Cooperative arrangements for water sharing and ecosystem protection under scarcity and drought:
Application to the Jucar Basin, Spain

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Motivation

- **River flows and aquatic ecosystems face increased scarcity.**
  - **Future climate change impacts would further exacerbate water scarcity.**
  - **Demands for environmental protection further increase competition.**
- **The existing literature <u>overlooks the strategic behavior of the stakeholders</u>**
- **This paper includes ecosystem benefits in the river sharing problem and incorporates the strategic behavior of the agents.**

Analytical Methodology

1. **An integrated hydro-economic model (3 components):**
   - **a reduced form hydrological model (RFHM),**
   - **a regional economic model, and**
   - **an environmental benefit model.**
2. **The linkage between the three components allows a rigorous quantitative impact assessment of drought on water availability in the river basin under study**
   - **the effects on the users' decisions**
     - **allocation among sectors,**
     - **spatial distribution by location**
     - **use of surface and groundwater, and**
     - **land use decisions by selecting the cropping patterns.**
   - **private and social economic benefits and costs of water use.**
3. **Cooperative game theory framework to analyze various coalitional arrangements among the basin riparians.**

Model Components (A)

The mathematical formulation of the RFHM is as follows:

- $Wout_d = Win_d - Wloss_d - Div_d^{IR} - Div_d^{URB}$ [1]
- $Win_{d+1} = Wout_d + r_d^{IR} \cdot (Div_d^{IR}) + r_d^{URB} \cdot (Div_d^{URB}) + RO_{d+1}$ [2]
- $Wout_d \geq E_d^{min}$ [3]

The optimization problem of the irrigation district is given by:

- $Max\ B_k^{IR} = \sum_{ij} C'_{ijk} \cdot X_{ijk}$ [4]
- subject to $\sum_i X_{ijk} \leq Tland_{kj}\ ;\ j = flood, sprinkler, drip$ [5]
- $\sum_{ij} W_{ijk} \cdot X_{ijk} \leq Twater_k$ [6]
- $\sum_{ij} L_{ijk} \cdot X_{ijk} \leq Tlabor_k$ [7]
- $X_{ijk} = \sum_n \alpha_n \cdot X_{ijkn}\ ;\ \sum_n \alpha_n = 1\ ;\ \alpha_n \geq 0$ [8]
- $X_{ijk} \geq 0$ [9]

Model Components (B)

The urban maximization problem is given by:

- $$Max\ B_u^{URB} = \left(a_{du} \cdot Q_{du} - \frac{1}{2} \cdot b_{du} \cdot Q_{du}^2 - a_{su} \cdot Q_{su} - \frac{1}{2} \cdot b_{su} \cdot Q_{su}^2\right)$$ [10]
- subject to $$Q_{du} - Q_{su} \leq 0$$ [11]
- $$Q_{du}\ ;\ Q_{su} \geq 0$$ [12]

The Albufera function is given by:

- $$E_{Albufera} = \alpha \cdot r_{ARJ}^{IR} \cdot \left(Div_{ARJ}^{IR}\right) + \beta \cdot r_{RB}^{IR} \cdot \left(Div_{RB}^{IR}\right)$$ [13]
- $$B_{Albufera} = \begin{cases} \delta_1 & if\ 0 \leq E_{Albufera} \leq E_1 \\ \delta_2 + \rho_2 \cdot E_{Albufera} & if\ \ E_1 < E_{Albufera} \leq E_2 \\ \delta_3 + \rho_3 \cdot E_{Albufera} & if\ \ E_2 < E_{Albufera} \leq E_3 \end{cases}$$ [14]

