alpha}(\beta_{22}(1-\theta_1))^{1-\alpha}\alpha W \tag{20}$$

and

$$(U_2^{FT})_1 = (\beta_{11}\theta_1)^{\alpha}(\beta_{22}(1-\theta_1))^{1-\alpha}(1-\alpha) W \tag{21}$$

as utilities for the respective countries in free trade, case 1.

4.2 Large country 1 water allocation

If θ_1 violates condition (19), then the world equilibrium price won't fall between the two autarky prices, and full specialization will not occur. Consider first a large θ_1

$$\theta_1 \geq \frac{\alpha\beta_{22}}{\alpha\beta_{22}+(1-\alpha)\beta_{12}} \tag{22}$$

implying that Country 1 gets a relatively large share of the water resource. Full specialization as in Case 1 won't occur for two reasons. First, the production of good 2 in country 2 would not meet the total demand in both countries. Second, if free trade pattern was similar to case 1, then free trade utility for country 1 would be lower than its autarky utility, $(U_1^{FT})_1 \leq U_1^A$ as implied by condition (22). Hence, Country 1 would not have an incentive to participate in such trade activity.

In this case, the world equilibrium price will be determined by the autarky price in country 1, since the small country 2 is not influential in world prices. Hence

$$\frac{\tilde{p}_1}{\tilde{p}_2} = \frac{\beta_{12}}{\beta_{11}} \tag{23}$$

defines the relative world equilibrium price. Country 2 still has a comparative advantage in good 2 in the sense that the relative price for good 2 is lower than the world price (price in country 1), so it still specializes in good 2 with production $y_{22}^* = \beta_{22}(1-\theta_1)W$.

As country 2 is small, it's production cannot meet total demand, hence country 1 will produce both goods. Its consumption is equal to the autarky consumption (bundle A in Figure 4a), while optimal consumption levels for country 2 are

$$c_{21}^* = \frac{\tilde{p}_2}{\tilde{p}_1}\beta_{22}\alpha(1-\theta_1)W, \quad c_{22}^* = (1-\alpha)\beta_{22}(1-\theta_1)W \tag{24}$$

which follows from (10) after substituting the world price (23). This is illustrated as bundle C in Figure 4b.

Optimal outputs of country 1 (bundle B in Figure 4a)

$$y_{11}^* = \beta_{11}\left(\alpha\theta_1 W + \frac{\beta_{22}}{\beta_{12}}\alpha(1-\theta_1)W\right) \tag{25}$$

$$y_{12}^* = \beta_{12}\left((1-\alpha)\theta_1 W - \alpha\frac{\beta_{22}}{\beta_{12}}(1-\theta_1)W\right) \tag{26}$$

follow from the market clearing conditions. Furthermore, these also imply that

$$w_{11}^* = \alpha\theta_1 W + \frac{\beta_{22}}{\beta_{12}}\alpha(1-\theta_1)W \tag{27}$$

$$w_{12}^* = (1-\alpha)\theta_1 W - \alpha\frac{\beta_{22}}{\beta_{12}}(1-\theta_1)W \tag{28}$$

which define water allocation within sectors in country 1. It can be verified that the total amount of water used by the two sectors equals the total amount allocated to country 1, i.e. $w_{11}^* + w_{12}^* = \theta_1 W$.

Utility of country 1 in this case equals the autarky level U_1^A. Given that the world price is β_{12}/β_{11}, we can find utility of country 2 by substituting the world price into the optimal consumption levels (24). Thus

$$(U_2^{FT})_2 = \left(\frac{\beta_{11}}{\beta_{12}}\alpha\right)^{\alpha}(1-\alpha)^{1-\alpha}\beta_{22}(1-\theta_1)W \tag{29}$$

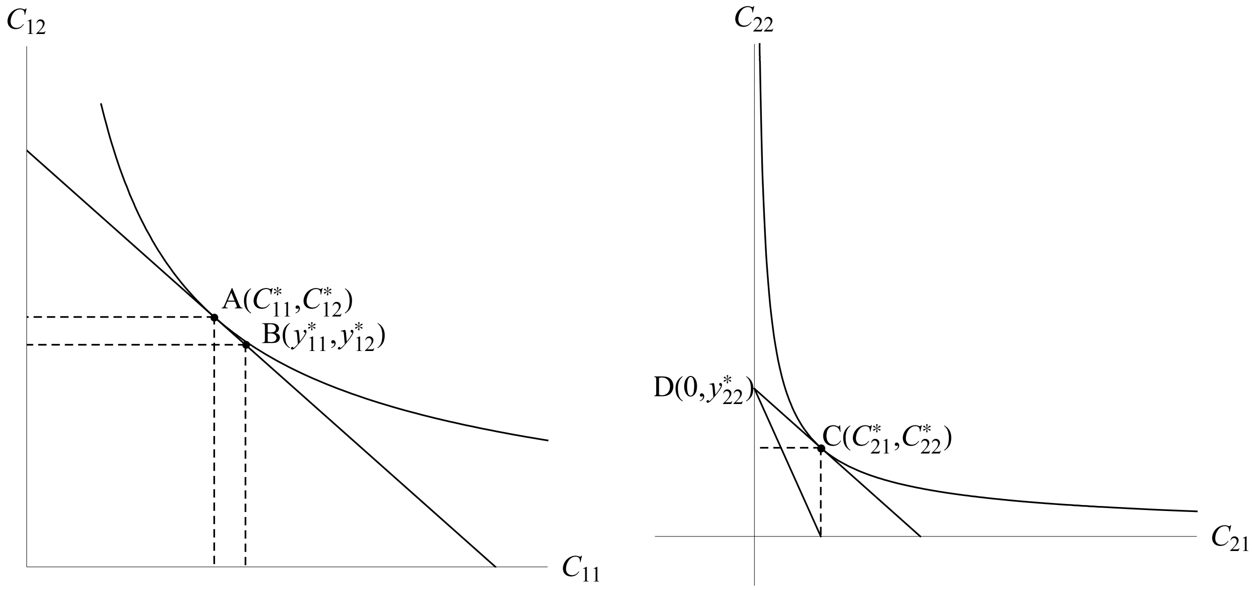
gives free trade utility for country 2 under case 2. We can verify that $(U_2^{FT})_2 > U_2^A$ based on the comparative advantage assumption $\beta_{12}/\beta_{11} < \beta_{22}/\beta_{21}$. Therefore, when two countries with large enough disparities in size (in terms of water allocation) are involved in free trade, the small country (country 2 in this case) gains from free trade while the large country still gets its autarky utility.

