Designing water markets to manage coupled externalities : an application to irrigation-induced salinity in Australia

Sophie Legras

Université de Montpellier and Australian National University

legras@ensam.inra.fr

Robert Lifran

INRA-LAMETA

lifran@ensam.inra.fr

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1. Introduction

Facing increasing demand for human uses, water resources are becoming scarcer throughout the world. Among the institutional arrangements proposed to cope with water scarcity, the definition and subsequent trading of water rights is usually recognized as one of the most efficient ways to manage the resource. Nevertheless, allocating water among different users often implies changes to the water cycle, and thus generates external effects. The situation is rendered even more complex in presence of coupled external effects. Understand coupled externalities as externalities rendered dependent by the underlying biological or hydrological system, so that managing one has consequences on the others. The aim of this paper is to explore some aspects of the complexity arising from several coupled externalities, and to compare various water market designs to overcome this issue.

There exists in fact few papers developing formal models of water markets [7]. However there is an abundant literature on site specific aspects of water markets, including simulations and description of the institutional contexts [2]. If simulations provide optimistic results [2], empirical analyses show more contrasted results. Tan [4] explains that authors who have a significant experience in water markets advocate a strong role for regulation to impact on the scope and direction of water reallocation, in order to account for environmental externalities. In this regard, the current development of water markets for managing water scarcity in Australia may not take sufficiently account of environmental issues arising from their implementation [6]. To tackle the consequences of diverting water from natural ecosystems for human use, the necessity to cap the amount of diverted water has been recognized early and the allocation of water made through the use of mixed instruments, such as cap and trade. At the same time, the development of irrigation induced negative environmental impacts (waterlogging, discharge of salty water). Operating a simplification of the issues at stake, irrigation-induced salinity can be reduced to a single objective to be attained : reducing the recharge to the aquifer down to a limit established in consistency with its hydrological characteristics. Then a satisfying management of water resources in the southeastern states of Australia should be able to maintain instream flows and reduce the recharge to aquifers. However, due to the hydrological linkages existing within catchment areas, environmental flows and irrigation- induced salinity turn out to be coupled externalities.

In this paper we provide a preliminary analysis of three types of water market mechanisms to manage water scarcity and irrigation-induced salinity. We consider two strategies for the regulator facing two main environmental objectives concerning coupled externalities : designing either one or two policy instruments. First, we analyze diversion rights market constrained by catchment, so that the total amount of diversion permits allocated per zone is consistent with the recharge constraint. Second, following Tinbergen's [5] principle we analyze a market for diversion rights extended to the whole system of catchments, accompanied by another policy instrument : either the enforcement of the recharge constraint or the introduction of a market for recharge rights. We propose a very stylized, static, model of irrigation-induced salinity, able to exhibit the main hydrological interactions at stake. Section 2 presents the model. Section 3 develops the program of the regulator. In Section 4, we address various designs for a system of water markets to manage irrigation-induced salinity. Section 5 provides some concluding remarks.

2. The model

Consider m hydrological zones, denoted by k, located along a river and ordered upstream-downstream. To each hydrological zone corresponds a unique watertable, which recharge management can totally be undertaken on this zone. In each of these zones, n_k agents denoted by $i \in [1..n_k]$ undertake irrigation. Agent i's utility function is :

$$B_i(u_{ik}, a_{ik}) = \rho_p f_i(u_{ik}) - \rho_E u_{ik} - C_a a_{ik} - \varepsilon_k \sum_i p(u_{ik}, a_{ik}),$$

where $f_i(u_{ik}) = A_i + B_i u_{ik} - \frac{C_i}{2} u_{ik}^2$ is the production function and $p(u_{ik}, a_{ik}) = \alpha_k u_{ik} - \delta_k a_{ik}$ is the percolation function. Control variables are u_{ik}, the quantity of water applied for irrigation, and a_{ik}, abatement decisions. α_k is a percolation rate, inversely related to the efficiency of irrigation technology supposed fixed for an agent. δ_k is an index of the efficiency of abatement actions : we only consider the case where abatement actions are costly to the irrigators, and do not provide any benefits apart from reduced percolation. ε_k is an individual damage term associated with irrigation-induced salinity that we consider as the effect of aggregate percolation in zone k. It is a translation of soil salinization and waterlogging in a static context. Parameters α_k, δ_k and ε_k are supposed to be catchment-specific. Indeed, their respective values depend on pedological characteristics, which are considered more homogeneous among, than between, catchments. ρ_P, ρ_E and $C_a$are cost or price terms.