Model components C

The basin optimization model

$$Max\left(\sum_{k} B_{k}^{IR} + \sum_{u} B_{u}^{URB} + B_{Albufera}\right)$$

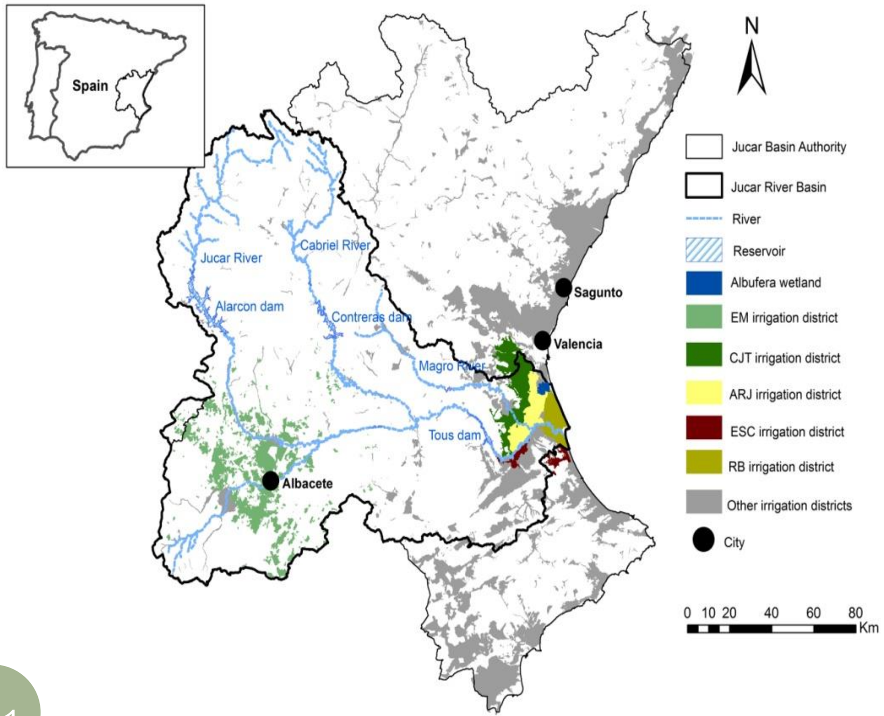
Subject to: (1)-(3); (5)-(9); (11)-(13)

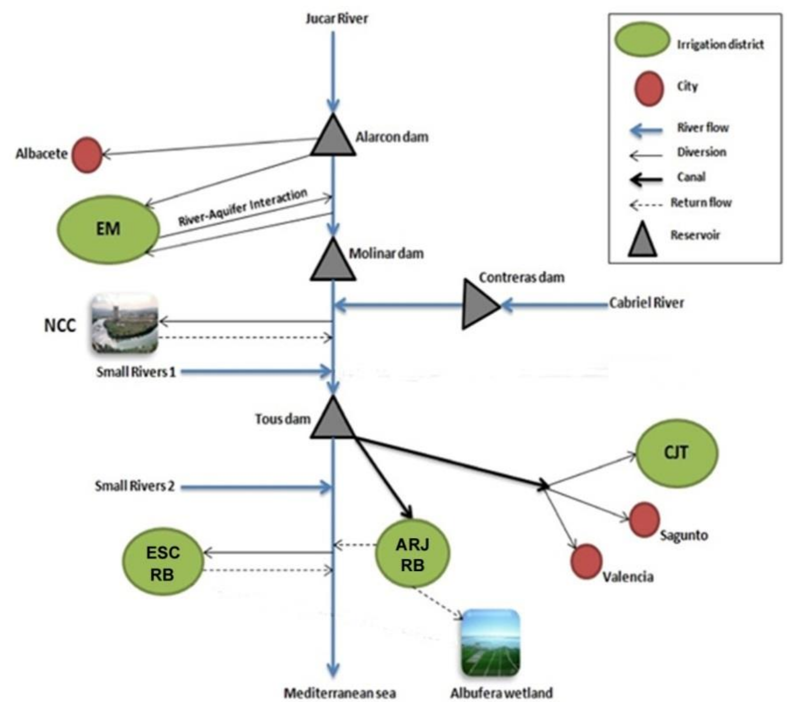
Cooperative Game Theory Framework

- Find an allocation of water/income for all basin sectors (players) that will be acceptable to each of the players
  - Shapley, Nash-Harsanyi, Nucleolus
  - Fulfills Core requirements
    - Individual rationality
    - Group rationality
    - Efficiency
  - Fulfills stability requirements
    1. Loehman Power Index
    2. Stability= CV of the power indexes of the different players

Study area: The Jucar River Basin (JRB)

The JRB is located in the regions of Valencia and Castilla La Mancha in Southeastern Spain. Consists of 2 main tributaries (Magro and Cabriel Rivers), reservoirs (Alarcon, Contreras, Tous), cities (Valencia, Sagunto, Albacete), irrigation districts (EM, CJT, ARJ, ESC, RB), and ecosystem (the Albufera wetland).





