Can hydro-economic river basin models simulate water shadow prices under asymmetric access?

Arnim Kuhn & Wolfgang Britz
Institute for Food and Resource Economics, University Bonn
DFG Forschergruppe 1501

Background

Our background:

- Hydro-economic river basin modelling in the Draa Valley, Morocco (GLOWA-IMPETUS) 2005-2009
- Since 2010: Model development for the Naivasha Catchment, Kenya (DFG Research Unit 1501 ‘Resilience, Collapse, Reorganisation’)
- Central question: how to simulate institutional problems arising in upstream-downstream settings
  (=> unregulated, asymmetric access to water)

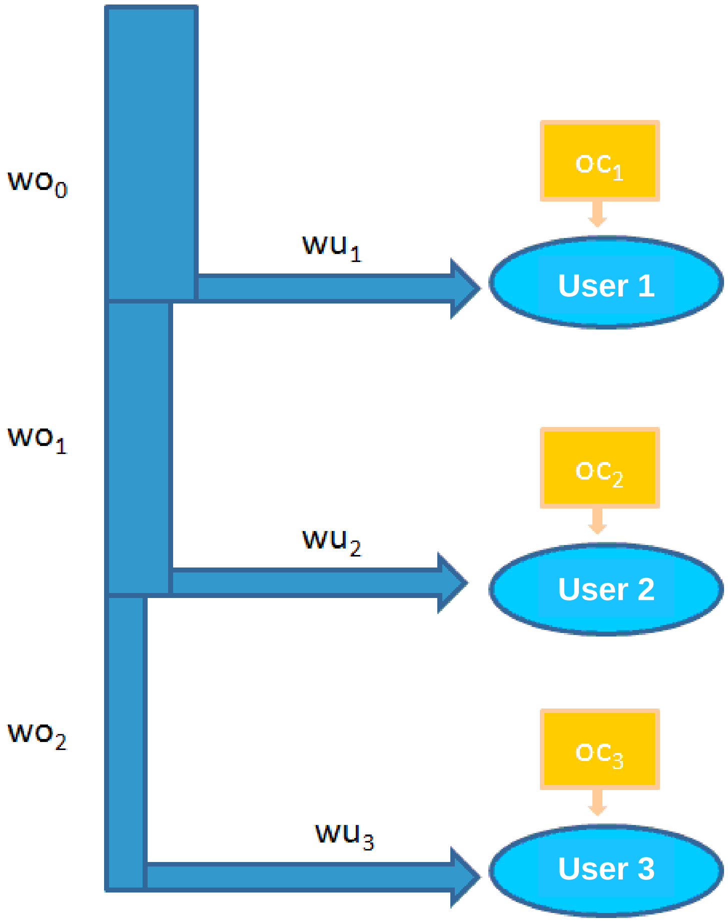
- **Hydro-Economic River Basin Model**s (HERBM) typically solved as **aggregate constrained optimization** problems:
  - Constraints describe both technology and hydrology explicitly and in rich detail
  - Objective function optimizes **aggregate social welfare criterion,** e.g. sum over profits of **all water users** in a basin

Problem setting

Key arguments

- HERBMs based on math. programming currently use an **aggregate optimization** (AO) format implemented (e.g.) as LP or NLP
- The optimization format of a HERBM **carries strong institutional assumptions**
- Thus, AO format that leads to **unrealistic simulation outcomes** as it presupposes either central planning or perfectly functioning water markets!
- For unregulated water use, an **individual optimization** (IO) format is more appropriate
- HERBMs in IO format can be implemented as **Mixed Complementary Problems** (MCP)

Problem setting



Independent, profit maximizing water users *i*, located in a river basin:

- Outflow at its node wo_i and water use wu_i are equal to inflow wo_{i-1}
- Users maximize profit π equal to revenues (quantities produced q times given price p) minus given variable cost per unit vc
- Each user has a certain operation capacity oc (= maximal output quantity)
- One unit of output requires one unit of water

