Should pumping fees be reallocated to the Crau farmers associations ?

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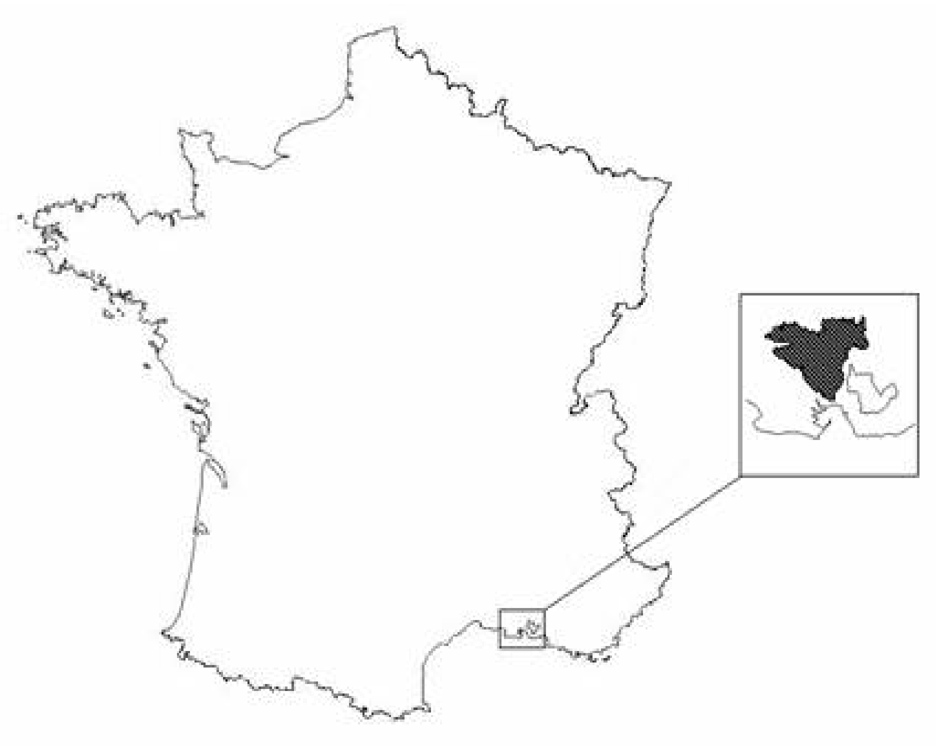
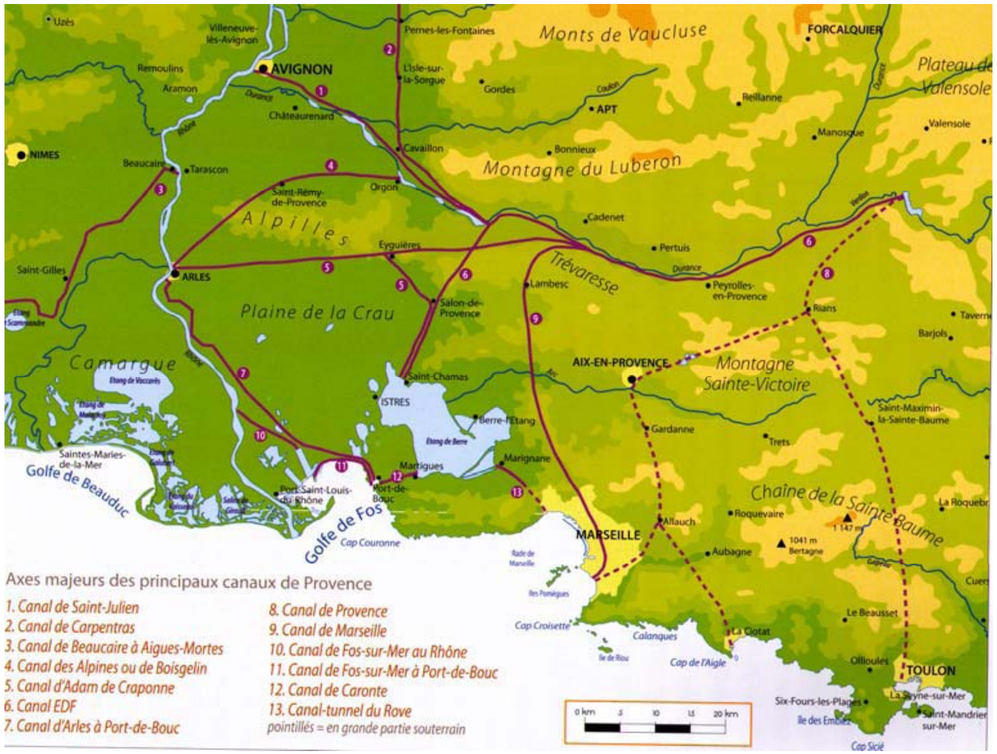
1/ THE STORY OF THE MODEL: THE CRAU GROUNDWATER