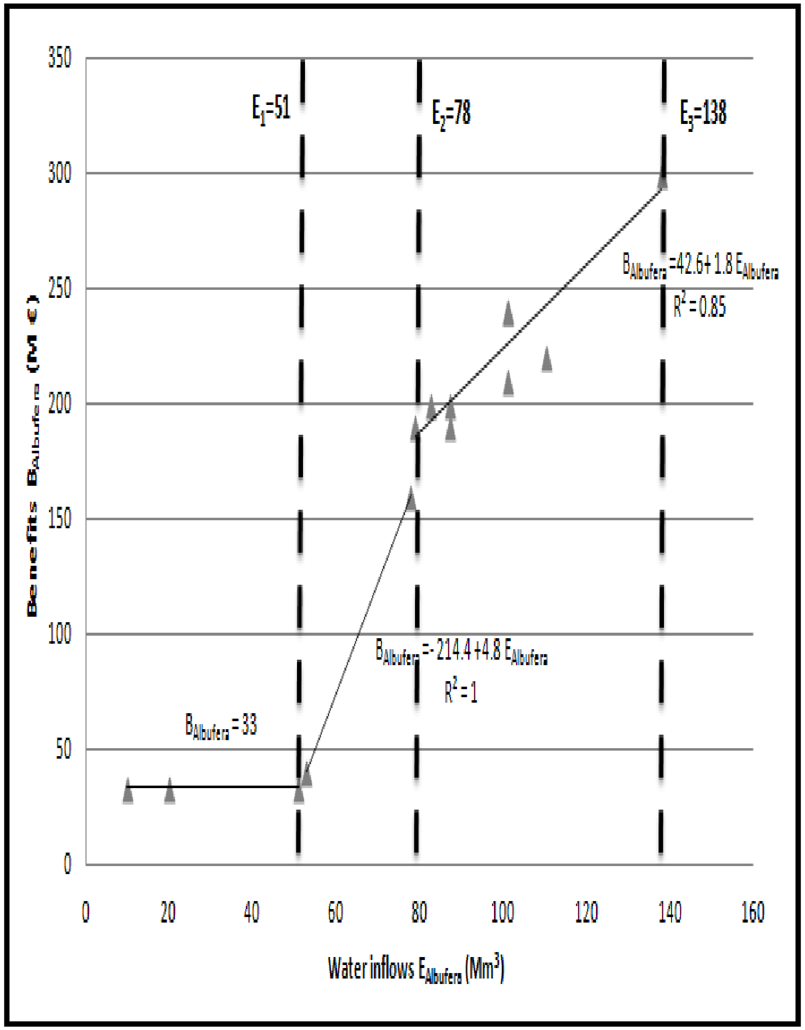
Calibration of the RFHM

The reduced form hydrological model (equations (1)-(3)) is a node-link network, with flows routed between nodes based on the principles of water mass balance and continuity of river flow.

