Cooperation and equity in resource sharing: The river sharing problem

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Set up

- River shared by n agents (e.g. countries, farmers)
- Each agent i enjoys a concave and single-peak benefit b_i from consuming water
- Transferable utility (transfers)
- Non-cooperative extraction inefficient
- Efficiency requires cooperation and compensations through side payments (e.g. water sharing agreements)

$\Rightarrow$ Which transfers? Which distribution of welfare?

Acceptable and fair way to share the benefit of water extraction
Sustainability in case of drought

Real world river sharing problem

- International rivers
  - International agreements (Columbia river, Syr Darya, Nile river, Mekong, Interstate water compacts,...)
  - International organizations for river management
  - International principles: absolute territorial integrity, unlimited territorial sovereignty,...
- Irrigation
  - Water rights (e.g. prior appropriation)
  - Water pricing and subsidies
  - Waters markets

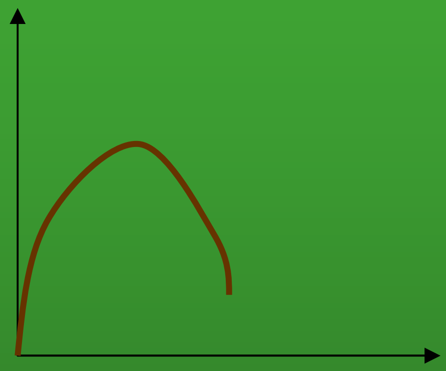
Model

- Agents $i \in N = \{1, ..., n\}$
- e_i: water flow controlled by i
- two goods: water x_i and money t_i
- i's utility with (x_i, t_i): $b_i(x_i) + t_i$ with $b_i > 0$ and up to a satiate level $\hat{x}_i$ and $b_i' < 0$.
- $e_i \leq \hat{x}_i$ without loss of generality
- Agents agree on an allocation or Water Sharing Agreement (WSA) $(x, t) = \{(x_i, t_i)\}_{i \in N}$
- (N, b, e) defines a river sharing problem

THE MODEL

production

$b_i\,(x_i)$



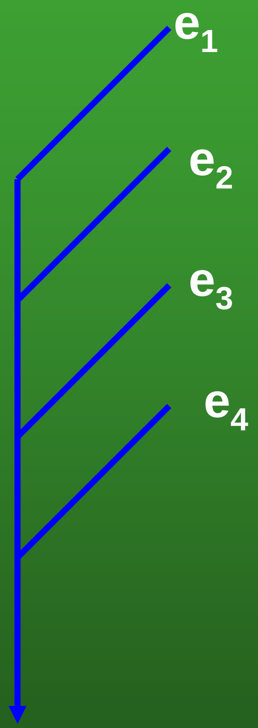
water x_i

Agents 1

2

3

4



Agent i's utility:

$b_i(x_i)+t_i$

Efficient allocation of water

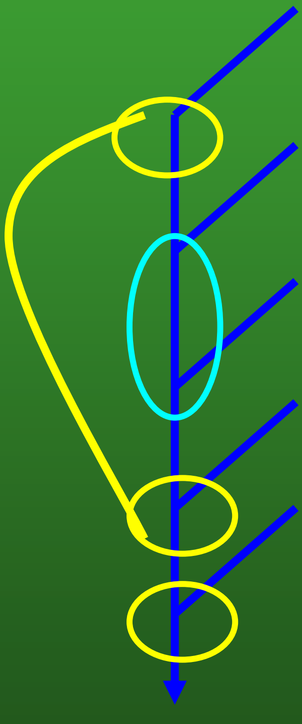
- x^* maximizes the sum of benefit subject to the feasibility constraints
- x^* defines partition of N into successive subsets N_k with
  - Equalization of marginal benefits within N_k
  - Members of N_k share the water they control
  - Lower marginal benefit moving from N_k to N_{k+1}.

