Dynamic management of water transfer between two interconnected river basins

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The context

- Two regions with interconnected river basins
- With water transfer that increases productivity in one region, but may cause environmental damage in the other one.
- Dynamic interaction between two regions

Inter-basin water transfers

Examples of inter-basin water transfer already in operation or in the planning stage can be found in the literature (see, for example, Bhaduri and Barbier (2008)).

Transfers can be set up within the same country (e.g. the Snowy River Scheme in Australia, the São Francisco Interlinking Project in Brazil, the Olmos Transfer Project in Peru, the South-North Water Transfer Project in China, or the Archeelos Diversion in Greece),

or between countries (e.g. from the Kosi in Nepal to the Ganges in India and Bangladesh, or the Lesotho Highlands Water Project between Lesotho and South Africa, to mention just a few).

Motivation of our model

The water transfer from the Tagus basin in the center of Spain to the Segura basin in south-eastern Spain is a good illustration of water transfer within the same country.
While the Segura basin is an arid area with low precipitation and high evapotranspiration, the Tagus basin is more humid.
The productivity of water also differs between the two regions.

The Spanish central government has built a 230 km network of canals, aqueducts and tunnels to transfer water from the Tagus to the Segura basin. As a result of the transfer, the water quality in the Tagus basin has deteriorated, leading the regional government in the Tagus basin to complain about the transfer, triggering a national political debate on alternatives like desalination plants.

The Tajo-Segura water transfer

Ballestero, E., 2004, Inter-Basin Water Transfer Agreements: A decision Approach to Quantity and Price, *Water Resources Management.*

- *The paper proposes a decision stochastic approach to determine quantity and price by simulating the recipient's demand curve and the donor's supply curve for transferable water.*
- *A case study on the Tajo-Segura aqueduct in Spain and the recipient area of Lorca is developed.*

Our problem

- Precipitations are higher in one river-basin (the donor), water productivity is higher in the other river-basin (the recipient).
- Existence of an aqueduct to conduct water from donor to recipient.
- Transfer of water causes environmental damages only in the donor's region.
- Alternative water supply for the recipient (investment in water-saving, water recycling or water production from desalination plants).

Dynamic dimension: intertemporal trade-off between current water transfer payments and investments to increase the capacity of usable water.

Our questions

- We want to know if transfer is profitable for both regions (compared with the case without transfer)

Water transfer from the donor to the recipient would help increase efficiency. From an economic point of view it can be regarded as a good decision (from a central government) or agreement (between the parts).

- We want to compare decentralized (perfect competition with different forms of market power) and centralized situation

The importance of the "dynamic description" of the problem.

- We want to compare with a kind of "static" situation of transfer.

The case study of Tagus-Segura transfer, we want to compare our results with those in Ballestero (2004).

Plan

1. The model: The donor and the recipient
2. The game: open loop and feedback equilibrium
3. The social optimum
4. Some comparisons between competitive equilibrium and cooperation.
5. The Stackelberg equilibria. More comparisons
6. The "corresponding" static game
7. The Tagus-Segura water transfer
8. Political recommendations
9. Extension: a constraint on the transfer

The Donor

- The river-basin in the donor region is characterized by relatively high precipitation rates and relatively low productive uses.
- The reduction in the water level (transfer $\tau(t)$) in the river causes a degradation of the quality of the water.
- The environmental amenities from the water level in the river is $E(\tau)$.
- The donor receives a monetary payment, $p(t)$, from the recipient for each unit of water transferred.

The instantaneous welfare function for the donor is

$$F^d(p(t), \tau(t)) = E(\tau(t)) + p(t)\tau(t).$$

The Recipient

Precipitations are low in the river-basin of the recipient region, but the productivity of water is high, then this region will be willing to pay for the water transferred from the donor.

The water used in the recipient region is diverse:

1. quantity transferred by the donor, $\tau(t)$.
2. an alternative source, to increase the available water volume $\Longrightarrow$ investment in equipment $s(t)$ and cost $C(s(t))$.
   $x(t)$, is the capacity to produce, recycle or save water with the current equipment

$$\dot{x}(t) = s(t) - \delta x(t), \qquad x(0) = x_0 \geq 0,$$

the welfare function of the recipient:

$$F^r(p(t), \tau(t), x(t), s(t)) = Q(\tau(t), x(t)) - p(t)\tau(t) - C(s(t)).$$

The Nash game

The donor determines the supply of water in order to maximize his discounted welfare:

$$\max_{\tau} \int_0^{\infty} [E(\tau(t)) + p(t)\tau(t)]\, e^{-\rho t} dt.$$

The recipient chooses the demand for water and the investment in capacity of usable water, to maximize discounted welfare:

$$\max_{\tau, s} \int_0^{\infty} [Q(\tau(t), x(t)) - p(t)\tau(t) - C(s(t))]\, e^{-\rho t} dt.$$

such that $\dot{x}(t) = s(t) - \delta x(t), \quad x(0) = x_0 \geq 0.$
Market condition: $\tau^D(p, x) = \tau^S(p)$.