1.1/ Location





Provence = Mediterranean climate

Dry area with no **surface water** lacks

Surface water stored and conveyed from wet mountains places to areas where needed for centuries

→ early agricultural dvpt of the region

1.2/ An institution with financial problems: the Crau association of irrigation

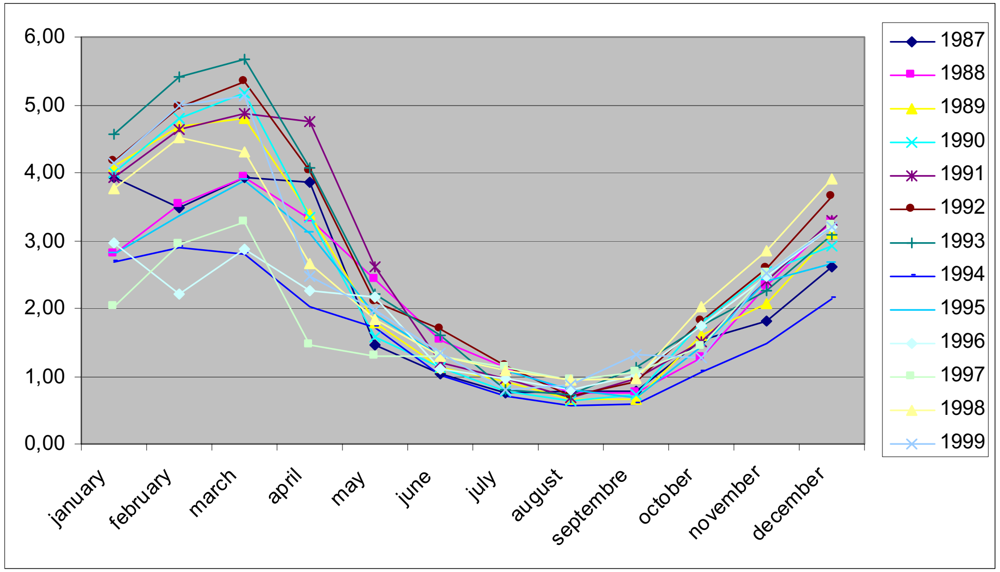
Surface hydraulic networks dating from the XVIth century still **collectively managed** by farmers: contributions + common rules

Border-check flood irrigation
= water simply allowed to run over the soil and to infiltrate, being spread over the entire field.

Financial problem = maintaining and operating costs shared between few farmers
→ parts of the network disused nowadays

1.3/ The Crau aquifer original hydraulic feature

- Surface hydraulic network of ground + border-check flood irrigation
  → large **percolations** to the aquifer located below
- 70% of the inflows come from surface irrigation without any chemicals (COP)
- The Crau aquifer pumping lifts:



Pumping lifts lower in the dry seasons than in the wet ones
= the groundwater stock is higher

Explanation: the irrigation period occurs in dry seasons

1.4/ Non atomistic groundwater users

- Groundwater distribution agencies for urban use
- Industrial users (for instance: oil production at Fos-sur-mer)
- Maximize their profits
- Groundwater pumping costs not only proportional to the amount pumped but also to the pumping lift (energy costs)
- Non atomistic users = each one is able to take into account the impact of his pumping decisions on the GW stock = to act strategically

1.5/ The recent creation of a Crau groundwater management committee

- 2004: creation of the Crau groundwater management committee because of the importance of this resource in the area
- **Composition**: the farmers association, the groundwater distribution agencies and the industrials
- **Objective**: to maximize the sum of his members' profits taking into account two externalities:
  - negative: groundwater pumping costs,
  - positive: percolations induced by surface water irrigation.
- How to reach an efficient outcome?
  - Taxing the groundwater extractions,
  - and using the money hence levied in order to finance more percolations.

We are going to propose a model in order to show this.