Value of a coalition

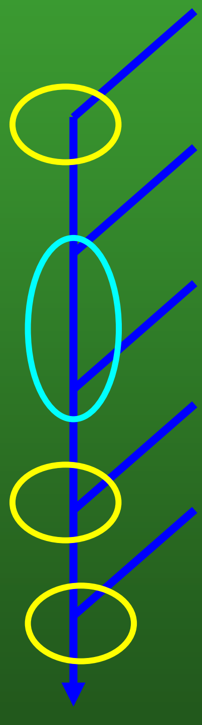
- An agent or a coalition of agents accepts $t = (t_1, \dots, t_n)$ if it obtains at least what it could obtain by itself
- The value v of a coalition S depends on the behavior of those outside S
- Game with *externalities*
- A partition $\mathcal{P}$ defines a non-cooperative sequential game among coalitions in $\mathcal{P}$ in a river sharing problem (N, b, e)
- $v(S, \mathcal{P})$ payoff of coalition S in this game

VALUE OF A COALITION

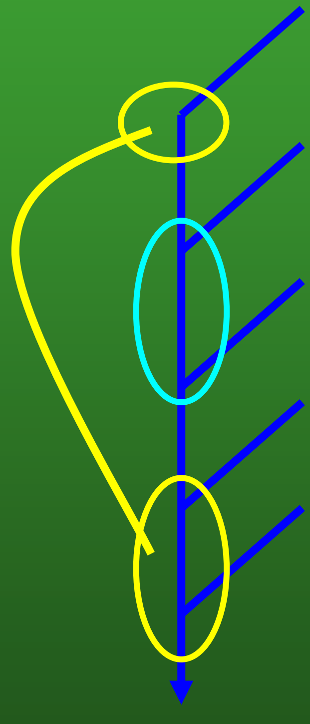
a partition



non-cooperative



cooperative



A game with externalities

- $\underline{v}(S) = v(S, \{S\} \cup \{\{i\} | i \in N \backslash S\})$
- $\overline{v}(S) = v(S, \{S, N \backslash S\})$
- $\underline{v}(S) \leq v(S, \mathcal{P})$
- $\underline{v}(S) \leq \overline{v}(S)$
- For any two disjoint coalitions $S, T \in \mathcal{P}$, $v(S, \mathcal{P}) + v(T, \mathcal{P}) \leq v(S \cup T, \mathcal{P}')$
- Might have $\overline{v}(S) < v(S, \mathcal{P})$

Core lower bounds

- Non-cooperative core lower bounds (γ-core)

$$\sum_{i \in S} (b_i(x_i^*) + t_i) \geq \underline{v}(S)$$

- Cooperative core lower bounds (δ-core)

$$\sum_{i \in S} (b_i(x_i^*) + t_i) \geq \bar{v}(S)$$

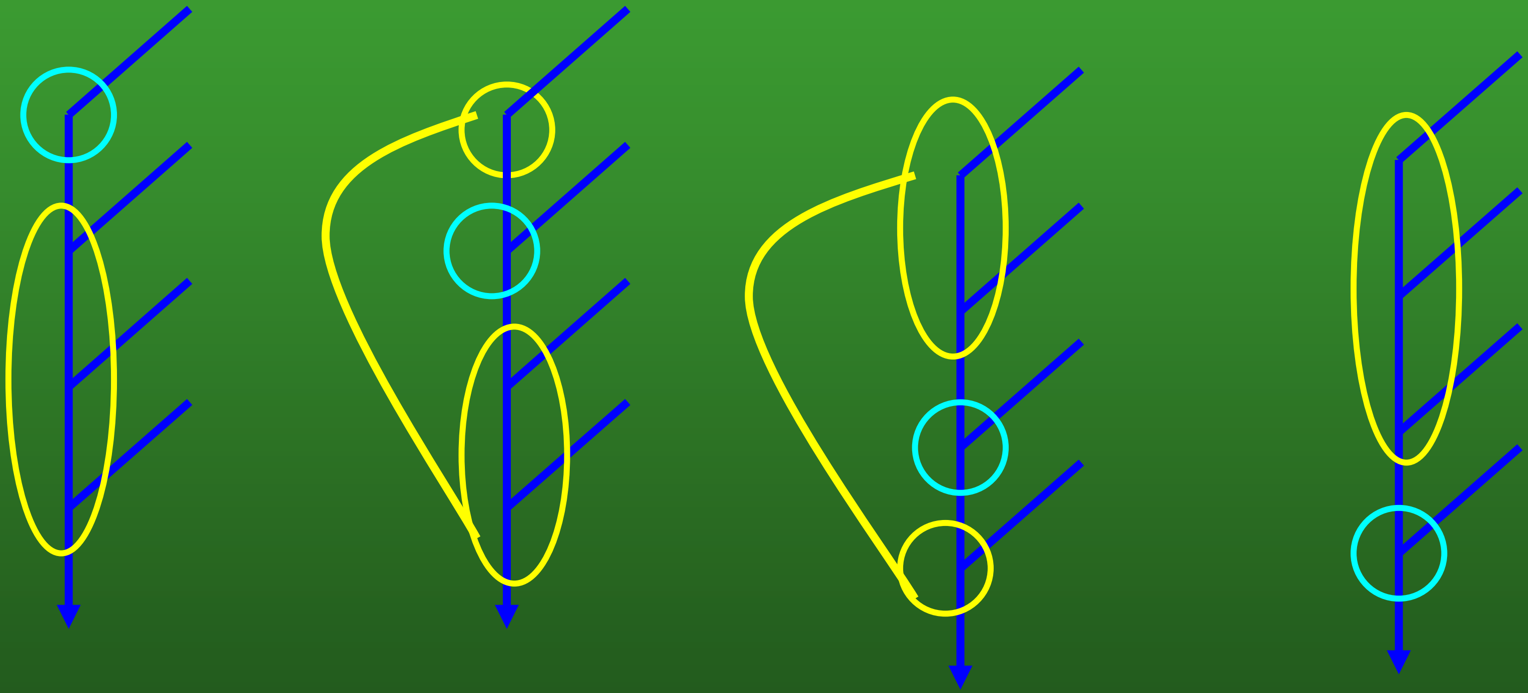
- Interpretation of absolute territorial integrity for international rivers