It is assumed that an aggregate quantity of water d_k is diverted from the river at one uptake point for each zone k, and that an amount rf_k of return flows goes back to the river from the underground system at zone k's outset point, such that : $d_k = \sum_i u_{ik}$ and $rf_k = \sigma_k \sum_i p(u_{ik}, a_{ik})$. σ_k is a return-flow parameter. Water available for diversion at point $k+1$ is described by the following equation:

$$q_{k+1} = q_k - d_k + rf_k \tag{1}$$

The assumption underlying these formulations is that only the actions undertaken on point k have an impact along the segment $[k, k+1]$ of the river (see Figure 1). Imagine the case of a fully regulated river : irrigation areas are provided with irrigation water diverted at identified uptake points along the river. Between these uptake points, water uses are assumed to be non-consumptive. Instream-users' interests are assumed to be accommodated by the regulator in defining and implementing a constraint on instream flows[1]. Returns flows have an ambiguous effect on the environment. In quantitative terms, they generate positive externalities by increasing river flows. In qualitative terms, however,

[1]See [1] for a model with consideration of instream users

they contribute to increasing salt concentration in river flows. Stream salinity causes various types of damage : to the environment, to irrigation activities and to infrastructures. Damage from instream salinity is expressed by : $\Gamma_k rf_k$, Γ_k being the marginal damage from salts contained in return flows from zone k.

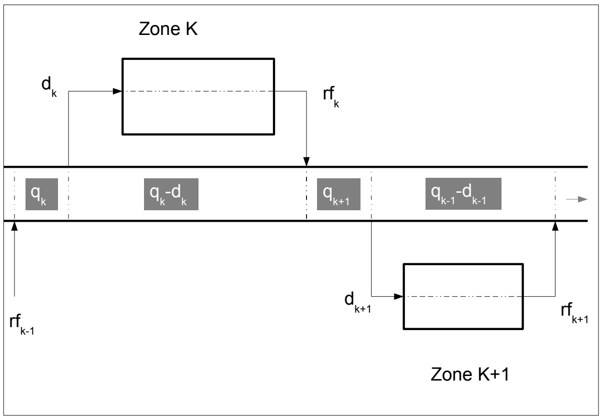

FIGURE 1. Hydrological model

In the next section, we analyze the optimal allocation of water derived by a benevolent regulator. In fact, it is a constrained optimal program, as some damages are not explicitly written. Instead we define two constraints which are supposed to internalize the various damage : a recharge constraint by zone and a constraint on environmental flows.

3. THE OPTIMAL ALLOCATION OF WATER

3.1. **Regulator's objectives.** The first objective of the regulator is to guarantee a minimum level of instream flows at each point along the river, in order to satisfy the needs of the environment and of a range of other non -consumptive users. We call this the environmental flow constraint.

(2) $$q_k - d_k \geq \bar{Q}, \forall k$$

This constraint imposes that a minimum flow $\bar{Q}$ remains in the river after each catchment's uptake point. Indeed, considering the structure of the hydrological model, the portion of the river between a zone's uptake and outset points is the most vulnerable by respect to flows. The fact that $\bar{Q}$ is the same for every catchment denotes a homogeneous view of the river : no particularly important ecological zones have been identified[2].

The second objective of the regulator is to maintain the level of the watertable below a critical point, above which salinization processes are enhanced. In each of the zone, the following recharge constraint is enforced :

$$\sum_i p(u_{ik}, a_{ik}) \leq \bar{R}_k, \forall k \tag{3}$$

It is assumed that both constraints are optimally set by the regulator, in order to deal with values which are not captured by the model. If the environmental flow constraint captures non-consumptive values, the recharge constraint captures values which are inherently dynamic and as such cannot be described by this model. In particular, this constraint allows taking account of the dynamic externalities arising between the irrigators.

