Managing conflicting objectives in hydro-economic models : A viability approach

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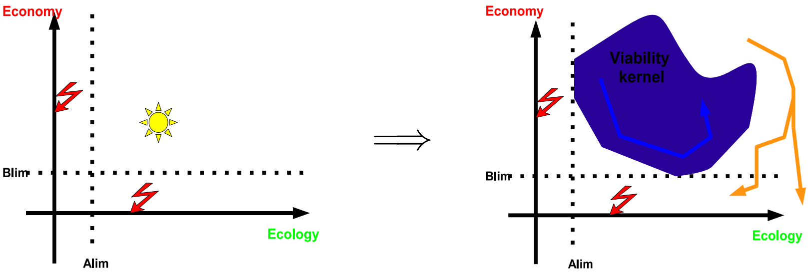
Motivations

- Groundwater resources are under extreme pressure worldwide : about 20% of the world's aquifers are over-exploited
- Main driver of water use : increasing demand for agricultural products
- By 2050 agriculture will need to produce more than 60% of food as compared to the current situation (FAO)
  $\Rightarrow$ Is it sustainable ? from the environmental, economic and social point of view ?

- A focus on feasibility in a dynamic context
- Capacity for a system to maintain conditions of existence through time
- Inter-temporal feasible paths that fulfilled constraints and targets over time



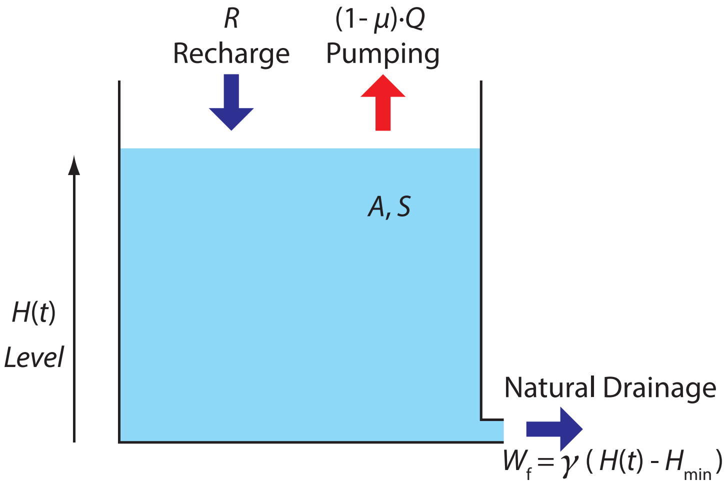
The viability approach in a stylised hydro-economic model

- Sustainability as a problem of constraints fulfillment
- Ecological constraint : minimum flow requirements for ecosystems
  $\Rightarrow$ Constraint on the natural drainage which sustains environmental flows
- Economic constraint : water allocation for irrigated agriculture by a water agency
  $\Rightarrow$ Which Cap ? Which amount of water quotas for farmers ?
- Social constraint : Participation of all the farmers
  $\Rightarrow$ Which minimal amount of water quotas and production for farmers ?

Application to the Tablas del Daimiel and the Western La Mancha Aquifer (Spain)

- The most important wetland located in the Mancha Humeda Biosphere Reserve designed by Unesco in 1980.
- Designated in 1966 as a national hunting reserve, in 1979 as an ornithological special protection area and in 1982 they were included in the RAMSAR Convention.
- Example of groundwater dependent-ecosystem (GDE)

The stylised "open" bathtub model



The resource dynamics

- A the area of the aquifer, S the storage coefficient, H the water table, $(1-\mu)\, Q(t)$ total extraction and W_f natural drainage

$$AS\,(H(t+1) - H(t)) = R - (1-\mu)\, Q(t) - W_f(t)$$

- Natural drainage (Gisser-Sanchez, 1980) with $\gamma > 0$

$$W_f(H(t)) = \gamma(H(t) - H_{\min})$$

- When $H \geq H_{\min}$: water flows from the aquifer to the river or ecosystem
- When $H < H_{\min}$: water flows from the river to the aquifer implying ecosystem damages

The economic model

- Rent of heterogenous farmers, y_i production, w_i water used, p_y the price of agricultural product

$$\pi_i = p_y y_i(w_i(t)) - c(H(t))w_i(t) - m(t)(w_i(t) - q_i^-(t))$$

- Crop-water production function

$$y_i(w_i(t)) = aw_i(t) - \frac{b_i}{2} w_i^2(t)$$

- Heterogenous farmers with $b_1 < b_2 < ... < b_n$ where n is the less efficient and 1 the most productive
- Marginal pumping cost

$$c(H(t)) = c_0 - c_1 H(t)$$

- Last term : quota market with $m(t)$ the permit price

Calibration of the case-study

Parameters	Description	Units	Value
AS	aquifer area $\times$ storativity	Mm^3	126.5
R	natural recharge	Mm^3/y	360
γ	slope of the nat. drainage fct	Mm^3/m	5.5384
μ	return flow coefficient		0.20
$H_0 = H^{\max}$	initial stock level	m	665
$H_{\min}$	minimum water table level	m	600
g	intercept of the water demand fct	€$/Mm^3$	4400.73
k	slope of the water demand fct	€$/Mm^3$	0.097
c_0	intercept of the pumping cost fct	€$/Mm^3/y$	266000
c_1	slope of the pumping cost fct	€$/Mm^3/m$	400