Results

- t satisfying the non-cooperative core lower bound always exists
- t satisfying the cooperative core lower bound always exists for $n = 3$ but might not exists for $n > 3$
  - Example of empty cooperative core with $n = 4$

EXAMPLE WITH FOUR PLAYERS

$v(1)=b_1(e_1)$ $v(2)=b_2(\hat{x}_2)$ $v(3)=b_3(\hat{x}_3)$ $v(4)=b_4(e_4)$



$v(1)+v(2)+v(3)+v(4) > v(1234)$

Related literature

International environmental agreements for greenhouse gas reduction

- Worldwide agreement possible in Chandler and Tulkens (1997) (core non-empty)
- Only partial agreement in Carraro and Siniscalco (1993) (empty core)
- Chandler and Tulkens (1997) consider the non-cooperative core lower bounds while Carraro and Siniscalco (1993) consider the cooperative core lower bounds

Aspiration welfare upper bounds

- Solidarity principle
- The aspiration welfare $w(S)$ of a coalition S is the highest welfare it could achieve in the absence of others
- Since $\sum_{T\in\mathcal{P}} w(T) > \underline{v}(N)$, every coalition should get no more than its aspiration welfare
- (x^*, t) satisfies the aspiration welfare upper bound iff for every $S \subset N$

$$\sum_{i\in S} (b_i(x_i^*) + t_i) \leq w(S)$$

- Equity principle for games with positive group externalities (Moulin, 1990)
- Interpretation of the unlimited territorial sovereignty for international rivers

The downstream incremental distribution 1/2

- Downstream incremental distribution z^d or transfer allocation t^d assigns to i its marginal contribution its predecessors in the river:

$$z_i^d \equiv b_i(x_i^*) + t_i^d = \underline{v}(1, ..., i) - \underline{v}(1, ..., i-1)$$

- Example with $n = 3$
$z_1^d = \underline{v}(1)$
$z_2^d = \underline{v}(1, 2) - \underline{v}(1)$
$z_3^d = \underline{v}(1, 2, 3) - \underline{v}(1, 2)$

Results 1/2

Proposition

The downstream incremental WSA (x^*, t^d) is the unique WSA satisfying the non-cooperative core lower bounds and the aspiration upper bounds

(generalizes Ambec-Sprumont 2002)

Results 2/2

Proposition

The downstream incremental WSA (x^*, t^d) *might violate the cooperative core lower bounds*

Proposition

The downstream incremental WSA (x^*, t^d) *satisfies all core lower bounds for any connected coalition if and only if cooperation exerts no externalities on the value, i.e.* $\underline{v}(i) = v(i, \mathcal{P})$

Implementation

- Negotiation game
- Agent *n* proposes an allocation (x, t) to the others
- If all accepts then implemented
- If one agent refuses, *n* excluded from the negotiation, then *n-1* proposes an allocation for and so on...
- The subgame perfect equilibria yields the downstream incremental distribution z^d that is (x^*, t^d) is the allocation implemented.