3.2. **Regulator's program.** The program of the regulator, that will serve as a benchmark to which the next cases will be compared, is to maximise the social welfare with respect to the quantity of water applied and the abatement decisions :

$$\max_{u_{ik}, a_{ik}} \sum_k \sum_i B(u_{ik}, a_{ik}) - \sum_k \Gamma_k r f_k$$

subject to equations (1), (2), (3) and initial conditions. This is a general constrained control problem, with two controls u_{ik} and a_{ik} and a state variable q_k which spatial evolution is given in equation (1). The Lagrangian is:

$$L^*(u_{ik}, a_{ik}, \omega(k), \mu_1(k), \mu_2(k)) = \sum_k \sum_i B(u_{ik}, a_{ik}) - \sum_k \Gamma_k r f_k +$$

$$\sum_k \omega(k)[q_k - d_k + r f_k - q_{k+1}] + \sum_k \mu_1(k)[q_k - d_k - \bar{Q}] + \sum_k \mu_2(k)[\bar{R}_k - \sum_i p(u_{ik}, a_{ik})],$$

[2]This corresponds to a method of assessing environmental flow needs : identify a study site illustrative of the river, assess the environmental needs, provide recommendations under different levels of risk. See http://www.dpiwe.tas.gov.au/inter.nsf/WebPages/JMUY-5F93LC?open

where $\omega(k)$ is the costate variable, $\mu_1(k)$ and $\mu_2(k)$ are the shadow costs associated with the regulatory constraints. The first order conditions for an interior solution are :

$$\frac{\partial L^*}{\partial u_{ik}} = \frac{\partial B}{\partial u_{ik}} - \Gamma_k \frac{\partial rf_k}{\partial u_{ik}} + \omega(k)(\frac{\partial rf_k}{\partial u_{ik}} - \frac{\partial d_k}{\partial u_{ik}}) - \mu_1(k)\frac{\partial d_k}{\partial u_{ik}} - \mu_2(k)\frac{\partial p(.)}{\partial u_{ik}} = 0 \tag{4}$$

$$\frac{\partial L^*}{\partial a_{ik}} = \frac{\partial B}{\partial a_{ik}} - \Gamma_k \frac{\partial rf_k}{\partial a_{ik}} + \omega(k)\frac{\partial rf_k}{\partial a_{ik}} - \mu_2(k)\frac{\partial p(.)}{\partial a_{ik}} = 0 \tag{5}$$

$$\frac{\partial L^*}{\partial q_k} = \omega(k) - \omega(k-1) + \mu_1(k) = 0$$

$$q_k - d_k - \bar{Q} \geq 0 \ , \ \mu_1(k)[q_k - d_k - \bar{Q}] = 0$$

$$\bar{R}_k - \sum_i p(u_{ik}, a_{ik}) \geq 0 \ , \ \mu_2(k)[\bar{R}_k - \sum_i p(u_{ik}, a_{ik})] = 0$$

Rearranging the expressions, we obtain :

$$\omega(k) = \frac{1}{1-\sigma_k\alpha_k}[\rho_P(B - Cu_{ik}) - \rho_E - \mu_1(k)] - \frac{\alpha_k}{1-\sigma_k\alpha_k}[\varepsilon_k + \mu_2(k) + \sigma_k\Gamma_k] \tag{6}$$

$$\mu_2(k) = \frac{C_a}{\delta} + \sigma_k\omega(k) - \varepsilon_k - \sigma_k\Gamma_k \tag{7}$$

$$\mu_1(k) = \omega(k-1) - \omega(k) \tag{8}$$

Equation (6) describes the cost $\omega(k)$ of reducing the water flow between zones k and $k+1$ by one unit. At the equilibrium, this cost equals the marginal benefit of allocating a extra unit of water to agent ik. This benefit is separated according to water use : consumption or percolation. The first bracketed term on the RHS of equation (6) is the net benefit of consuming a extra unit of water for agent i : the marginal benefit of consuming a extra unit of water, minus the extra cost of meeting the environmental flows constraint in zone k by diverting water. The coefficient $1/1-\sigma_k\alpha_k$ renders this net benefit per unit of water consumed. The second bracketed term of the RHS of equation (6) is the marginal cost of percolating one unit of water: direct damage to user ik, extra cost of meeting the recharge constraint and damage of an increased stream salinity downstream. The coefficient $\alpha_k/1-\sigma_k\alpha_k$ renders this net cost per unit of water percolated.

Equation (7) shows the cost of meeting the recharge constraint in each zone. It is equal to the abatement cost, C_a/δ_i, plus the cost of reducing the flow downstream, $\sigma_k\omega(k)$, plus the benefits accruing from avoided damage : individual damage, $-\epsilon_k$, and downstream instream salinity damage, $-\sigma_k\Gamma_k$.