The objectives of the water agency

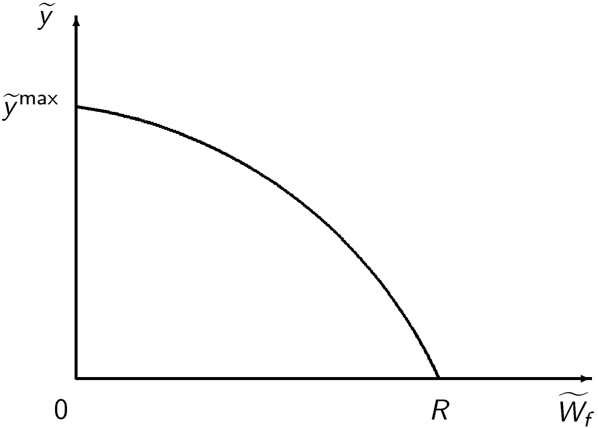
- Environmental objective

  $W_f(t) \geq \widetilde{W_f}$

  $\widetilde{W_f}$=target
- Individual production objective

  $y_i(t) \geq \widetilde{y}$

  $\widetilde{y}$=target



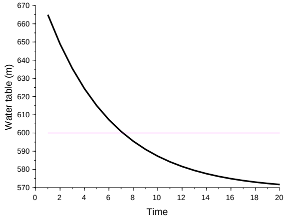
The constraints faced by the water agency

- The environmental target $W_f(t) \geq \widetilde{W_f}$ implies that the water table remains above $H_{\min}$ + a term depending on the target

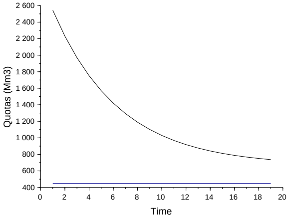
$$H(t) \geq H_W = H_{\min} + \frac{\widetilde{W_f}}{\gamma}$$

- The individual production target $y_i(t) \geq \widetilde{y}$ implies that the water cap remains above a minimum amount of quota (lower bound)
- The groundwater market condition $m^*(t) \geq 0$ implies that the water cap remains below a maximum amount of quota (upper bound)

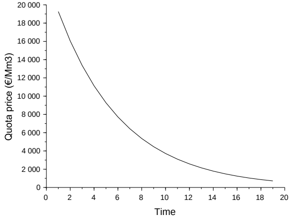
When the environmental target is not binding with $H_{min} = 600$



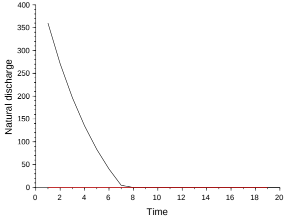
(a) Water table $H(t)$



(b) Quota $Q(t)$



(c) Quota price $m(t)$

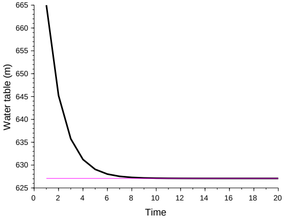


(d) Natural drainage $W_f(t)$

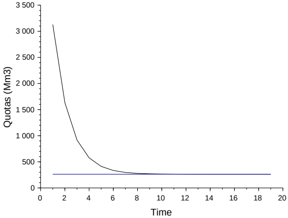
Interpretation

- The water agency implements an excessive water cap
- The water table falls below the critical water table $H_{\min} = 600m$ after 6 years
- Natural drainage is nil and the aquifer is fed by the river creating ecosystem damages
- The quota price decreases because the pumping cost increases and reduces water demand

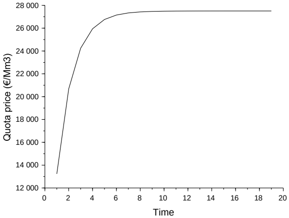
When the environmental target is binding with the target $\widetilde{W_f} = 150 Mm^3$



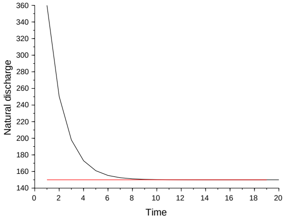
(e) Water table $H(t)$



(f) Quota $Q(t)$



(g) Quota price $m(t)$



(h) Natural drainage $W_f(t)$

Interpretation

- To ensure that natural drainage satisfies the constraint $\widetilde{W_f} = 150Mm^3$, the water table has to remain above $H_W > 627m$ in the long term and during all the trajectory path
- It implies that the water cap has to reduced and equals to $262Mm^3$ at the steady state
- The quota price increases because water demand remains important

Trade-off between the two objectives

$\widetilde{W_f}$	$\widetilde{y_f}^{\max}$	H_W	Q_W
0	3691	$H_{\min} = 600$	$\frac{R}{1-\mu} = 450$
50	3202	609	387
100	2706	618	325
150	2201	627	262
200	1689	636	200
250	1170	645	137
300	643	654	75
$R = 360$	0	$H^{\max} = 665$	0

Conclusion

- Sustainability in terms of constraints to satisfy
  - constraints on environmental flows
  - constraints on agricultural production
- Trade-off in terms of production gain/loss for less/more water for the environment
  - not an unique solution but a corridor of possible trajectories
  - room of negotiation between the water agency, the farmers and the ecosystem

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