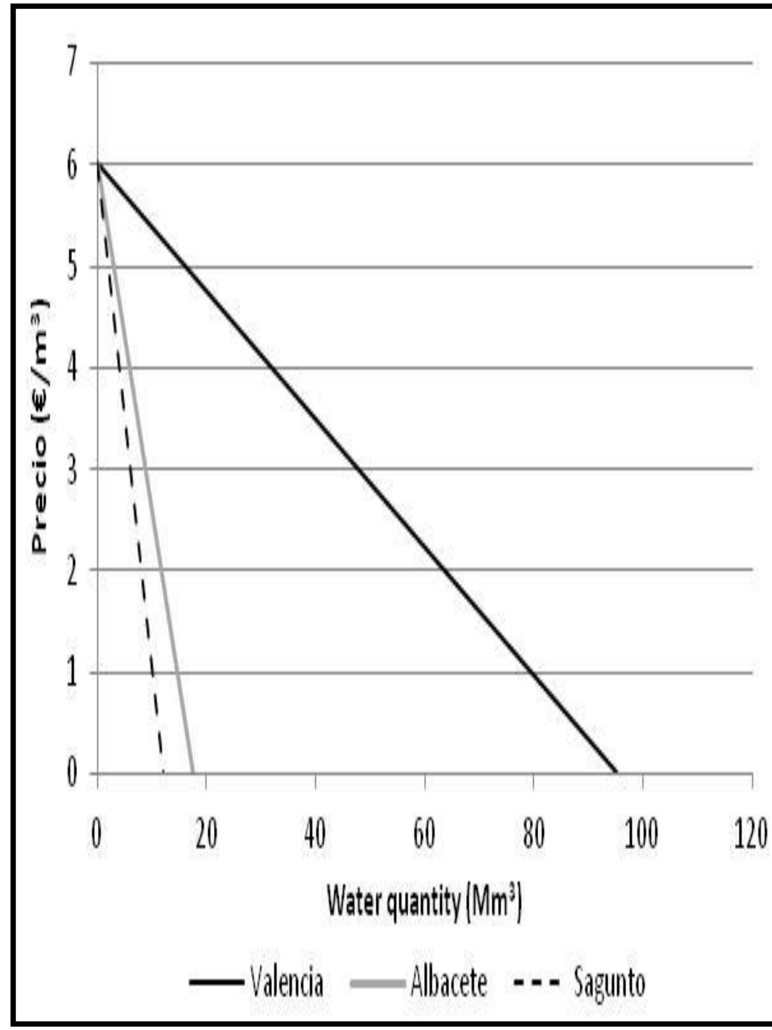
Demand nodes	Normal flow year		2006 MD (-22%)		2007 SD (-44%)		2008 VSD (-66%)		Statistical measures	
	Sim	Ob	Sim	Ob	Sim	Ob	Sim	Ob	R^2	NSE
Albacete	17	17	8	8	11	11	9	10	0.99	0.98
EM	13	13	0	0.2	4	5	1	0	0.99	0.98
NCC	14	14	14	14	14	14	14	14	-	1
Valencia	94	95	41	42	59	47	56	66	0.86	0.86
Sagunto	8	8	3	4	5	5	5	4	0.84	0.81
CJT	64	70	6	7	9	14	7	5	0.99	0.98
ARJ	200	213	92	120	129	100	123	110	0.76	0.76
ESC	33	38	10	20	18	10	17	10	0.55	0.54
RB	243	254	87	110	136	110	126	120	0.91	0.91
Albufera	51	55	21	27	30	24	29	26	0.85	0.85
Total	738	777	282	352	415	340	387	365	0.91	0.91

- **<u>The economic component:</u>** allows simulating the benefits of economic activities in each demand node:
  - **<u>irrigation districts</u>:** a farm-level mathematical programming model is developed for each district **(equations (4)-(9))** .
  - **<u>Urban demand nodes</u>:** a social surplus model is developed for each urban demand node **(equations (10)-(12))**.
- **<u>The environmental component:</u>** allows estimating the benefits provided by the Albufera wetland to society **(equations (13)-(14))**.
  - **<u>The environmental benefits</u> have been estimated using various ecosystem health indicators and environmental valuation studies.**
  - **<u>The environmental benefit function</u> is a piecewise linear function of water inflows to the wetland.**

Environmental benefit function of the Albufera wetland



Inverse Urban Demand Functions



Source. Collazos (2004)