2/ THE RELATED LITERATURE

- Recent literature on water = game theory setting

- Significant economies of scale in **surface water** projects
  → mainly static cooperative game theory literature (Parrachino, Dinar, Patrone, 2006)

- **Groundwater**: resource conveyance to each agent naturally ensured by the aquifer + renewable resource with time lag
  → dynamic non cooperative game theory settings in the recent literature:

  - Differential games with homogeneous agents (Rubio and Casino, 2001)

  - 2 agents, 2 periods, incomplete information (Saak and Peterson, 2007)

- But we want to concentrate on the Crau hydraulic feature = to have GW and SW uses in a unified framework

- Literature on **conjunctive use of SW and GW**:
    - Spatial optimization (Chakravorty, Umetsu, 2003)
    - Stochastic optimal control (Tsur, Graham-tomasi, 1991)

Separate use of GW (urban and industrial) and SW (farmers) ≠ substitute goods

- Literature focusing primarily on the **external hydraulic link between GW and SW**:
    - GW pumping effect on a river flow in an optimal control setting (Burness, Chermak, Brookshire, 2004)
    - Return flow externality in water development projects (Holland, 2006)

SW irrigation effect on the GW stock height + heterogeneous GW users

→ *strategic static setting with complete information*

3/ OUR ASSUMPTIONS

Classical hydrologic assumptions

- GW basin has parallel sides with a flat bottom, R: natural recharge
- Changes in the water level transmitted instantaneously to all users
- Concentrated on interior solutions = storativity assumed sufficiently large in order to never overflows

The farmers institution

- Operates by its own rules and generates percolations to the aquifer
- y = volume of surface water percolating to the aquifer

  = corresponds to an optimal running of this institution

- $C(\Delta)$ = the cost of the deviation Δ from this optimal running to one generating larger percolations

Standard properties of a cost function: $\nearrow$, convex, $c(0) = 0$, $\lim_{\Delta \to 0} \frac{dC}{d\Delta} = 0$ and $\lim_{\Delta \to +\infty} \frac{dC}{d\Delta} = +\infty$

The groundwater users $j = 1...m$

- The groundwater users play a game, simultaneously deciding on x_j and receiving $\pi_j(x_j, S)$

- x_j: the volume of groundwater pumped by firm j

- $\pi_j(x_j, S)$: the profits accruing to firm j strictly concave in x_j ($\nearrow$ and $\searrow$) and $\forall S$, $\pi_j\,(0, S) = 0$

- $X := \sum_{j=1}^{m} x_j$ total volume of groundwater pumped, $S := R + y - X$ residual stock of groundwater

- S : indicator of the groundwater pumping costs

- $\partial_S \pi_j > 0$: a higher residual stock means lower pumping costs and higher profits

- π_j globally strictly concave: $\partial^2_{S,S} \pi_j < 0$

- $+$ best responses strategic substitutes: $\partial^2_{x_j,S} \pi_j \geq 0 =$ externalities not to severe

- More technical assumptions (interiority) on the marginal rates of substitution:

$\forall x_j > 0, \lim\limits_{S \to 0} \partial_{x_j}\pi_j / \partial_S \pi_j < 1$: when $S \to 0$ each GW user has always an incentive to decrease x_j

$\forall S > 0, \lim\limits_{x_j \to 0} \partial_{x_j}\pi_j / \sum\limits_{k=1}^{m} \partial_S \pi_k > 1$: when $S > 0$ the GW committee has always an incentive to make sure each firm pump water

$\forall S > 0, \lim\limits_{x_j \to \infty} \partial_{x_j}\pi_j / \partial_S \pi_k < 1$: but the GW users have never an incentive to pump too large volumes

4/ THE NASH GROUNDWATER ALLOCATION

Definition 1 *Given y, a Nash equilibrium allocation of groundwater $x_j^n(y)$ is given by:*

$$\forall j = 1, \ldots, m \; x_j^n(y) \in \arg\max_{x_j \in \mathbb{R}_+} \pi_j \left(x_j, R + y - x_j - \sum_{\substack{k=1 \\ k \neq j}}^{m} x_k^n \right) \; s.t. \; R + y - x_j - \sum_{\substack{k=1 \\ k \neq j}}^{m} x_k^n \geq 0$$

Proposition 1 *For any $y > 0$, this game admits an* ***unique interior Nash equilibrium*** *s.t.:*

$$\forall j = 1, \ldots, m \; \partial_{x_j}\pi_j \left(x_j^n, R + y - x_j^n - \sum_{\substack{k=1 \\ k \neq j}}^{m} x_k^n \right) - \partial_S \pi_j \left(x_j^n, R + y - x_j^n - \sum_{\substack{k=1 \\ k \neq j}}^{m} x_k^n \right) = 0$$

5/ THE OVER EXPLOITATION OF GROUNDWATER...