4.3 Small country 1 water allocation

The case of a relatively small θ_1

$$\theta_1 \leq \frac{\alpha\beta_{21}}{\alpha\beta_{21} + (1-\alpha)\beta_{11}} \tag{30}$$

Figure 4: Utility Maximization Under Free Trade: Case 2



(a) Country 1 **(b)** Country 2

Case 2: Large country 1 water allocation($\theta_1 = 0.9$). Figures generated with parameter values $\alpha = 0.4$, $\beta_{11} = 5$, $\beta_{12} = 4$, $\beta_{21} = 3$, $\beta_{22} = 6$.

is symmetric to case 2. Country 2 now becomes the large country, produces both goods and its consumption levels and utility are equal to the autarky levels. The world equilibrium price ratio

$$\tilde{p}_1/\tilde{p}_2 = \beta_{22}/\beta_{21} \tag{31}$$

equals country 2's autarky price ratio.

Figure 5 illustrates the equilibrium in this case. Country 1 specializes in producing good 1, $y^*_{11} = \beta_{11}\theta_1 W$, and its consumption levels are

$$c^*_{11} = \alpha\beta_{11}\theta_1 W \qquad c^*_{12} = \frac{p_1}{p_2}\beta_{11}(1-\alpha)\theta_1 W \tag{32}$$

from the utility maximization problem (10) with the world price ratio equal to β_{22}/β_{21}. The expression

$$(U_1^{FT})_3 = \alpha^\alpha \left(\frac{\beta_{22}}{\beta_{21}}(1-\alpha)\right)^{1-\alpha} \beta_{11}\theta_1 W \tag{33}$$

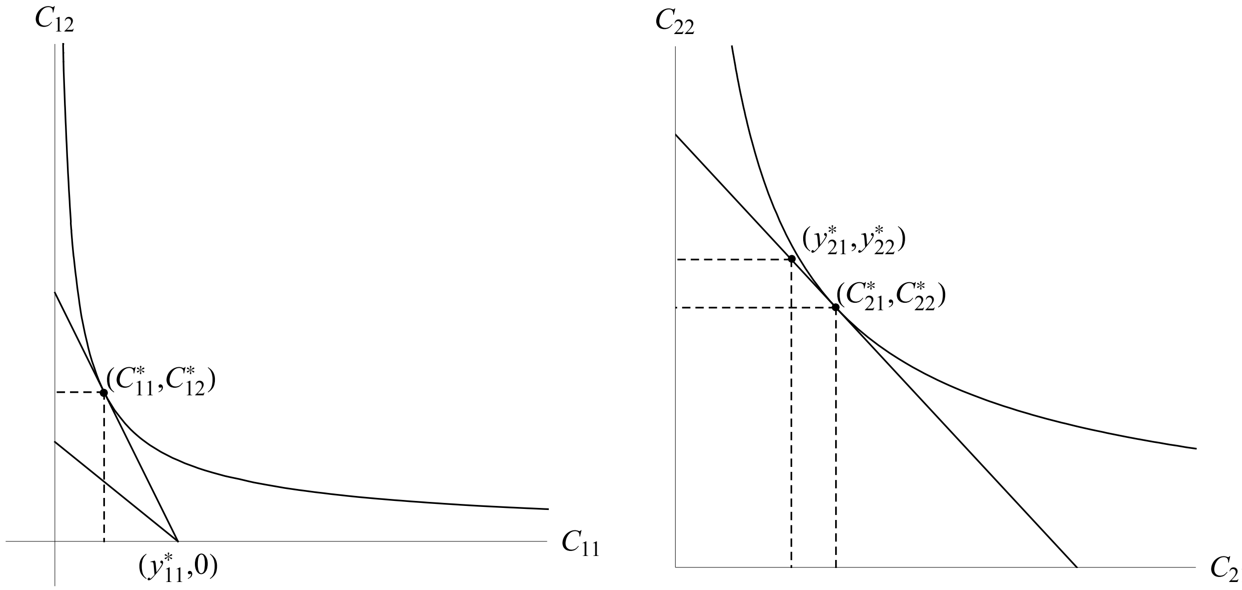
gives free trade utility for country 1 in case 3.

Country 2's consumptions equal autarky consumptions and its outputs are

$$y^*_{21} = \beta_{21}\left(\alpha(1-\theta_1)W - \frac{\beta_{11}}{\beta_{21}}(1-\alpha)\theta_1 W\right) \tag{34}$$

$$y^*_{22} = \beta_{22}\left((1-\alpha)(1-\theta_1)W + \frac{\beta_{11}}{\beta_{21}}(1-\alpha)\theta_1 W\right) \tag{35}$$

Figure 5: Utility Maximization Under Free Trade: Case 3



(a) Country 1 **(b)** Country 2

Case 3: Small country 1 water allocation($\theta_1 = 0.1$). Figures generated with parameter values $\alpha = 0.4$, $\beta_{11} = 5$, $\beta_{12} = 4$, $\beta_{21} = 3$, $\beta_{22} = 6$.

from market clearing and the production and consumption levels of country 1. As before, a consistency check indicates that country 2's water resource constraint is satisfied by these relations.

5 Welfare Analysis

This section synthesizes the above three cases which are conditional on the water allocation parameter θ_1 to analyze the qualitative properties of the welfare functions. As noted above, these welfare functions give country utilities as functions of the water allocation parameter θ_1. The specific questions of interest include monotonicity of the welfare functions in water allocation, a comparison of the welfare gains from additional water allocated to a given country under autarky and free trade, and conditions under which it might be in the self-interest of countries to share water.