The game conditions

1. **Cooperative management of water, using the concept of flexible water allocation rule [*Kilgour and Dinar (2001)*]*.***
2. **The users are grouped into four groups of players: INE(3), IE(2), C(3), E(1).**
3. **Status quo (non-cooperation): players have predetermined administrative water allocations depending on the climate condition.**
4. **Under cooperation: Players in need for water can compensate other players for using less water (Not exactly water Market-mimicking present institutions).**
   1. **Non-regulated cooperation.**
   2. **Regulated cooperation.**

2 cooperative scenarios

- **Scenario 1: Non-regulated cooperation without environmental damages internalization**
  - Allows the cooperation among players to share water resources with transfer payments. Under this scenario, player E (the Albufera-passive player) receives water from the return flows of player IE
- **Scenario 2: Regulated Cooperation with environmental damages internalization**
  - intervention by the basin authority to protect the Albufera and to internalize environmental damages. This scenario introduces a new variable in the model, which is the direct diversion of water to the Albufera.
  - The mechanism for water diversions to the Albufera is that the basin authority pays players to reduce their water use in order to feed the wetland (Water Bank)

Results of non-cooperative water management

- **Drought events in the Jucar River Basin under the current institutional setting (administrative water allocation) may reduce social welfare between 63 and 138 million € (11 to 25%)**
- **These negative impacts affect all water users in the basin. The impacts are especially strong for irrigated agriculture (10 to 30 % of benefit losses) and the environment (above 50 % of benefit losses)**

Results of cooperative water management

In parenthesis are incremental cooperation gains compared with non-cooperation

Results of cooperative Vs. non-cooperative water management without environmental damages internalization (10^6 €) (Scenario 1)

Coalitional arrangements	Players	Normal flow	Mild drought	Severe drought	Very severe drought
Non-cooperation	{INE}	132.0	119.2	109.3	100.5
	{IE}	58.3	51.7	43.5	35.0
	{C}	282.6	277.0	267.6	242.3
	{E}	74.7	37.2	33.0	33.0
	Total	547.7	485.1	453.4	410.9
Full cooperation	{INE,IE,C,E}	582.4 (6%)	517.8 (7%)	474.5 (5%)	427.3 (4%)

Results of cooperative Vs. non-cooperative water management with environmental damages internalization (10^6 €) (Scenario 2)

Coalitional arrangements	Players	Normal	Mild drought	Severe drought	Very severe drought
Non-cooperation	{INE}	132.0	119.2	109.3	100.5
	{IE}	58.3	51.7	43.5	35.0
	{C}	282.6	277.0	267.6	242.3
	{E}	74.7	37.2	33.0	33.0
	Total	547.7	485.1	453.4	410.9
Full cooperation	{INE,IE,C,E}	742.3 (36%)	735.0 (52%)	710.1 (57%)	659.6 (61%)

- Results indicate that cooperation in the JRB to share water resources is always better than non-cooperation.
- When environmental damages are internalized through the direct diversion of water to the Albufera wetland the cooperative results are more appealing.
- The values of the characteristic functions under the two scenarios of cooperation show superadditivity. This property is important because it indicates that the players have an incentive to cooperate. However, it does not guarantee the stability of cooperation nor the equity. There is a need for reallocation of incremental benefits using the CGT allocation schemes.

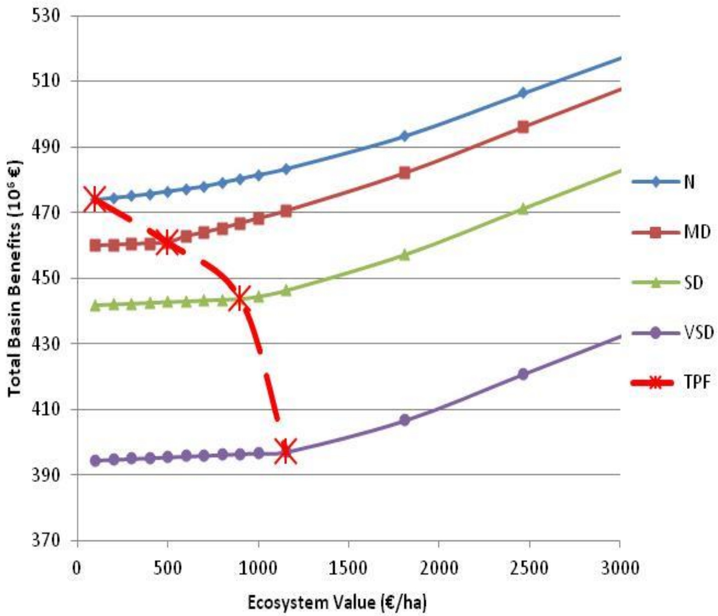
Power and stability indexes in scenario 2