Sustainability with variable water flow

- What if less of more water than expected $e_i' \neq e_i$ for some $i \in N$? Do agents still agree to share water?
- Sustainability of (fixed) water sharing agreements (x, t) to variable water flow?
- Ongoing research joint with Ariel Dinar (UC Riverside)
- Theory with application to Aral Sea basin
- "Hot topic" due to climate change

Examples of (fixed) WSA

- Ganges treaty between India and Bangladesh
  - 50% sharing if flow lower than 70000 cubsec
  - 35000 to Bangladesh and balance of flow to India if between 70000 and 75000
  - 45000 to India and balance of flow to Bangladesh if above 75000
- 1929 Nile Water Agreement between Egypt and Sudan
  - 55.5bn cubic meters of water guaranteed to Egypt
- Syr Daria river
  - Water released in summer by Kyrgyzstan in exchange of oil from Uzbekistan and Kazakhstan
- Colorado river
  - Fixed water allocation and fiscal transfers

The Water Sharing Agreement

- Realized water flows $e' = (e'_1, ..., e'_n) \neq e$ and core WSA (x^*, t)
- Each country $i > 1$ receives $\sum_{j<i}(e_j - x^*_j)$ from upstream countries in exchange of $\sum_{j<i} t_j$
- Each agent controls $E'_i = e'_i + \sum_{j<i}(e_j - x^*_j)$ from which it has to release $\sum_{j>i}(e_j - x^*_j)$ in exchange of $\sum_{j\leq i} t_j$ which limits its share to $e'_i - e_i + x^*_i$
- Payoff if Agent i does not pay upstream agents for water released:

$$b_i(\min\{e'_i, \hat{x}_i\})$$

- Payoff Agent i does not release water downstream:

$$b_i(\min\{E'_i, \hat{x}_i\}) - \sum_{j\in P^0 i} t_j$$

Sustainability

Definition

A WSA (x, t) satisfies the no-payment defection constraints iff for every $i \in N$

$$b(x_i') + t_i \geq b_i(\min\{e_i', \hat{x}_i\}).$$

Definition

A WSA (x, t) satisfies the no-release defection constraint iff for every $i \in N$

$$b(x_i') + t_i \geq b_i(\min\{E_i', \hat{x}_i\}) - \sum_{j \in P^0 i} t_j$$

with $x_i' \equiv \min\{e_i' - e_i + x_i^*, \hat{x}_i\}$

Two WSAs

- The downstream incremental WSA (x^*, t^d) (or distribution z^d) where x^* is the efficient allocation based on mean flows and

$$b_i(x_i^*) + t_i^d = \underline{v}(1, ..., i) - \underline{v}(1, ..., i-1) = z_i^d$$

It lexicographically maximizes the welfare of n, $n-1$,...,1 in the set of the core WSAs

- The upstream incremental WSA (x^*, t^u) with

$$b_i(x_i^*) + t_i^u = \underline{v}(i, ..., n) - \underline{v}(i+1, ..., n) = z_i^u$$

Result

Proposition

The upstream incremental WSA (or distribution) might violates the core non-cooperative lower bounds for $n \geq 3$

Proof: By example with $n = 3$,
$b_1(x) = b_2(x) = b_3(x) = x(12 - x) = b(x)$ and $e = (4, 6, 2)$ then
$z_1^u + z_3^u = 52 < 54 = \underline{v}(1, 3)$

The constrained upstream incremental WSA

- Upstream incremental WSA constrained by the satiated benefit $b_i(\hat{x}_i)$ for every $i \in N$ (fair upper bound)
- (x^*, t^{cu}) assigns

$$z_i^{cu} = b_i(x_i^*) + t_i^{cu} \equiv \min\{v(Fi, e) - v(F^0 i, e) + r(i-1), b_i(\hat{x}_i)\}$$

with $r(i-1) = \min\{z_{i-1}^{cu} - b_{i-1}(\hat{x}_{i-1}), 0\}$

Results 1/2

Proposition

The constrained upstream incremental WSA is a core WSA

- It lexicographically maximizes the welfare of 1, 2,...,n in the set of the core and fair WSAs
- The downstream incremental WSA satisfies the aspiration welfare upper bounds more stringent than the satiated benefit constraints

Results 2/2

Proposition

The constrained upstream (downstream) incremental WSA is the most (least) sustainable FWSA in the sense that it maximizes (minimizes) the range of reduced water flows for which a core and fair WSA is sustainable

Proof To be completed...

- Corollary: It defines minimal water flow for which no WSA is sustainable
- Policy implication: implement the constrained upstream incremental WSA to favor sustainability
- Coalition defection to be addressed

Extensions

- Non consumptive uses of water (hydropower, recreational, navigation,...)
- Pollution (ongoing research with Lars Ehlers)
- Dynamic of the resource