5.1 Welfare functions

We define the bounds as

$$m_1 = \frac{\alpha\beta_{21}}{\alpha\beta_{21} + (1-\alpha)\beta_{11}} \qquad m_2 = \frac{\alpha\beta_{22}}{\alpha\beta_{22} + (1-\alpha)\beta_{12}}. \tag{36}$$

for convenience in partitioning the water allocation space.

Country 1's welfare is

$$U_1^A = (\alpha\beta_{11})^\alpha((1-\alpha)\beta_{12})^{1-\alpha}\theta_1 W \tag{37}$$

under autarky, and

$$U_1^{FT} = \begin{cases} (U_1^{FT})_3 = \alpha^\alpha \left(\frac{\beta_{22}}{\beta_{21}}(1-\alpha)\right)^{1-\alpha}\beta_{11}\theta_1 W & \text{if} \quad 0 \le \theta_1 \le m_1 \\ (U_1^{FT})_1 = (\beta_{11}\theta_1)^\alpha(\beta_{22}(1-\theta_1))^{1-\alpha}\alpha W & \text{if} \quad m_1 < \theta_1 < m_2 \\ (U_1^{FT})_2 = (\alpha\beta_{11})^\alpha((1-\alpha)\beta_{12})^{1-\alpha}\theta_1 W & \text{if} \quad m_2 \le \theta_1 \le 1 \end{cases} \tag{38}$$

in free trade equilibrium. Likewise, country 2's welfare is

$$U_2^A = (\alpha\beta_{21})^\alpha((1-\alpha)\beta_{22})^{1-\alpha}(1-\theta_1)W \tag{39}$$

under autarky, and

$$U_2^{FT} = \begin{cases} (U_2^{FT})_3 = (\alpha\beta_{21})^\alpha((1-\alpha)\beta_{22})^{1-\alpha}(1-\theta_1)W & \text{if} \quad 0 \le \theta_1 \le m_1 \\ (U_2^{FT})_1 = (\beta_{11}\theta_1)^\alpha(\beta_{22}(1-\theta_1))^{1-\alpha}(1-\alpha)W & \text{if} \quad m_1 < \theta_1 < m_2 \\ (U_2^{FT})_2 = \left(\frac{\beta_{11}}{\beta_{12}}\alpha\right)^\alpha(1-\alpha)^{1-\alpha}\beta_{22}(1-\theta_1)W & \text{if} \quad m_2 \le \theta_1 \le 1 \end{cases} \tag{40}$$

in free trade.

5.2 Qualitative properties

We now analyze the qualitative properties of the welfare functions, in particular monotonicity. As delineated below, there are three cases to consider depending on the production parameters. Note that in all these cases, country 1 is assumed to have a comparative advantage in good 1 (Eq. 3), which implies that $m_1 < m_2$.

Case P1. $\beta_{11} > \beta_{21}$ and $\beta_{12} > \beta_{22}$.

In this case, country 1 not only has a comparative advantage in good 1, but also absolute advantages in both goods. It can be shown that when $\beta_{11} > \beta_{21}$, $m_1 < \alpha$, and when $\beta_{12} > \beta_{22}$, $m_2 < \alpha$. Hence, $m_1 < m_2 < \alpha$.

The welfare functions in this case are shown in Figure 6a. The welfare function for country 1 is monotonically increasing as the water allocated to it increases. As country 2 gets increased water allocation, welfare first increases, then decreases for $\theta_1 \in (m_1, m_2)$, and then increases again.

Intuitively, since country 1 has absolute advantages in both goods, it does not have incentives to share water with the other country. The loss from sharing water cannot be offset by the gains from trade, hence the more water the better. However, for country 2, when its water allocations reaches the level of $(1 - m_2)$, it would be worse off by getting additional water. If initially, $\theta_1 \in (m_1, m_2)$, country 2 would even be better off by giving up some water. This can happen because the more water country 2 gets, the more goods it has to produce by itself. But country 2 has lower productivity coefficients, thus it could give up water to country 1 to produce at lower costs, and then gain via trade.

Case P2. $\beta_{11} < \beta_{21}$ and $\beta_{12} < \beta_{22}$.

In this case, country 2 has absolute advantages in both goods. Given that $\beta_{11} < \beta_{21}$ and $\beta_{12} < \beta_{22}$, $\alpha < m_1 < m_2$. This case is symmetric to Case P1.

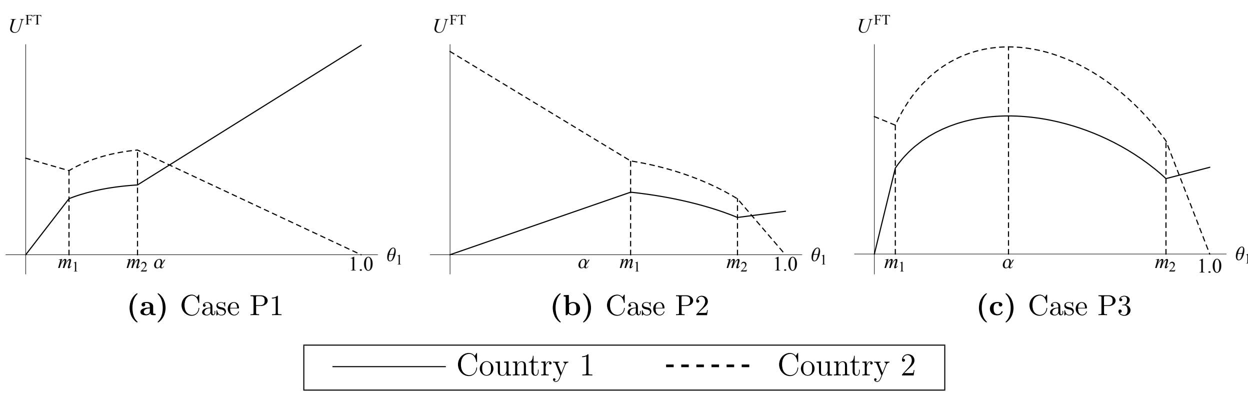
Figure 6b shows that country 2's welfare function will be monotonically increasing with water allocated to it, θ_2, while for country 1, welfare starts to decrease when $\theta_1 > m_1$, and increases again when θ_1 exceeds m_2. There is a region where its welfare will be decreasing with the water allocation parameter θ_1. This result once again demonstrates that increased water allocations may not be welfare-enhancing in the presence of productivity differences. This occurs because the gain from more water cannot offset the loss in trade.