Equation (8) illustrates the path of the cost of reducing water to downstream users. It depends on k, and not i, due to the structure of the model, with one uptake point for an irrigation area, rather than individual riparian diverters. As $\mu_1(k) > 0$, $\triangle\omega(k) < 0$. As water goes downstream, less agents are affected by individual decisions regarding diversion or abatement [7]. As equation showed in (8), a shift of water diversion from $k-1$ to $k+1$ reduces the environmental flow constraint for zone k. As we do not consider any instream users in this model, this reduction of the environmental flow constraint is the only benefit accruing from changing the location of diversion.

4. Various designs for water markets

4.1. **A definition of the markets under study.** The main market design we develop in this paper is a series of cap and trades for diversion rights, each cap being defined at the catchment scale (case A). This means that a diversion cap is defined for each zone, in consistency with the recharge constraint set by the regulator. Trade is not allowed between zones so that the *status quo* situation is approximated. Indeed, the current development of water markets in Australia is such that one can consider that barriers to trade prevent trade between zones, except a few exceptions[3]. Case A is an example of the design of a single instrument to manage two objectives. Then we present two different types of market designs, both allowing trade of diversion rights within the whole system of m catchments, and making use of two instruments to manage two objectives. In case B, it is supposed that the regulators seeks to have the recharge objective attained through the enforcement of the coupling constraint equation (3). In case C, we consider that this

[3]Note that currently caps are defined in consistency with a scarcity constraint, not a recharge one.

constraint is managed through the use of a market for tradeable recharge rights on each zone. Such a market has been proposed by Whitten et al. [8], but not formally analyzed.

In the case of a **basin-wide market**, the regulator issues a total amount $\bar{W}$ of diversion permits in the system : $\bar{W} = \sum_k \sum_i w^0_{ik}$ where w^0_{ik} is the initial allocation of agent i from zone k. The amount of permits bought (resp. sold) by agent ik from (resp. to) agent j from zone h is w^{jh}_{ik} (resp. w^{ik}_{jh}) . Consequently, agent ik's final holding is :

$$w(ik) = w^0_{ik} + \sum_h \sum_j [w^{jh}_{ik} - w^{ik}_{jh}]$$

The amount of permits bought by ik depends on the price of the permits : p^{jh}_{ik}. It is also the reservation price at which ik is willing to sell his permits.

In the case of **a series of markets constrained by zones**, the regulator issues a total number of permits $\bar{W}_k$ in each hydrological zone, so that $\bar{W}_k = \sum_i w^0_{ik}$. Agents cannot buy or sell permits outside their hydrological zone. It is thus imposed that $w^{ik}_{jh} = 0, \ \forall j \neq k$. As a consequence, agent ik's final holding is :

$$w(ik) = w^0_{ik} + \sum_j [w^{jk}_{ik} - w^{ik}_{jk}]$$

Recharge markets are, by construction, constrained by zone. Indeed, the cap (the maximum amount of percolated water to be produced) is defined according to each watertable's characteristics, and corresponds to conditions on the stationarity of the watertable. Hence the regulator issues a maximum amount of recharge permits, $\bar{R}_k$, for each zone in consistency with the hydrological state of the underlying aquifer. User ik holds $r(ik)$ permits :

$$r(ik) = r^0_{ik} + \sum_j [r^j_i(k) - r^i_j(k)]$$

The analyses presented in the remainder of this paper are undertaken according to the constraints and definitions given in the following table.

Nature of the rights	*Compliance constraint*	*Market clearing conditions*
Case A : Zonal cap and trades on diversion		
$\sum_i w_{ik}^0 = \bar{W}_k = f(\bar{R}_k)$	$u_{ik} = w_{ik}$	$\sum_i (w_{ik} - w_{ik}^0) = 0\ ^*$
Case B : global cap and trade on diversion		
$\sum_k \sum_i w_{ik}^0 = \bar{W}$	$u_{ik} = w_{ik}$	$\sum_k \sum_i (w_{ik} - w_{ik}^0) = 0\ ^\sharp$
Case C : case A + zonal cap and trades on recharge		
$\sum_k \sum_i w_{ik}^0 = \bar{W}$	$u_{ik} = w_{ik}$	$\sum_k \sum_i (w_{ik} - w_{ik}^0) = 0\ ^\sharp$
$\sum_i r_{ik}^0 = \bar{R}_k$	$p(u_{ik}, a_{ik}) = r_{ik}$	$\sum_i (r_{ik} - r_{ik}^0) = 0\ ^*$

$^\sharp$ intra and inter zone trading * intra zone trading only

Next, we analyze case A, and derive the conditions for this market design to be optimal. We show that it is highly improbable that these conditions are met. Then we address cases B and C by pointing two interesting preliminary results.