The recipient is a farsighted player whose maximization problem is subject to the evolution of the capacity of usable water. The donor behaves as a static or myopic player.

The Nash game. First result

For any differential game between a static and a farsighted player described by:

$$\max_{\tau} \left[E(\tau) + p\tau \right], \quad \max_{\tau, s} \int_0^\infty \left[Q(\tau, x) - p\tau - C(s) \right] e^{-\rho t} dt,$$

$$\text{s.a.:} \quad \dot{x} = f(s, x), \quad \tau^D(p, x) = \tau^S(p).$$

The optimal price and quantity can be written as the same function of the state variable under the feedback or the open-loop Nash equilibria.

Centralised problem. Social optimum

We define the social optimum as the maximisation of the joint welfare of the two player

$$\max_{\tau,s} \int_0^\infty [E(\tau) + Q(\tau, x) - C(s)]\, e^{-\rho t} dt,$$

$$\text{s.a.:} \quad \dot{x} = f(s, x).$$

Social Optimum and Nash equilibrium: Second result

For any differential game between a static and a farsighted player as described before the non-cooperative open-loop equilibrium coincides with the social optimum.

There are two main characteristics of the game that lead to the equivalence between open-loop Nash and cooperation:

- The optimal decision on water transfer does not influence the dynamics of the state of the system.
- The stock or the investments in capacity of usable water do not directly affect the donor's welfare ($F^d(p, \tau)$ is independent of x and s).

The Nash game. Resolution

For the Donor, The environmental amenities are

$$E(\tau(t)) = c\left(R - \frac{1}{2}\frac{\tau(t)^2}{R}\right), \qquad R, c > 0.$$

R is the maximum possible water surplus in the river without risking the exhaustion of the reservoir.

- in the absence of water transfer, environmental amenities increase linearly with the water surplus in the river: cR.
- the marginal reduction in environmental amenities is inversely proportional to this surplus and proportional to the share of water transferred: $c\tau(t)/R$.

For the recipient:

- welfare comes from the amount of available water, $\tau(t) + x(t)$.
- welfare increases with the amount of available water at a decreasing rate.
- quadratic investments costs.

$$F^r(p(t), \tau(t), x(t), s(t)) = Q(\tau(t), x(t)) - p(t)\tau(t) - C(s(t)) =$$

$$= d\left(\tau(t) + x(t) - \alpha\frac{(\tau(t) + x(t))^2}{2}\right) - p(t)\tau(t) - \beta\frac{s(t)^2}{2}$$

The Nash game. Comparison Open loop - Feedback.

Comparison: Capacity of usable water, transfer and price.

- $x^{OL}(t) < x^{F}(t) \quad \forall t > 0$;
- $\tau^{OL}(t) > \tau^{F}(t)$, and $p^{OL}(t) > p^{F}(t) \quad \forall t > 0$.

In OL, the recipient invests less and accepts a higher water transfer at a higher price. In feedback, the recipient invests more and induces a lower transfer amount at a lower price.

What about welfare?

A problem with the game with commitment = centralised solution

- The donor's welfare is higher under open-loop than under feedback: $V_d^{OL} > V_d^F$.
- The recipient is better off when his decisions are linked to the stock of usable water. $V_r^{OL}(x_0) < V_r^F(x_0)$.

Tthe Stackelberg games

- Hierarchical modes of play: the donor or the recipient could be regarded as the Stackelberg leader and his/her opponent as the follower.

The leader is in position to make an offer to its opponent, thereby maximizing its welfare under the demand constraint (for recipient) or the supply constraint (for donor).

The price of the water transfer does not come from the equality between supply and demand. It will be the stackelberg leader who, knowing the reaction function of its counterpart, chooses the price and consequently the amount of water transfer.

The Stackelberg games: First result

We can prove that τ is smaller in the Stackelberg cases than in the Nash cases.