Case P3. $\beta_{11} > \beta_{21}$ and $\beta_{12} < \beta_{22}$.

In this case, neither country has absolute advantages in both goods. Country 1 has a comparative advantage in good 1 and country 2 has a comparative advantage in good 2. As a result, $m_1 < \alpha < m_2$.

In Figure 6c, when $\theta_1 \in (m_1, m_2)$, both countries' welfare functions are concave with a local maximum at $\theta_1 = \alpha$. It would be in both countries' mutual interest to set the water allocation parameter θ_1 equal to α if the welfare at the two boundary points ($\theta_1 = 0$ or $\theta_1 = 1$) does not exceed the welfare at $\theta_1 = \alpha$ (which is possible with some parameter specification). Even if the extreme welfare levels are higher, they are not necessarily attainable in reality.

Figure 6: Welfare functions Under Free Trade



(a) Case P1 **(b)** Case P2 **(c)** Case P3

Case P1: Country 1 has absolute advantage in both goods, with $\alpha = 0.4, \beta_{11} = 9, \beta_{12} = 8, \beta_{21} = 2, \beta_{22} = 6$.
Case P2: Country 2 has absolute advantage in both goods, with $\alpha = 0.4, \beta_{11} = 4, \beta_{12} = 1, \beta_{21} = 7, \beta_{22} = 9$.
Case P3: Each country only has comparative advantage in one good, with $\alpha = 0.4, \beta_{11} = 10, \beta_{12} = 1, \beta_{21} = 1, \beta_{22} = 10$.

5.3 Water valuation under autarky and free trade

With intermediate water allocation, even if a country's welfare function under free trade is not declining, it is less steeply sloped under free trade than autarky, as illustrated by Figures 6, $\partial U_1^{FT}/\partial\theta_1$ is smaller than $\partial U_1^{A}/\partial\theta_1$ when $\theta_1 \in (m_1, m_2)$. This means that in the presence of trade, the marginal valuation of water can be lower with trade than without. This has two implications. First, even if it is in the country's self-interest to obtain more water, the gains are less than they would otherwise be. Thus, even if trade does not completely eliminate conflict over water, it can serve to reduce the level of conflict. Second, these results show that partial equilibrium studies could mis-estimate welfare gains if there are strong general equilibrium effects such as trade impacts.

5.4 Conflict and cooperation

To summarize, when one of the countries has absolute disadvantages in both goods, its welfare function will start to turn down after it gets a substantial amount of water. Because when the other country only gets a small portion of water, it won't be able to meet the demand of the large country (in terms of water) in trade. This can be seen from Case P1 and Case P2, where country 2's welfare function turns down when it has absolute disadvantages and country 1's welfare function turns down when it has absolute disadvantages.

The other country which has absolute advantages has monotonically increasing welfare function. However, the middle part of the graph has flatter slope than the other two parts, illustrating that the gains from more water is somewhat, though not completely offset by the losses from trade when water allocation facilitates full specialization.

In the last case, when each country only has a comparative advantage in one good, the gains from trade are more obvious. Both countries' welfare functions will turn down as they get substantial amount of water. Hence, countries would agree to share the water at $\theta_1 = \alpha$. Both countries' welfare functions will reach a local maximum. Also, notice that the welfare when one country gets all the water may be greater than the sharing strategy. However, for one country to block the other country's access to the river water is not quite realistic.

6 The Water and Trade Game with Discrete Strategies

The welfare functions derived the from the previous trade model are now used in this and the subsequent section to analyze political strategies and equilibrium. We consider a non-cooperative approach in this section and a cooperative approach in the next section to improve upon the non-cooperative outcome.

The international cooperation literature notes the possibility of issue linkage with trade as a prominent example. For example, Kolstad (2010) discusses various forms of issue linkage with respect to transboundary pollution, while Bennett et al. (1998) and Pham-Do et al. (2011) consider issue linkage in the context of international river basins. Accordingly, we now consider political equilibrium formulated as a water and trade interconnected game. Suppose country 1 is the upstream country and country 2 is a downstream country. Country 1 has the priority to choose the water allocation by deciding how much to allocate to itself and leaves the rest to the other country, and also chooses to trade with other country or not. That is to say, country 1's strategy profile has two elements, a water allocation parameter and a trade policy. At the same time, country 2 only decides on whether to open to trade or not.

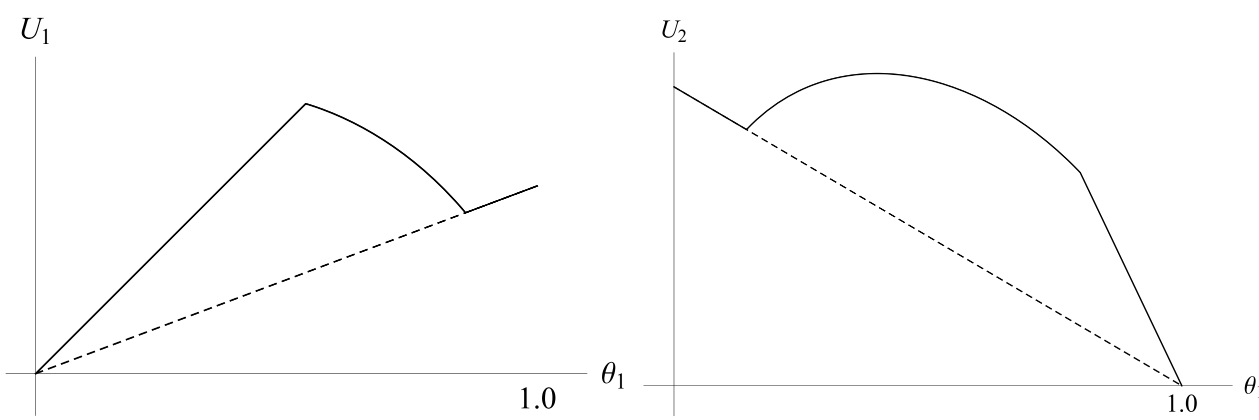
Following the literature, we formulate this as a two-player water-trade interconnected discrete game (Bennett et al., 1998). Table 1 shows the construction of a general payoff matrix. As illustrated in the table, country 1 can choose between two levels of water $\theta_1 = \theta_{high}$ and $\theta_1 = \theta_{low}$. The low *theta* value might be determined by rainfall and runoff occurring in each country, or it might be based on historical usage. The precise circumstances leading to this initial distribution aren't relevant here, we simply take this distribution as given. The high value strategy can be conceptualized as a water diverting program. If the program is launched, then the water diverted by country 1 increases from θ_{low} to θ_{high}. Both countries choose a trade policy between free trade and autarky. Trade relations will be established only when both countries choose to trade.