Only didactic model to highlight the solution strategy

Aggregate optimization and its FOCs

$$\max_{q_i, wo_i} \pi = \sum_i q_i \overline{p} - q_i \overline{vc_i}$$

$$s.t. \quad q_i \le \overline{oc_i} \left[\lambda_i\right]$$

$$q_i = wu_i$$

$$wo_{i-1} = wu_i + wo_i \left[\mu_i\right]$$

$$q_i \ge 0, wo_i \ge 0, wu_i \ge 0$$

FOCs =>

$$\overline{vc_i} + \lambda_i + \mu_i \ge \overline{p} \perp q_i \ge 0$$

$$\overline{oc_i} \ge q_i \perp \lambda_i \ge 0$$

$$wu_i \ge q_i \perp wu_i \ge 0$$

$$wo_{i-1} = wo_i + wu_i \perp \mu_i$$

$$\mu_i \ge \mu_{i+1} \perp wo_i \ge 0$$

Upstream user releases water at his node when his water shadow price equals that of his downstream neighbor

The “**aggregate optimization (AO)**” solution (maximizing sum of profits) implies **equal marginal return to water** of all water users

Individual optimization and its FOCs

But why should an independent user use less water to increase profits of its downstream neighbor? - Each user maximizes only his own profits:

$$\max_{q_i, wo_i} \pi_i = q_i \overline{p} - q_i \overline{vc_i}$$

$$\begin{aligned} s.t. \quad & q_i \leq \overline{oc_i} \; [\lambda_i] \\ & q_i = wu_i \\ & wo_{i-1} = wu_i + wo_i \; [\mu_i] \\ & q_i \geq 0, wo_i \geq 0, wu_i \geq 0 \end{aligned}$$

(as before)

FOCs =>

$$\begin{aligned} & \overline{vc_i} + \lambda_i + \mu_i \geq \overline{p} \perp q_i \geq 0 \\ & \overline{oc_i} \geq q_i \perp \lambda_i \geq 0 \\ & wu_i \geq q_i \perp wu_i \geq 0 \\ & wo_{i-1} = wo_i + wu_i \perp \mu_i \end{aligned}$$

(as before)