- When the donor is the leader, he does not like transfer because it implies a loss in environmental amenities, he fixes a high price and the recipient demands less water.
- When the recipient is the leader we would expect the opposite. However the increase in the recipient welfare does not come from larger transfers but from lower prices.

The Stackelberg games: comparisons

$$x^{\mathrm{OL}}(t) < x^{\mathrm{rL}}(t) < x^{\mathrm{F}}(t) < x^{\mathrm{dL}}(t) \quad \forall t > 0.$$

1. $s^{\mathrm{OL}}(0) < s^{\mathrm{rL}}(0) < s^{\mathrm{F}}(0) < s^{\mathrm{dL}}(0)$ and $\bar{s}^{\mathrm{OL}} < \bar{s}^{\mathrm{rL}} < \bar{s}^{\mathrm{F}} < \bar{s}^{\mathrm{dL}}$.
2. $p^{\mathrm{rL}}(0) < p^{\mathrm{F}}(0) < p^{\mathrm{dL}}(0)$ and $\bar{p}^{\mathrm{rL}} < \bar{p}^{\mathrm{F}} < \bar{p}^{\mathrm{dL}}$.
3.
   1. $\tau^{\mathrm{rL}}(0) < \tau^{\mathrm{F}}(0) = \tau^{\mathrm{OL}}(0)$ and $\bar{\tau}^{\mathrm{rL}} < \bar{\tau}^{\mathrm{F}} < \bar{\tau}^{\mathrm{OL}}$,
   2. $\tau^{\mathrm{dL}}(0) < \tau^{\mathrm{F}}(0) = \tau^{\mathrm{OL}}(0)$ and
      $\tau^{\mathrm{dL}}(t) < \tau^{\mathrm{F}}(t) < \tau^{\mathrm{OL}}(t), \quad \forall t > 0.$
4. $0 > \frac{\partial}{\partial \tau} E'(\tau) \geq \frac{\partial}{\partial \tau} Q'_{\tau}(\tau, x) \Rightarrow \tau^{\mathrm{rL}}(t) > \tau^{\mathrm{dL}}(t),\ \forall t \geq 0.$

Some conclusions

When the recipient is the Stackelberg leader, he fixes a lower price initially and in the long run. In consequence, the incentive to invest in water equipment is also lower than in the competitive solution. The capacity of usable water grows lower. In parallel, because the price decreases deeper, the water transfer supplied by the donor at the initial time and in the long run, is also lower.

The donor-leader can charge a higher price both initially and in the long-run. A greater price enhances the incentive to invest in water equipment. Investment is greater, at least at the beginning and in the long run. A higher investment increases the capacity of usable water higher at any point in time. Because the capacity of usable water is higher, and the price of the water transfer is generally higher, the recipient demand less water. In consequence, the amount of water transfer is lower at any time.

Equilibria and no water transfer

When investments in new capacity are costly, $\beta > 0$, payoffs for the two players at the Nash equilibrium (OL or Feedback) and at the Stackelberg equilibrium (donor or recipient leader) are strictly greater than under the assumption of no water transfer between the regions.

Static versus dynamic game

- we suppose that capacity of usable water immediately adjusts to the optimal level, once the investment decision is taken.
- we consider that this capacity, never declines, that is that the depreciation rate is zero.

The payoff functions for the two players in the static setting read:

$$F^d(p,\tau) = c\left(R - \frac{1}{2}\frac{\tau^2}{R}\right) + p\tau,$$

$$F^r(p,\tau,s) = d\left[x + \tau - \frac{\alpha}{2}(x+\tau)^2\right] - p\tau - \frac{1}{2}\beta s^2, \quad x = x_0 + s.$$

where s is the investment decision and x the capacity of usable water.

Static versus dynamic game

- In the static game the Nash equilibrium is Pareto efficient.
- In the dynamic game the lack of an enforcement mechanism leads the recipient to deviate from the open-loop solution which coincided with the cooperative solution. The Nash feedback dynamic equilibrium is not Pareto efficient.

- We relate our results to the data of the Tagus-Segura water transfer described in Ballestero (2004).
- The main difference is the possibility to invest in alternative water supplies.
- We calibrate our model in such a way that the transfer and the prices that solve the static game "without x AND WITHOUT s" match the values found by Ballestero.
- We next assume the discount rate $\rho = 0.001$ and the equipment depreciation rate $\delta = 0.1$. Initial capacity for usable water is: $x(0) = 0$.