Table 1: General Payoff Matrix

			Country 2	
			Autarky	Trade
Country 1	θ_{low},	Autarky	$(U_1^A(\theta_{low}), U_2^A(\theta_{low}))$	$(U_1^A(\theta_{low}), U_2^A(\theta_{low}))$
	θ_{low},	Trade	$(U_1^A(\theta_{low}), U_2^A(\theta_{low}))$	$(U_1^{FT}(\theta_{low}), U_2^{FT}(\theta_{low}))$
	θ_{high},	Autarky	$(U_1^A(\theta_{high}), U_2^A(\theta_{high}))$	$(U_1^A(\theta_{high}), U_2^A(\theta_{high}))$
	θ_{high},	Trade	$(U_1^A(\theta_{high}), U_2^A(\theta_{high}))$	$(U_1^{FT}(\theta_{high}), U_2^{FT}(\theta_{high}))$

In order to figure out the Nash equilibrium to this normal game, we need to analyze the welfare functions for both countries under the two scenarios of trade relations. From Figure 7 that compares the welfare functions under free trade and autarky, we can see either country's free trade utility is always greater than or equal to autarky utility, hence both countries are more prone to choose a "trade" strategy to an "autarky" one when the parameters dictate that. However that does not excludes the "autarky" strategy from being chosen when the two scenarios give same welfare or when the other country already chooses autarky.

Figure 7: Welfare Functions Under Autarky and Free Trade



(a) Country 1 **(b)** Country 2

Free Trade - - - - - - Autarky

For country 1, it also needs to compare its free trade welfare for different values of water allocation parameter θ_1. Hence Figure 8 plots out all possible shapes of country 1's welfare functions under various parameter specifications. The free trade welfare functions for country 1 can be either increasing or decreasing, hence it is possible for country 1 to choose either the low or high value of water allocation.

From these two perspectives, the resulting equilibrium to the game will not be unique and highly depends on the parameters. Therefore, we consider two numerical examples in the subsequent analysis to illustrate possible outcomes.

Table 2 is generated with production coefficients $\beta_{11} = 9, \beta_{12} = 8, \beta_{21} = 2, \beta_{22} = 6$, which is the case shown in Figure 8a and Country 1 has absolute advantage in both goods. The two discrete water allocation strategies are chosen such that in this range of parameter values, country 1's welfare increases with θ_1. In this instance, higher θ_1 value will grant country 1 higher welfare no matter under autarky or free trade, hence country 1 will always choose the large allocation, and there are two pure strategy Nash equilibria: $\{(\theta_{high} = 0.3, \text{Autarky}), \text{Autarky}\}$ and $\{(\theta_{high} = 0.3, \text{Trade}), \text{Trade}\}$. The solution shows that the water allocation is unambiguously $\theta_{high} = 0.3$, but the resulting trade situation will be ambiguous. The payoffs under the two equilibria are $(1.2835, 1.3808)$ and $(1.4079, 2.1118)$ respectively. Both countries can be better off under the trade equilibrium and this equilibrium can be sustained in a repeated play, however this is beyond the scope of this paper and will not be discussed here. This kind of outcome can be realized as long as Country 1's free trade welfare function increase with θ_1, as shown in Case P1 under all water allocation strategy space, Case P2 when $\theta_{low}, \theta_{high} \in (0, m_1) \cup (m_2, 1)$ and Case P3 when $\theta_{low}, \theta_{high} \in (0, \alpha) \cup (m_2, 1)$.

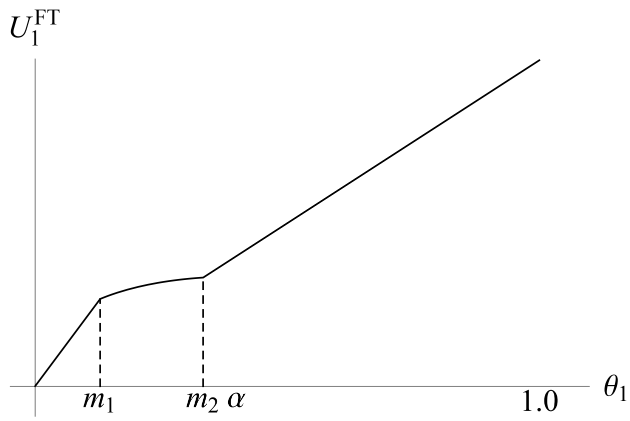
Table 2: Payoff Matrix: Case 1

			Country 2	
			Autarky	Trade
Country 1	$\theta_{low} = 0.2$,	Autarky	(0.8556, 1.5780)	(0.8556, 1.5780)
	$\theta_{low} = 0.2$,	Trade	(0.8556, 1.5780)	(1.2969, 1.9454)
	$\theta_{high} = 0.3$,	Autarky	(1.2835, 1.3808)	(1.2835, 1.3808)
	$\theta_{high} = 0.3$,	Trade	(1.2835, 1.3808)	(1.4079, 2.1118)

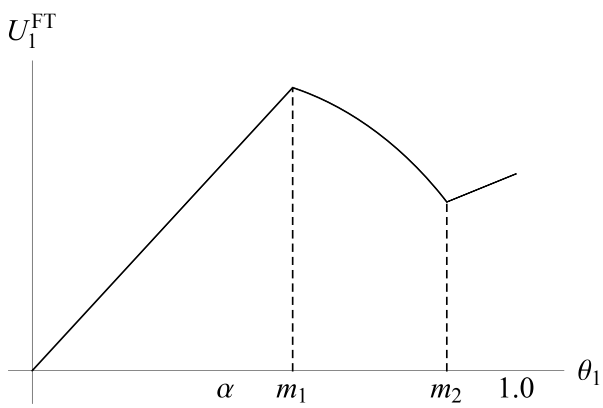
Note: Country 1's welfare increases with θ_1, with $\beta_{11} = 9, \beta_{12} = 8, \beta_{21} = 2, \beta_{22} = 6$.

