Opportunity cost of environmental flows. Application to the management of the Orb river basin (France) in a global change scenario

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Content

• Introduction
• Case study: the Orb river basin
• Method
• Results and analysis
• Limits and conclusions
Context:

“The challenge for *river scientists* is to help decision makers predict the *consequences of varying degrees of alteration of the flow regime* so that the implication for society are understood; in return, *society must clarify the goals for river management* so that river scientists can determine appropriate flow recommendations.” (Acreman and Dunbar, 2004)
Context:

  
  Overarching goal: “Good status” of all European water bodies

  Programme of Measures (PoM) defined in River Basin Management Plan

  “The economic analysis shall contain enough information in sufficient detail in order to (...) make judgment about the most cost-effective combination of measures in respect of water uses to be included in the program of measures under the Article 11 based on estimates of the potential costs of such measures.” (WFD Annex III, EU, 2000)
Context:

- Environmental in-stream flow requirements:

  "quantity, timing and quality of water flows required to sustain freshwater and estuarine ecosystems and the human livelihood and well-being that depend on these ecosystems" (Brisbane Declaration, 2007)

  More than 200 individual methodologies to estimate environmental flows (Tharme, 2003)
Research gap

* Bridging the gap between the definition of environmental flow requirements and its economic consequences on river basin management

- Specific objectives:
  - To develop a **Least-Cost River Basin Optimization** model (LCRBO) to estimate the cost variation of a PoM under various level of environmental constraints
  - To apply the model in **the Orb river basin** (France)
  - To analyze the impact in terms of **opportunity cost** under a global change scenario
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• Introduction

• Case study: the Orb river basin

• Method

• Results and analysis

• Limits and conclusions
The Orb river basin

- Setting the scene
  - Mediterranean basin (1580 km²)
  - High population growth (+1.4%)
  - Development of irrigated vineyard
  - The Monts d’Orb reservoir (30.6 Mm³)
  - Two inter-basin transfers
  - Risk of not meeting the WFD good status for quantitative unbalance in the future
The Orb river basin

- **Main characteristics:**
  - Annual precipitation: 1000 mm per year (range from 600 to 1600 mm)
  - Annual average natural flow: 850 Mm$^3$

- **Diversity of habitats**
  - upstream/downstream classification
  - three main types of habitats
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General modeling framework

- Urban Water demand Model
  - Urban demand scenarios
    - Environmental Flow requirement
    - Reservoir operation

- Agricultural demand model
  - Agricultural demand scenarios
    - Connectivity matrix
      - Optimization model
        - Optimized PoM

- Hydrological model
  - Hydrological scenarios
    - Urban water saving measures
    - Agricultural water saving measures

- 9 Climate models
  - Climate scenarios

Environmental Flow requirement
Reservoir operation
Optimization model
Optimized PoM
Climate model

- Emission scenario A1B
- “Weather type” downscaling

(Quintana-Seguí, et al. 2009)
Demand models (BRGM, 2012)

- Ad Hoc demand models
- 2030 Evolution scenarios
Hydrological model

- Monthly 2-Parameters model
- GR2M, (Mouelhi, et al., 2006)

Environmental Flow requirement
Reservoir operation
Connectivity matrix
Optimization model
Optimized PoM

Urban Water demand Model
Agricultural demand model
Hydrological model

9 Climate models
14 Climate scenarios
Urban demand scenarios
Agricultural demand scenarios
Hydrological scenarios

Urban Water saving measures
Agricultural Water saving measures
Reservoir operation
Optimization model
Connectivity matrix
Environmental Flow requirement
Measures & Constraints

- Urban and Agricultural water saving measures
- Reservoir management constraint (Flood,...)

Urban Water demand Model
Agricultural demand model
Hydrological model

Environmental Flow requirement
Connectivity matrix
Optimization model
Optimized PoM

Measures & Constraints

- Urban and Agricultural water saving measures
- Reservoir management constraint (Flood,...)