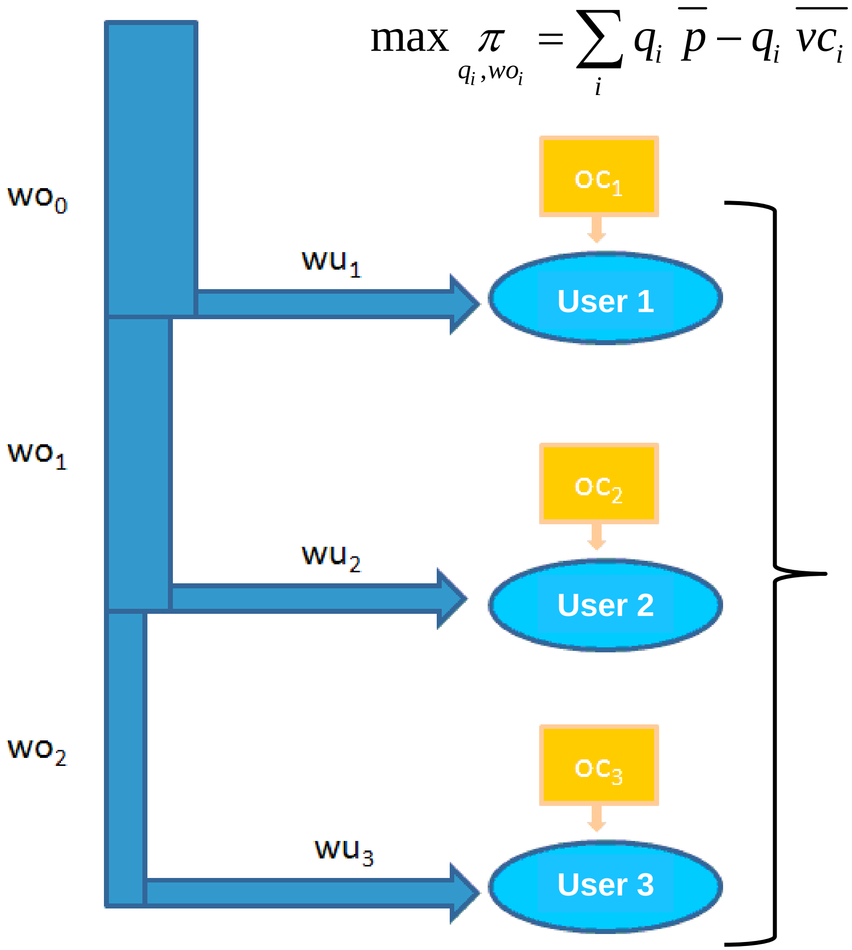
$$\mu_i \geq 0 \perp wo_i \geq 0$$

A user only releases water at its node
if economic returns to additional water are zero

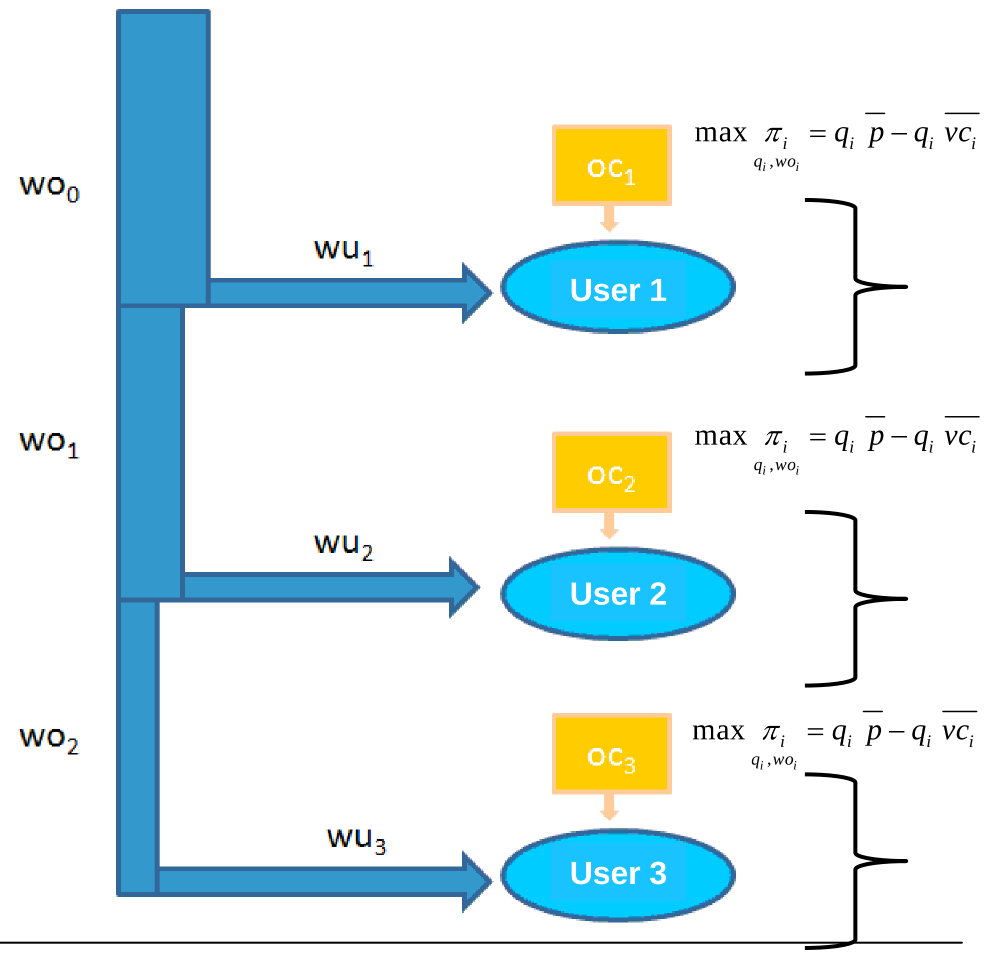
The “**individual optimization (IO)**” solution (maximizing profits independently) **does not impose equal shadow prices of water**