Table 3 considers the case where country 1's welfare is decreasing as θ_1 increases. Production coefficients are $\beta_{11} = 4, \beta_{12} = 1, \beta_{21} = 7, \beta_{22} = 9$ such that country 2 has absolute advantage in both goods and this correspond to the case in Figure 8b. In this instance, higher θ_1 is better for country 1, however, it is still possible for country 1 to select the low water allocation, i.e. to voluntarily share water with the downstream country when both countries choose to trade. As a result, the two pure strategy Nash equilibria are $\{(\theta_{high} = 0.7, \text{Trade}), \text{Trade}\}$ and $\{(\theta_{low} = 0.6, \text{Trade}), \text{Trade}\}$. This outcome will be more complicated than the previous case as both the water allocation parameter and the trade situation will be uncertain. This can occur when country 2 has absolute advantages in

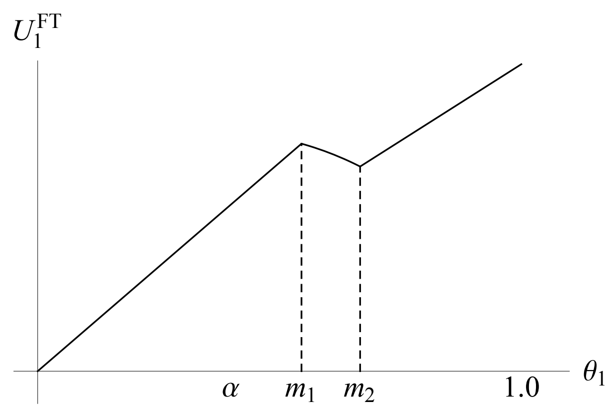
Figure 8: Country 1's Welfare Under Free Trade: All Cases



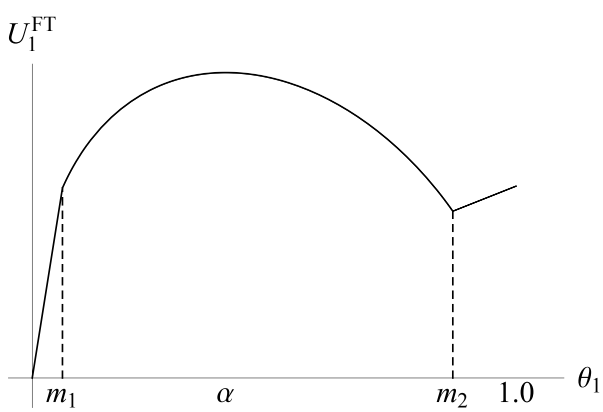
(a) Case P1: $\beta_{11} = 9, \beta_{12} = 8, \beta_{21} = 2, \beta_{22} = 6$



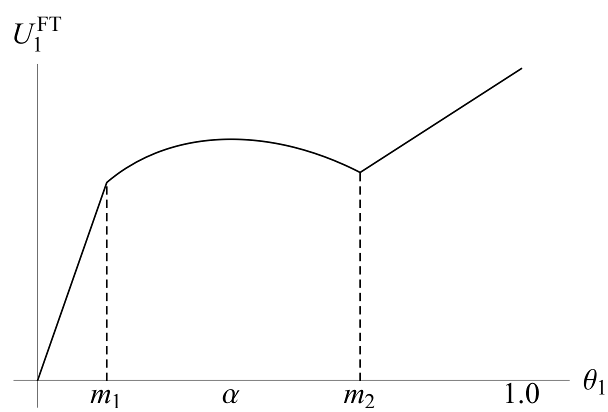
(b) Case P2: $\beta_{11} = 4, \beta_{12} = 1, \beta_{21} = 7, \beta_{22} = 9$



(c) Case P2: $\beta_{11} = 5, \beta_{12} = 3, \beta_{21} = 9, \beta_{22} = 9$



(d) Case P3: $\beta_{11} = 10, \beta_{12} = 1, \beta_{21} = 1, \beta_{22} = 10$



(e) Case P3: $\beta_{11} = 8, \beta_{12} = 3, \beta_{21} = 2, \beta_{22} = 9$

both goods (Case P2 when $\theta_{low}, \theta_{high} \in (m_1, m_2)$), or when country 1 only has comparative advantage in good 1 (Case P3 when $\theta_{low}, \theta_{high} \in (\alpha, m_2)$).

Table 3: Payoff Matrix: Case 2

			Country 2	
			Autarky	Trade
Country 1	$\theta_{low} = 0.6$,	Autarky	(0.5330, 1.6610)	(0.5330, 1.6610)
	$\theta_{low} = 0.6$,	Trade	(0.5330, 1.6610)	(1.2244, 1.8366)
	$\theta_{high} = 0.7$,	Autarky	(0.6218, 1.2457)	(0.6218, 1.2457)
	$\theta_{high} = 0.7$,	Trade	(0.6218, 1.2457)	(1.0958, 1.6437)

Note: Country 1's welfare decreases with θ_1, with $\beta_{11} = 4, \beta_{12} = 1, \beta_{21} = 7, \beta_{22} = 9$.

The equilibrium in Table 3 where countries share water and engage in free trade is facilitated by the fact that the upstream country 1 with water property rights is disadvantaged in production (either absolute disadvantage in both goods or comparative advantage in just one good). Clearly cooperation is easier to achieve when each country has leverage in some dimension.

