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)

⇒ Is it sustainable? from the environmental, economic and social point of view?
Viability approach (Aubin, 1991)

- 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?
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

\[ R \text{ Recharge} \]
\[ (1-\mu)\cdot Q \text{ Pumping} \]

\[ H(t) \text{ Level} \]

\[ W_f = \gamma (H(t) - H_{\text{min}}) \]

Natural Drainage

Viable groundwater management
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 $\gamma > 0$

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

- When $H \geq H_{\text{min}}$ : water flows from the aquifer to the river or ecosystem
- When $H < H_{\text{min}}$ : 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 \( b_1 < b_2 < \ldots < b_n \) 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

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Description</th>
<th>Units</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>AS</td>
<td>aquifer area × storativity</td>
<td>$Mm^3$</td>
<td>126.5</td>
</tr>
<tr>
<td>R</td>
<td>natural recharge</td>
<td>$Mm^3/y$</td>
<td>360</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>slope of the nat. drainage fct</td>
<td>$Mm^3/m$</td>
<td>5.5384</td>
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<tr>
<td>$\mu$</td>
<td>return flow coefficient</td>
<td></td>
<td>0.20</td>
</tr>
<tr>
<td>$H_0 = H_{max}$</td>
<td>initial stock level</td>
<td>m</td>
<td>665</td>
</tr>
<tr>
<td>$H_{min}$</td>
<td>minimum water table level</td>
<td>m</td>
<td>600</td>
</tr>
<tr>
<td>$g$</td>
<td>intercept of the water demand fct</td>
<td>€/$Mm^3$</td>
<td>4400.73</td>
</tr>
<tr>
<td>$k$</td>
<td>slope of the water demand fct</td>
<td>€/$Mm^3$</td>
<td>0.097</td>
</tr>
<tr>
<td>$c_0$</td>
<td>intercept of the pumping cost fct</td>
<td>€/$Mm^3/y$</td>
<td>266000</td>
</tr>
<tr>
<td>$c_1$</td>
<td>slope of the pumping cost fct</td>
<td>€/$Mm^3/m$</td>
<td>400</td>
</tr>
</tbody>
</table>
The objectives of the water agency

- **Environmental objective**
  \[ W_f(t) \geq \tilde{W}_f \]
  \( \tilde{W}_f = \text{target} \)

- **Individual production objective**
  \[ y_i(t) \geq \tilde{y} \]
  \( \tilde{y} = \text{target} \)

JCP Viable groundwater management
The constraints faced by the water agency

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

\[ H(t) \geq H_W = H_{\min} + \frac{\tilde{W}_f}{\gamma} \]

- The individual production target $y_i(t) \geq \tilde{y}$ 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 $H_{\text{min}} = 600$

(a) Water table $H(t)$

(b) Quota $Q(t)$

(c) Quota price $m(t)$

(d) Natural drainage $W_f(t)$
- The water agency implements an excessive water cap
- The water table falls below the critical water table $H_{\text{min}} = 600 \text{ m}$ 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 \( \tilde{W}_f = 150 M m^3 \)

(e) Water table \( H(t) \)

(f) Quota \( Q(t) \)

(g) Quota price \( m(t) \)

(h) Natural drainage \( W_f(t) \)
To ensure that natural drainage satisfies the constraint $\overline{W_f} = 150 \, Mm^3$, the water table has to remain above $H_W > 627 \, m$ in the long term and during all the trajectory path.

It implies that the water cap has to be reduced and equals to $262 \, Mm^3$ at the steady state.

The quota price increases because water demand remains important.
Trade-off between the two objectives

<table>
<thead>
<tr>
<th>$\tilde{W}_f$</th>
<th>$\tilde{y}_f^{\max}$</th>
<th>$H_W$</th>
<th>$Q_W$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>3691</td>
<td>$H_{\min} = 600$</td>
<td>$\frac{R}{1-\mu} = 450$</td>
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<tr>
<td>50</td>
<td>3202</td>
<td>609</td>
<td>387</td>
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<td>645</td>
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<td>654</td>
<td>75</td>
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<tr>
<td>$R = 360$</td>
<td>0</td>
<td>$H^{\max} = 665$</td>
<td>0</td>
</tr>
</tbody>
</table>

JCP  Viable groundwater management
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

Esteban and Dinar (2016). The role of GDE in groundwater management. *Nat. Resour. Model*