Aggregate versus individual optimization

Aggregate optimization



Individual optimization



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Implementation in algebraic modelling

- Problem: IO requires handling multiple objective functions!
  - This is not possible in a classical LP or NLP format
  - A different problem format has to be used!

- Use the Mixed Complementary Problem (MCP) format:
  - Stack FOCs from IO of all users in the basin
  - Link users through equations describing hydrological relations
  - Cut the shadow price relation between users
  - This resembles **simultaneous agent based modeling** reflecting spatial externalities

Didactic application

- A **simple numerical case** with **three users**:
  - identical operation capacities *oc*=50, price *p*=100
  - Basin inflow 120 < operation capacity of industry (3x50=150)
  - variable costs *vc* [60,50,40], i.e. downstream users more efficient
- We analyze **four water management institutions**:
  - **No management** (each firm might use all the water at its node)
  - Water **pricing**, water price = 39
  - **Non-tradable water rights** of 45 units per user
  - **Tradable water rights** (45 units assigned, 1 unit transaction costs)

  (details on the KKTs for the four institutions in paper)
- **Comparing** outcomes (shadow prices, water use, profits ..)
  - using the conventional **AO** solution
  - with the newly proposed **IO** solution strategy

=> GAMS, ‚PATH' solver

Results for didactic 3 user case

		No management		Water pricing		Non-tradable rights		Tradable rights	
		IO	AO	IO	AO	IO	AO	IO	AO
Water use *wu*	User 1	50	20	50	20	45	30	20	20
	User 2	50	50	50	50	45	45	50	50
	User 3	20	50	20	50	30	45	50	50
Outflow to next user *wo*	User 1	70	100	70	100	75	90	100	100
	User 2	20	50	20	50	30	45	50	50
	User 3	-	-	-	-	-	-	-	-
Water rights (when tradable, after trade) *wr*	User 1	-	-	-	-	45	45	20	35
	User 2	-	-	-	-	45	45	50	50
	User 3	-	-	-	-	45	45	65	50
Shadow prices μ for water use *wu*	User 1	-	40	-	1	-	40	-	40
	User 2	-	40	-	1	-	40	-	40
	User 3	60	40	21	1	60	40	41	40
Profits of users	User 1	2000	800	50	20	1800	1200	1800	1200
	User 2	2500	2500	550	550	2250	2250	2295	2295
	User 3	1200	3000	420	1050	1800	2700	2180	2795
Total profits		5700	6300	1020	1620	5850	6150	6275	6290
Water pricing revenues		-	-	4680	4680	-	-	-	-
Total profits plus revenues		5700	6300	5700	6300	5850	6150	6275	6290

AO gives unrealistic results:

Upstream users reduce water use to increase profits of downstream neighbors

Local water shadow prices biased

Profit distribution and total profits biased (even for tradable rights)

Conclusions

- **Aggregate optimzation …**
  - leads to **biased results** when agents take individual optimal decision and have asymmetric access to resources
  - Implies non-existent institutional structure …
  - … and therefore gets the **reference situation** wrong!
- **Individual optimization using MCP** allows in an elegant way …
  - **Simultaneous solution** for many water users (agents)
  - Keeping the correct **individual optimization logic …**
  - … while still observing **hydrological relations** between water users
  - Starts with the **appropriate reference situation** for policy and institutional analysis