The literature emphasizes issue linkage as a way to solve international cooperation problems (Bennett et al., 1998; Pham-Do et al., 2011), with trade policy as a specific example. The analysis in this section offers a somewhat different perspective, in that introducing trade does not give the second country any explicit leverage over the actions of the first country holding the water rights. Trade does influence the welfare function of the water-rights holding country, and in some circumstances it will be of self-interest for that country to jointly allocate water as noted previously. However, a threat by the second country to impose autarky is not credible since it is never better off doing this.

Thus, while trade can influence the political outcome, it is not necessarily through the channel of political bargaining power as in the issue linkage literature. Rather it may be through the evaluation process of individual country's welfare. The outcome is determined solely by the self-interest of the water-rights country, the other country does not have any credible bargaining power, at least within the context of the game-theoretic model here under standard rationality assumptions. Of course, richer game-theoretic models with asymmetric information or perhaps repeated play might yield a different outcome, and likewise for models with continuous, credible trade policies.

A methodological conclusion from these results is that the discrete strategy game is a limited analytical engine for this problem. The difficulty is that for a given trade model parameterization, the choice of discrete strategies is arbitrary but can influence the qualitative properties of the Nash equilibrium, i.e. whether or not joint water allocation is self-interest. Similar conclusions hold for trade policy as the game in this section only considers the extremes of autarky and free trade.

7 Nash Bargaining

The noncooperative approach gives uncertain outcomes. Both countries will be better off by choosing the trade equilibrium, but the autarky equilibrium is still possible to be realized. In this section, we consider the case when the autarky equilibrium is indeed realized and let this equilibrium be the initial conditions between the two countries in a cooperative Nash bargaining setting(John F. Nash, 1950). Both countries will be better off by yielding to a cooperative equilibrium. In this analysis, coercion is not possible; countries only agree to move from their initial distribution out of self-interest, that is individual rationality is satisfied. Another property that needs to be satisfied is group rationality, which means there is no other outcomes that will make both parties better off than the current equilibrium. Furthermore, we assume that the two countries have equal bargaining power.

In this bargaining problem, the two countries' preferences are given by their free trade welfare functions, as they will be cooperating with each other (trade in this case). The payoff vector $U = (U_1^{FT}, U_2^{FT}) \in P$, a two dimensional space. When the two countries fail to reach an agreement, there will be an disagreement (conflict) payoff vector, $t = (t_1, t_2)$, which is given by the initial conditions. The Nash solution to the bargaining problem $\bar{U} = (\bar{U}_1, \bar{U}_2)$, is given by maximizing the Nash product,

$$(\bar{U}_1 - t_1)(\bar{U}_2 - t_2) = \max_{U \in P}[(U_1 - t_1)(U_2 - t_2)] \tag{41}$$

In a situation where production coefficients are specified like $\beta_{11} = 9, \beta_{12} = 8, \beta_{21} = 2, \beta_{22} = 6$, as in Case P1, the autarky noncooperative equilibrium in Section 6 gives the two countries payoffs of $(U_1^A(0.3), U_2^A(0.3)) = (1.28, 1.38)$. This pair of payoffs will be regarded as an initial condition between the two countries as they start the bargaining. It plays a role of a threat payoff vector such that when disagreement arises and negotiation fails, the initial payoffs will be the resulting payoffs. The bargaining solution is illustrated in Figure 9. It gives rise to a water allocation of $\theta_1 = 0.435$, with payoff vector $(\bar{U}_1, \bar{U}_2) = (1.86, 1.81)$, both countries are better off compared to the initial $(1.28, 1.38)$. Both individual and group rationality are satisfied as both individuals are better off than initial conditions and no individual can be better off without sacrificing the other. Also note that the payoff vector space is not convex due to the fact that the welfare functions are not monotone.

Consider Case P2, when country 2 has absolute advantage and production coefficients are $\beta_{11} = 4, \beta_{12} = 1, \beta_{21} = 7, \beta_{22} = 9$. The noncooperative Nash equilibrium in Section 6 gives an autarky payoff of $(U_1^A(0.7), U_2^A(0.7)) = (0.62, 1.25)$, and we take this as the disagreement payoff vector. The Nash bargaining solution is illustrated in Figure 10, which gives $\theta_1 = 0.481$ and payoff vector $(\bar{U}_1, \bar{U}_2) = (1.14, 2.16)$.

A similar analysis can be conducted for Case P3 (Figure 6c). It is in both countries' consent to achieve an equilibrium allocation of $\theta_1^* = \alpha$ and $(\bar{U}_1, \bar{U}_2) = (2.04, 3.06)$(Figure 11).

There are several general conclusions from this analysis. First, there is no necessary unique bargaining solution for a given model parameterization. The self-interest outcome from bargaining can be dependent on the initial allocation and technical conditions. We showed some possible bargaining outcomes given certain initial allocations and production parameter specification. Second, bargaining can result in self-interested, mutually beneficial reallocation due to the presence of trade. While this can occur in each of the three Cases