4.2. **A series of zonal cap and trades for diversion.** In this case, we assume that the regulator computes the zonal caps for diversion $\bar{W}_k$ in consistency with the recharge constraint equation (3). Irrigators only account for the instream flow constraint (2). Furthermore, if they account for the state variable, equation (12), they do not use it in their decision making program, as they cannot trade with upstream or downstream users.

Proposition 1. *A Nash Equilibrium exists for a given diversion rights price.*

Proof. It can be verified that agents' strategies u_{ik} and a_{ik} are selected from a convex, closed and bounded sets. Furthermore the utility function is continuous and concave in each control. Then from Theorem 1 from Rosen [3] we know that this game admits an equilibrium point. □

Note that the unicity of the equilibrium point is not *a priori* assured in reason of the coupling constraint equation (2) [3].

Proposition 2. *There exists an equilibrium to the diversion rights market in zone k when $\forall i, j \in [1..n_k]$ we have $\partial B^i/\partial u_{ik} - \eta_1^{ik} = \partial B^j/\partial u_{ik} - \eta_1^{jk}$.*

Proof. The program of an individual agent is :

$$\max_{u_{ik}, w(ik), a_{ik}} B(u_{ik}, a_{ik}) - \sum_j p_{ik}^{jh} w_{ik}^{jh} \text{ subject to } w(ik) - u_{ik} = 0.$$

We derive the first-order conditions from the Lagrangian :

$$L^C = B^i(u_{ik}, a_{ik}) - \sum_j p_{ik}^{jk} w_{ik}^{jk} + \eta_1^{ik}[q_k - d_k - \bar{Q}] + \beta_1^{ik}[w(ik) - u(ik)],$$

(9) $$\frac{\partial L^C}{\partial u_{ik}} = \frac{\partial B^i}{\partial u_{ik}} - \eta_1^k - \beta_{ik} = 0,$$

(10) $$\frac{\partial L^C}{\partial a_{ik}} = \frac{\partial B^i}{\partial a_{ik}} = 0,$$

(11) $$\frac{\partial L^C}{\partial w_{ik}^{jk}} = -p_{ik}^{jk} + \beta_{ik} = 0.$$

From these equations, we get the payoff from buying a diversion permit, which is set equal to the marginal benefit of using this permit minus the market price. A decision to buy a permit will be made according to this relation. An agent i will buy a permit from an agent j as long as : $\partial B^i/\partial u_{ik} - \eta_1^{ik} - p_{ik}^{jk} > 0$. The opportunity cost of a permit equals the marginal benefit from using it, so that the payoff, for jk, from selling a permit to ik is : $p_{jk}^{ik} - [\partial B^j/\partial u_{ik} - \eta_1^{jk}]$. Agent jk will have an incentive to sell a permit as long as the payoff is positive. Hence, if $\partial B^j/\partial u_{ik} - \eta_1^{jk} < \partial B^i/\partial u_{ik} - \eta_1^{ik}$, any $p_{jk}^{ik} \in [\partial B^j/\partial u_{ik} - \eta_1^{jk}, \partial B^i/\partial u_{ik} - \eta_1^{ik}]$ will induce a transfer of rights from jk to ik. In the same manner, if $\partial B^j/\partial u_{ik} - \eta_1^{jk} > \partial B^i/\partial u_{ik} - \eta_1^{ik}$, any $p_{ik}^{jk} \in [\partial B^i/\partial u_{ik} - \eta_1^{ik}, \partial B^j/\partial u_{ik} - \eta_1^{jk}]$ will induce a transfer from ik to jk. Only when the marginal benefits are equal there is no incentive to trade. □

Proposition 3. *This system of markets for diversion rights leads to the optimal allocation of water only under highly restrictive conditions.*