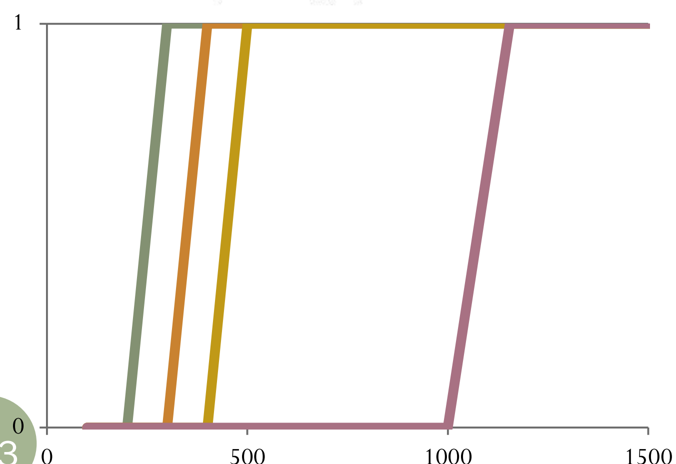
Scenario 1 are not in the Core: Not acceptable by the players.

Stability increases as drought intensifies

Cooperative solution	Power indexes of players (θ_i^a)				Stability index $\overline{\theta_a}$
	INE	IE	C	E	
Normal Flow					
Shapley	0.43	0.05	0.00	0.52	1.05
Nash-Harsanyi	0.25	0.25	0.25	0.25	0.00
Nucleolus	0.00	0.00	0.00	1.00	1.99
Mild drought					
Shapley	0.36	0.13	0.03	0.48	0.83
Nash-Harsanyi	0.25	0.25	0.25	0.25	0.00
Nucleolus	0.69	0.17	0.02	0.13	1.20
Severe drought					
Shapley	0.30	0.20	0.14	0.36	0.39
Nash-Harsanyi	0.25	0.25	0.25	0.25	0.00
Nucleolus	0.48	0.17	0.17	0.17	0.61
Very severe drought					
Shapley	0.22	0.32	0.17	0.30	0.27
Nash-Harsanyi	0.25	0.25	0.25	0.25	0.00
Nucleolus	0.25	0.25	0.25	0.25	0.00

Tipping point (between Scenario1 and 3 is moving to higher values as drought severity intensifies





The value of the Albufera and the climate condition affect the policy decision concerning the protection of the wetland.

<u>Under a normal flow scenario</u>, farmers are willing to sell water to the basin authority to feed the wetland and the social welfare is higher under Scenario 2 compared to Scenario 1 when the value of the wetland is higher than 200 euro/ha. <u>If the value of the Albufera is lower than or equal to 200 euro/ha then social welfare is higher under Scenario 1 and there is no need to provide the Albufera with water coming from the irrigation districts.</u>

<u>When drought severity intensifies</u>, the value of water to irrigation districts (the shadow price) increases and then farmers would sell water to the basin authority to feed the Albufera if the Albufera has a high enough economic value to compensate what they would loose from giving up part of their irrigation activities.

Conclusion

- **Difficulties to achieve a stable water sharing agreement among private decision-makers in the JRB.**
- **Any cooperative agreement to share water resources among private decision-makers may improve the economic benefits of water users but it may have little effect on ecosystems protection without additional incentives or regulations.**
- **A cooperative sharing agreement that includes the internalization of environmental damages such as scenario 2 could have beneficial effects on both private water users and ecosystems (public good).**
- **The internalization of environmental damages seems to increase stability to water sharing agreements , depending on the value of ecosystem under study.**