Numerical illustration: the Tagus-Segura transfer

static game and dynamic game, depending on the value of β (which measures the cost of investment)

	$\beta = \hat{\beta}$			$\beta \to \infty$
	Static	OL	F	
$\bar{\tau}$	57.56	33.16	24.83	58
$\bar{p}$	0.45	0.26	0.19	0.46
$\bar{x}$	0.55	31.68	42.31	0
$\bar{\tau} + \bar{x}$	58.12	64.85	67.14	58

$\hat{\beta}$ s/t difference between OL and F is greatest

The Tagus-Segura transfer. Results

Taking into account a dynamic model

- We observe that the opportunity to invest in alternative water supplies reduces the recipient's dependence on water transfer.
- Less water is transferred at a lower price, and the price decreases over time.
- The investment in alternative water supplies is higher under feedback strategies.

$$V_d^{\text{dL}} > V_d^{\text{OL}} > V_d^{\text{F}} > V_d^{\text{rL}},$$

$$V_r^{\text{rL}} > V_r^{\text{F}} > V_r^{\text{OL}} > V_r^{\text{dL}}.$$

The joint welfare under Feedback Nash equilibrium is closer to the social optimum that the case when the recipient is the leader. The worst case in terms of joint welfare would be to give the donor the market power.

$$V^{\text{C}} \equiv V^{\text{OL}} > V^{\text{F}} > V^{\text{rL}} > V^{\text{dL}}$$

Political recommendations

If we are considering a central government which has built an aqueduct to transfer water between two regions within the country:

1. Government concerned on joint welfare: Perfect competition would produce the joint welfare closest to the SO.
2. Government concerned on environmental problems: giving the donor a monopoly power would best preserve the quality of the water in the donor river-basin (in the example $\tau^{dL} << \tau^{F}$) and it would induce the recipient to make the highest investment to improve the capacity of usable water ($x^{dL} > x^{F} > x^{rL}$).
3. It is interesting to notice that a market power given to the recipient, paradoxically can help to maintain a better water quality than in the perfectly competitive case ($\tau^{rL} < \tau^{F}$), while at the same time, the joint welfare is not so strongly reduced as in the case of a monopolistic donor as water provider ($V^{rL} > V^{dL}$).

Extensions: Taking into account the constraint on the transfer

In the paper we say that for environmental reasons the transfer is smaller than R.
R is the maximum possible water surplus in the river without risking the exhaustion of the reservoir.
This constraint must affect investment, for the Nash transfer solution

$$0 \leq \tau(x) = \frac{dR}{R\alpha d + c}(1 - \alpha x) \leq R \ \forall x,$$

$$\Longleftrightarrow$$

$$x_{min} := \frac{1}{\alpha}\left(1 - \frac{R\alpha d + c}{d}\right) \leq x \leq \frac{1}{\alpha}.$$

Taking into account the constraint on the transfer

As in the case without constraints the non-cooperative open-loop solution coincides with the solution of the cooperative game. Nash

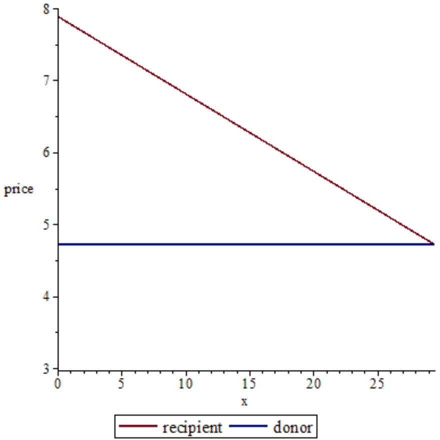
OL equilibrium: Optimal transfer is:

$$\tau(x) = \begin{cases} \frac{dR}{Y+c}(1-\alpha x) & \text{if} \quad x > x_{min} \\ R & \text{if} \quad x \leq x_{min} \end{cases}$$

$$p(x) = \begin{cases} \frac{dc}{Y+c}(1-\alpha x) & \text{if} \quad x > x_{min} \\ A(x) & \text{if} \quad x \leq x_{min} \end{cases}$$

Taking into account the constraint on the transfer

with $c \leq A(x) \leq d(1-\alpha(R+x))$.



how to share the surplus: Bargaining

Extensions

- We have analyzed the interaction between the players assuming that the aqueduct already exists. An immediate natural extension would be to analyze how to share the fixed cost of building the aqueduct.
- How can the donor be "more dynamic"...?
- ...