Proof. Equations (9) and (4) are compatible if :

$$p_{ik}^{jk} + \eta_1^{ik} = \omega(k)[1 - \alpha_k\sigma_k] + \alpha_k\sigma_k\Gamma_k + \mu_1^k + \alpha_k\mu_2^k.$$

Equations (10) and (5) are compatible if :

$$\sigma_k[\Gamma_k - \omega(k)] + \mu_2^k = 0.$$

If the recharge constraint is non binding, $\mu_2^k = 0$ which implies $\Gamma_k = \omega(k)$. This means that the equalization of the first-order conditions on the choice of the level of abatement forces Γ_k to equal $\omega(k)$. Interestingly, the term $\sigma_k[\omega(k) - \Gamma_k]$ measures the difference of importance between quantitative and qualitative impacts of discharges from the watertable. Its sign reflects the relative importance of social benefits due to increased water flowing downstream of zone k compared to the social cost of increased instream salinity generated by k. Only when the social benefits from discharging balance the associated social costs do individual agents perform optimally by respect to abatement choice. If the recharge constraint is binding, then compatibility with the optimal solution requires that $\mu_2^k = \sigma_k[\omega(k) - \Gamma_k]$. The cost of respecting the recharge constraint has to be equal to the net social benefits from reducing the recharge to the aquifer. In both cases, the first order conditions on the choice of the level of irrigation become : $p_{ik}^{jk} + \eta_1^{ik} = \omega(k) + \mu_1^k$. If there exists a mechanism that induces individual agents to account for a shadow cost of the coupling constraint on environmental flows just equal to the optimal shadow cost, then $p_{ik}^{jk} = \omega(k)$. The optimal price per zone is then just equal to the co-state variable derived in the optimal case. □

With this system agents are not directly induced to abate more that what is individually optimal (balancing the avoided individual damage and the cost of abating). Note that, if these conditions are met, a series of markets for diversion rights as defined above would ensure that the optimal solution is met if the zonal caps $\bar{W}_k$ are defined as follows, where a^* is the optimal abatement decision : $\bar{W}_k = 1/\alpha_k[\bar{R}_k + \delta_k \sum_j a^*]$.

4.3. **Basin-wide cap and trades for diversion.** In this section, we present preliminary results related to cases B and C. Their analysis is rendered more complex in reason of the possibility for agents to trade with agents from other hydrological zones. This implies an asymmetry of trade according to the location of the trading partner [7]. The resolution process is the same as in the previous case. The existence of an equilibrium is assured due to the concavity of the game, but there may be a problem of multiplicity of equilibria due to the presence of the coupling constraints equations (2) and (3). The demonstration of the existence of the market equilibria is in progress and not developed here. First, we develop the asymmetries of trade between zones. Second, we show the impact of a recharge rights market on the functioning of the diversion rights market.

An upstream/downstream asymmetry of trade. Following Weber [7], we derive a series of expressions from the structure of the model that allow to illustrate the impact of trades on water flowing down the river. Considering the constraints accounting for by individual agents, in particular the environmental flow constraint (2), an agent perceives the river flow reaching his zone as follows :

$$q_k = q_0 - \sum_{h=0}^{k-1} d_h + \sum_{h=0}^{k-1} r f_h. \tag{12}$$

This means that an agent knows that the amount of water available for diversion in his zone depends on the actions undertaken by upstream users. In cases B and C users can trade with any user in any zone, they can assess the impact of their trading decisions on the water that will reach their zones. Note that trades with users located downstream or in the same zone ($h \geq k$) do not have any consequence on water available for diversion in zone k, as the summation stops at $k-1$.

We have : $\partial w(ik)/\partial w_{ik}^{jh} = 1$ and $\partial w(ik)/\partial w_{jh}^{ik} = -1$. Any purchase by agent ik translates into an increase of his final holding; inversely, any sale by agent ik means a decrease of its final holding. We also have that : $\partial w(ik)/\partial w(jh) \leq 0$. Any increase in ik's final holding means a transfer from another user, whose final holding decreases consequently. And inversely. From the definitions of diversions and return flows, we have : $\partial d_h / \partial w_{jh}^{ik} = 1$, $\partial rf_h / \partial w_{jh}^{ik} = \sigma_k \alpha_k$. A purchase of permits by agent jh allows him to use more water, increasing diversions to his zone, as well as return flows from his zone. Then trades with upstream users have the following impacts.