Figure 9: Nash Bargaining Solution: Case P1

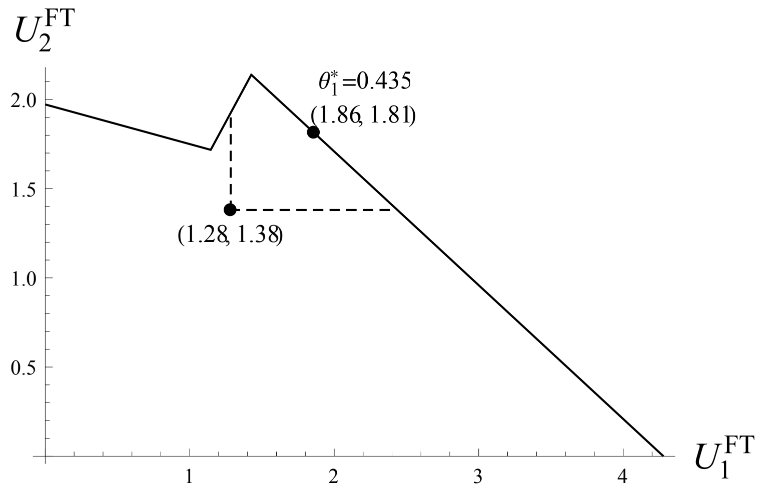


Figure 10: Nash Bargaining Solution: Case P2

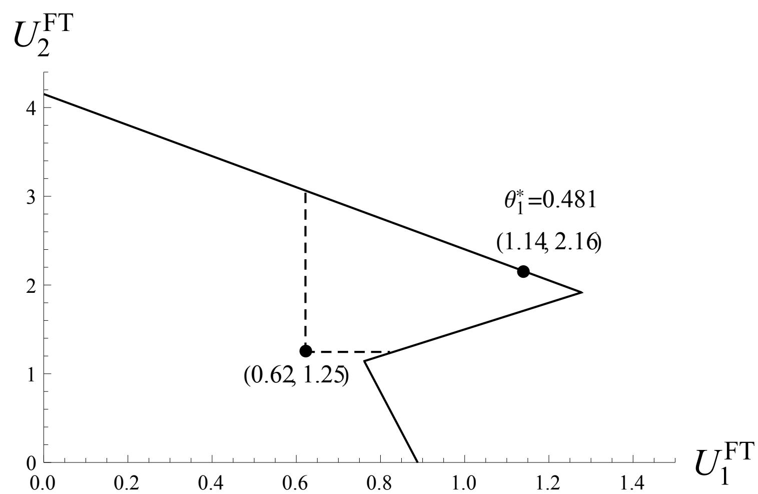
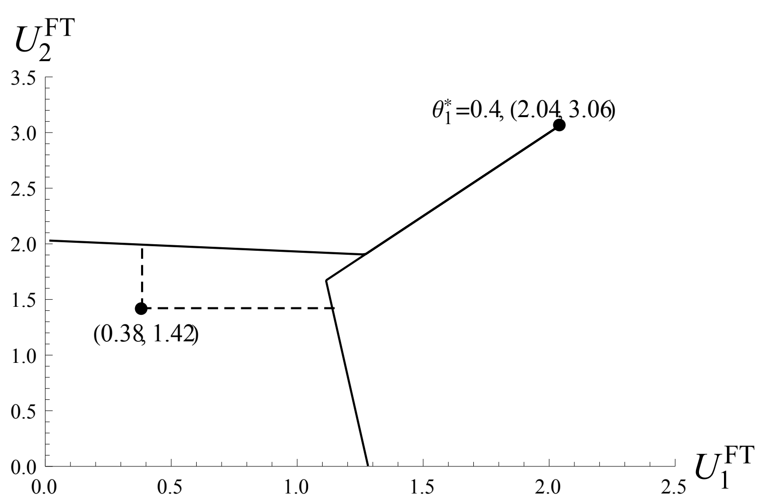


Figure 11: Nash Bargaining Solution: Case P3



P1-P3, it is most pronounced for the specific instance illustrated in Case P3 in which no country has absolute advantages in production. Third, a bargaining solution yields to an intermediate and equitable water allocation (θ_1 value around 0.4-0.5).

Finally, we note that some of the outcomes noted above may be specific to the particular parameterization used. While Figures 6a-6c accurately convey monotonicity properties of the welfare functions for the respective Cases P1-P3, they may not be completely general with respect to the height of the endpoints relative to interior points. This can potentially affect the equilibrium outcomes in some instances.

8 Conclusions

The paper models water allocation for two countries which share a river and also engage in trade. Trade is a two-country/two-good Ricardian model, with water as the only factor of production and country variation in productivity as the conceptual motivation for trade. The analysis considers behavioral regimes of autarky and free trade. In each instance, equilibrium consumptions and prices are derived for a given water allocation, and these in turn are used to derive country welfare as a function of water allocation. Game-theoretic models for political equilibrium are then formulated and analyzed utilizing the welfare functions from the economic model. Game-theoretic analysis of international water allocation has been studied in the previous literature. However, to our knowledge, the economic analysis of the welfare functions under trade and the subsequent game-theory models derived from those functions are novel.

Country welfare depends on the water allocation and the subsequent welfare functions exhibit some regularity. (1) First, consistent with standard trade theory, countries gain from free trade in the sense that the free trade welfare is larger or at least equal to autarky welfare. (2) As long as a country does not have absolute advantages in both goods, the benefit of getting more water will finally be offset by a trade loss as it gets more water, which is then reflected as a decrease in the welfare function. (3) Even if a country has absolute advantages in both goods, the benefit of getting more water will still be, though not completely, offset by the loss from trade, reflected by a flatter growth in the welfare function with intermediate water allocation.

Thus, when riparian countries are engaged in free trade, and for certain parameter specifications, there are circumstances in which country welfare can actually be decreasing in water allocation. Hence, it would be in the countries' self-interest to share water. Furthermore, even if the welfare function is increasing in water allocation, trade means that the gains from additional water can be smaller than that under autarky. This observation then serves to reduce conflict over the resource, although not necessarily eliminating it.

Political equilibrium is analyzed both as a noncooperative game and as a cooperative bargaining problem. First considered is a discrete strategy game with two water allocations for one country, and autarky/free trade options for both country. The primary conclusion here is that the trade policy of the second country may not be credible as a means of getting additional water since free trade is generally advantageous to that country over autarky. In this setting, then, the primary role of trade is not as a bargaining tool, but rather it affects country's evaluation of their welfare function and self-interest in water allocation. Under the bargaining problem, we treat the Nash equilibrium in the noncooperative game as an initial condition, and find that both countries could be better off by moving to a cooperative bargaining solution. However, the resulting equilibrium also depends on the initial conditions and parameter specifications.

In general, moving to a general equilibrium setting can potentially be conflict-reducing, although not necessarily conflict-eliminating. This is due to the fact that in general equilibrium, there can be additional channels through which water allocation affects an entity, and some of these may be adverse. This work also implies that—in contrast to much of the literature—in the presence of trade, country welfare is a function of not only its own water allocation, but also that of the other countries. In general, if there are n countries involved in trade and water is fully allocated, then country welfare will be a function of $n-1$ water allocations.

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