Environmental Flow requirement
Connectivity matrix
Optimization model
Optimized PoM

(Adapted from BRLi, 2011)
Environmental flow requirements

- In-stream minimum flow threshold (current approach)
  - Definition based on habitat and hydraulic methods (Ginger, 2011)
  - 3 levels of minimum flow defined as single value at each node of the model

![Threshold Levels Diagram]

- Critical
- Perturbated
- Satisfactory
- Confortable

<table>
<thead>
<tr>
<th>Threshold Level</th>
<th>Average Value (% Monthly Flow)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower</td>
<td>8%</td>
</tr>
<tr>
<td>Intermediary</td>
<td>12%</td>
</tr>
<tr>
<td>Higher</td>
<td>15%</td>
</tr>
</tbody>
</table>

(Adapted from Ginger, 2008)
Environmental flow requirements

- The eco-deficit approach (new approach)
  - The paradigm of the natural flow regime (Poff, et al., 1997)
  - Eco-deficit: the difference between the flow duration curves (FDC) of the natural flow regime and the modified one (Vogel, et al., 2007; Riegels, et al., 2010)
  - Applied in the optimization level as a constraint with a given level of reliability
General modeling framework

9 Climate models

- Climate scenarios

Urban Water demand Model

- Urban demand scenarios

Environmental Flow requirement

Agricultural demand model

- Agricultural demand scenarios

Optimization model

- Connectivity matrix

- Reservoir operation

- Optimization PoM

Hydrological model

- Hydrological scenarios

- Urban water saving measures

- Agricultural water saving measures
River basin optimization model

• Modeling software:
  ▪ GAMS General Algebraic Modeling System (Rosenthal, 2008)
  ▪ Linear and Mixed Integer Programming (Cplex solver)

• Conceptual model:
River basin optimization model

1st option: Existing practices (M1)

• Objective Function: Minimize the total cost of the PoM

\[
\text{Cost PoM} = \sum \text{Act} \times \text{Measure Cost} + \sum \text{EnvDefict} \times 10^{12}
\]

• Constraints on

  ▪ Demand delivery

\[
\text{Qsupplied} = \sum \text{UrbanDemand} - \sum \text{UrbanWaterSavings} \times \text{Act} + \sum \text{AgriDemand} - \sum \text{AgriWaterSavings} \times \text{Act}
\]

  ▪ Environmental flow

\[
\text{EnvDeficit} = \text{Qriver} - \text{Min Flow Requirement}
\]
River basin optimization model

2\textsuperscript{nd} option: introducing the Ecodeficit (M2)

- Constraints on:
  - Ecodeficit
    
    \[
    \text{EcoDeficit} = Q_{\text{river}} - \text{Natural Flow}
    \]
  - Calculation of environmental failures
    
    \[
    \text{EnvFailure} = 1 \text{ if } \left| \text{EcoDeficit} \right| \geq \text{FailureThreshold} \times \text{NaturalFlow}
    \]
    
    \[
    \text{MonthlyEnvReliability} = 1 - \left( \sum \text{EnvFailure} \right) / \text{Number of Months}
    \]
  - Constraint on the Environmental reliability
    
    \[
    \text{MonthlyEnvReliability} \geq \text{ReliabilityThreshold}
    \]
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M1: Single value in-stream flow threshold

- Comparison between three levels of minimum flow constraints

Total cost of the programme of measures to meet the 3 levels of environmental constraint
M1: Single value in-stream flow threshold

- Marginal cost of the flow constraints

<table>
<thead>
<tr>
<th>Node</th>
<th>Max Marginal cost (€/Mm³/Month)</th>
<th>Max Marginal cost (€/m³)</th>
<th>Intermediary Flow Constraint (Mm³/Month)</th>
</tr>
</thead>
<tbody>
<tr>
<td>O1</td>
<td>281 788 €</td>
<td>0.282 €</td>
<td>1.374</td>
</tr>
<tr>
<td>O4</td>
<td>288 697 €</td>
<td>0.289 €</td>
<td>3.370</td>
</tr>
<tr>
<td>O12</td>
<td>286 740 €</td>
<td>0.287 €</td>
<td>3.629</td>
</tr>
</tbody>
</table>

Distribution of the marginal cost of the PoM by sub basins
M1: Single value in-stream flow threshold

- Marginal cost of the flow constraints

![Marginal cost at the reservoir node and reservoir volume](chart.png)
M2: Introducing the Ecodeficit

• By setting a reliability constraint on the Ecodeficit
  • Improvement of the flow regime downstream of the reservoir
  • Tradeoffs between environmental and agricultural reliability

• Total Annual Equivalent Cost: 1,500,000 €
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Conclusions

• Main contributions
  
  • Development of a Least Cost River Basin Optimization Model to assess the cost of opportunity of environmental flows
  
  • Application in real case study the Orb river basin (France)
  
  • Interpretation of the opportunity cost of various level of environmental flows in a global change scenario

• General conclusion
  
  LCRBO modeling is an approach that gives some elements to bridge the gap between environmental and economic objectives of the Water Framework Directive
Main limitations:

• Data availability and assumptions
• Perfect foresight of optimization
• Perfect cooperation assumed by the optimal solution
• Environmental flow definition
• No assessment of water quality issues
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Thank you!

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References