$$\frac{\partial q_k}{\partial w_{ik}^{jh}} = (\sigma_h \alpha_h - 1) \frac{\partial d_h}{\partial w_{ik}^{jh}} = 1 - \sigma_h \alpha_h \geq 0$$

When agent ik purchases a permit from an upstream agent jh, he allows more water to reach his zone, as agent jh does not divert the corresponding amount of water. The counterpart is that agent jh does not produce the corresponding return flows. The net result is positive, so that more water is available for diversion in zone k.

$$\frac{\partial q_k}{\partial w_{jh}^{ik}} = (\sigma_h \alpha_h - 1) \frac{\partial d_h}{\partial w_{jh}^{ik}} = \sigma_h \alpha_h - 1 \leq 0$$

When agent ik sells a permit to an upstream agent jh, more water is diverted upstream, and return flows are generated. The net result is negative. The impact of total trades undertaken by ik with upstream users is :

$$\frac{\partial q_k}{\partial w(ik)} = \sum_{h=0}^{k-1} \frac{\partial q_k}{\partial w_{ik}^{jh}} - \sum_{h=0}^{k-1} \frac{\partial q_k}{\partial w_{jh}^{ik}} \tag{13}$$

Consequently, agent ik's trade decisions have an indirect impact on q_k and thus on the value of the instream flow constraint. His trading decisions can make it more or less binding. Hence there is an asymmetry of trade according to the location of the trading partner along the river.

Impact of the recharge market on the diversion market. We consider the first-order conditions obtained for case C. The maximisation program is as follows :

$$\max_{u_{ik}, w(ik), a_{ik}, r(ik)} B(u_{ik}, a_{ik}) - \sum_h \sum_j [p_{ik}^{jh} w_{ik}^{jh}] - \sum_j [p_i^j r_i^j(k)] \tag{P.C}$$

subject to $w(ik) - u_{ik} = 0$ and $r(ik) - p(u_{ik}, a_{ik}) = 0$, to equation (2), and with (12). Forming the Lagrangian and deriving the first order conditions, we obtain :

$$\frac{\partial L^C}{\partial u_{ik}} = \frac{\partial B}{\partial u_{ik}} - p_{ik}^{jh} + \eta_1^{ik}[\frac{\partial q_k}{\partial u_{ik}} - 1] - \alpha_k \rho_i^j = 0 \tag{14}$$

$$\frac{\partial L^C}{\partial a_{ik}} = \frac{\partial B}{\partial a_{ik}} + \delta_k \rho_i^j = 0 \tag{15}$$

From (14), two remarks can be made. First, as addressed in the previous point, the price for diversion rights depends on the location of the trading partners, through the term $\partial q_k / \partial u_{ik}$. Second, this price also depends negatively on the equilibrium price for recharge rights, ρ_i^j. Such a system of two markets implicitly constrains one market by the other. Indeed, making use of a diversion permit requires that one holds a permit for the associated recharge, so that the market are coupled.

5. Conclusion

This paper presents a preliminary analysis of different market designs to manage coupled externalities. In order to attain two coupled objectives, the management of the recharge of a series of aquifers and the management of water scarcity in the surface system, we consider three types of market designs. The resolution process is rendered difficult due to the fact that the environmental constraints set by the regulator are coupling constraints, so that there is an issue of multiple equilibria. We provide the full resolution for a case where the two objectives are accomodated with a unique instrument, a series of cap and trades defined at the hydrological zone level. This instrument does not prove able to support the optimal solution, or only under highly restrictive conditions, mainly due to the fact that there is no explicit incentive to abate. We also address a couple of preliminary results from the other cases, where the regulator defines two policy instruments to attain two objectives. First, we put in perspective the presence of asymmetries in trades, according to the location of the trading partners. Indeed, an agent trading with an upstream user has a direct influence on the water available for diversion in his zone. This has consequences on the characterization of the market equilibrium, in progress and therefore not presented here. Second, we show how a market for recharge rights potentially constrains the market for diversion rights. This results in a form of environmentally-driven constraint on water trade. Our analysis bears some limitations. First,we do not allow evolving irrigation technology. This would have consequences by introducing a more stringent tradeoff between reducing the amount of water applied for irrigation, and investing in a more efficient technology. Second, we consider a static setting, which means that we cannot fully account for the essentially dynamic nature of groundwater. The next step on our research agenda is to develop a dynamic model of this context.

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