- When choosing the amount of groundwater to pump, each groundwater user considers the induced increase in his own pumping costs (because of the decrease of the residual stock) but not the one in the other firms pumping costs.

$\Rightarrow$ global over-exploitation of groundwater

Definition 2 *Given y, the efficient groundwater allocation is a vector $\left(x_j^e\right)_{j=1}^m \in \mathbb{R}_+^m$ s.t.:*

$$\left(x_j^e\right)_{j=1}^m \in \underset{\left(x_j\right)_{j=1}^m \in \mathbb{R}_+^m}{\arg\max} \sum_{j=1}^m \pi_j \left(x_j, R + y - X\right) \quad \text{s.t.} \quad y - X \geq 0$$

Proposition 2 *For a given y, $X^e(y) := \sum_{j=1}^m x_j^e(y) < X^n(y) := \sum_{j=1}^m x_j^n(y)$*

and $\Pi^e(y) := \sum_{j=1}^m \pi_j^e(y) \geq \Pi^n(y) := \sum_{j=1}^m \pi_j^n(y)$

- An appropriate intervention of the groundwater committee could correct this inefficiency.

...AND THE OPTIMAL TAXATION OF GROUNDWATER EXTRACTIONS

- Nash FOC:

$$\forall j = 1, \ldots, m \quad \partial_{x_j} \pi_j \left(x_j^n, R + y - x_j^n - \sum_{\substack{k=1 \\ k \neq j}}^m x_k^n \right) - \partial_S \pi_j \left(x_j^n, R + y - x_j^n - \sum_{\substack{k=1 \\ k \neq j}}^m x_k^n \right) = 0$$

- Efficient FOC:

$$\forall j = 1, ..., m \quad \partial_{x_j} \pi_j \left(x_j^e, R + y - X^e \right) - \sum_{k=1}^{m} \partial_S \pi_k \left(x_j^e, R + y - X^e \right) = 0$$

- Pigovian tax to implement in order to slow down the GW overexploitation:

$$t_j(y) = \sum_{\substack{k=1 \\ k \neq j}}^m \partial_S \pi_k \left(x_k^e(y), R + y - X^e(y) \right)$$

- Lump-sum transfer in order to insure that each user's profits are the same before and after the tax being collected:

$$F_j(y) = \left[\pi_j \left(x_j^n, R + y - X^n \right) - \pi_j \left(x_j^e, R + y - X^e \right) \right] + \mathbb{I}_{x_j > 0} t_j x_j^e$$

Proposition 3 *For a given y, the unique Nash groundwater allocation of our first game when modified with the fiscal scheme $\left(t_j(y), F_j(y) \right)_{j=1}^m$ corresponds to the efficient allocation introduced in definition 2.*

6/ TOWARD A REALLOCATION OF THE GROUNDWATER FEES TO THE FARMERS ASSOCIATION

Proposition 4 $\Pi^n(y)$ *after fiscal scheme implementation increasing in* y

Proposition 5 *The implementation of the fiscal scheme leaves to the groundwater committee an amount of money:* $\Pi^e(y) - \Pi^n(y) \geq 0$

- Next idea = to use the gains in order to increase the set of surface water percolations by encouraging the farmers' institution to deviate from her optimal running through financing some maintaining costs for instance

- The groundwater allocation being an efficient one, what is the optimal Δ^* that can be implemented?

  - The groundwater committee sets Δ to Δ^* such that:

    $\Delta^* \in \arg\max_{\Delta \geq 0} \Pi^e(y + \Delta) - C(\Delta)$

  - The maximum amount of tax that can be collected, $\Pi^e(y + \Delta^*) - \Pi^n(y)$, covers the cost induced $C(\Delta^*)$.

7/ CONCLUSION AND EXTENSIONS

Proposition 6 *Two part fiscal scheme controlling over-exploitation:*

$$t_j = \sum_{\substack{k=1 \\ k \neq j}}^{m} \partial_S \pi_k \left(x_k^{e*}, R + y + \Delta^* - X^{e*}\right)$$

$$F_j = \left[\pi_j \left(x_j^n, R + y - X^n\right) - \pi_j \left(x_j^{e*}, R + y + \Delta^* - X^{e*}\right)\right] + \mathbb{I}_{x_j > 0} t_j x_j^{e*}$$

+ Gains can always be used in order to reach an optimal percolation of surface water to the aquifer

- Easy implementation by the groundwater committee with complete information

- Extension 1 = incomplete information setting

- Extension 2 = hydraulic link in a dynamic setting