清華大學 Tsinghua University

Reservoir Operation for Multi-stakeholder Cooperation

Jianshi Zhao and Pan Liu

Tsinghua University and Wuhan University, China

June 27 2018

1.Introduction

Introduction

Cascade reservoir system

⇩

Flood control, Water supply, Hydropower, Ecology, Navigation etc.

⇩

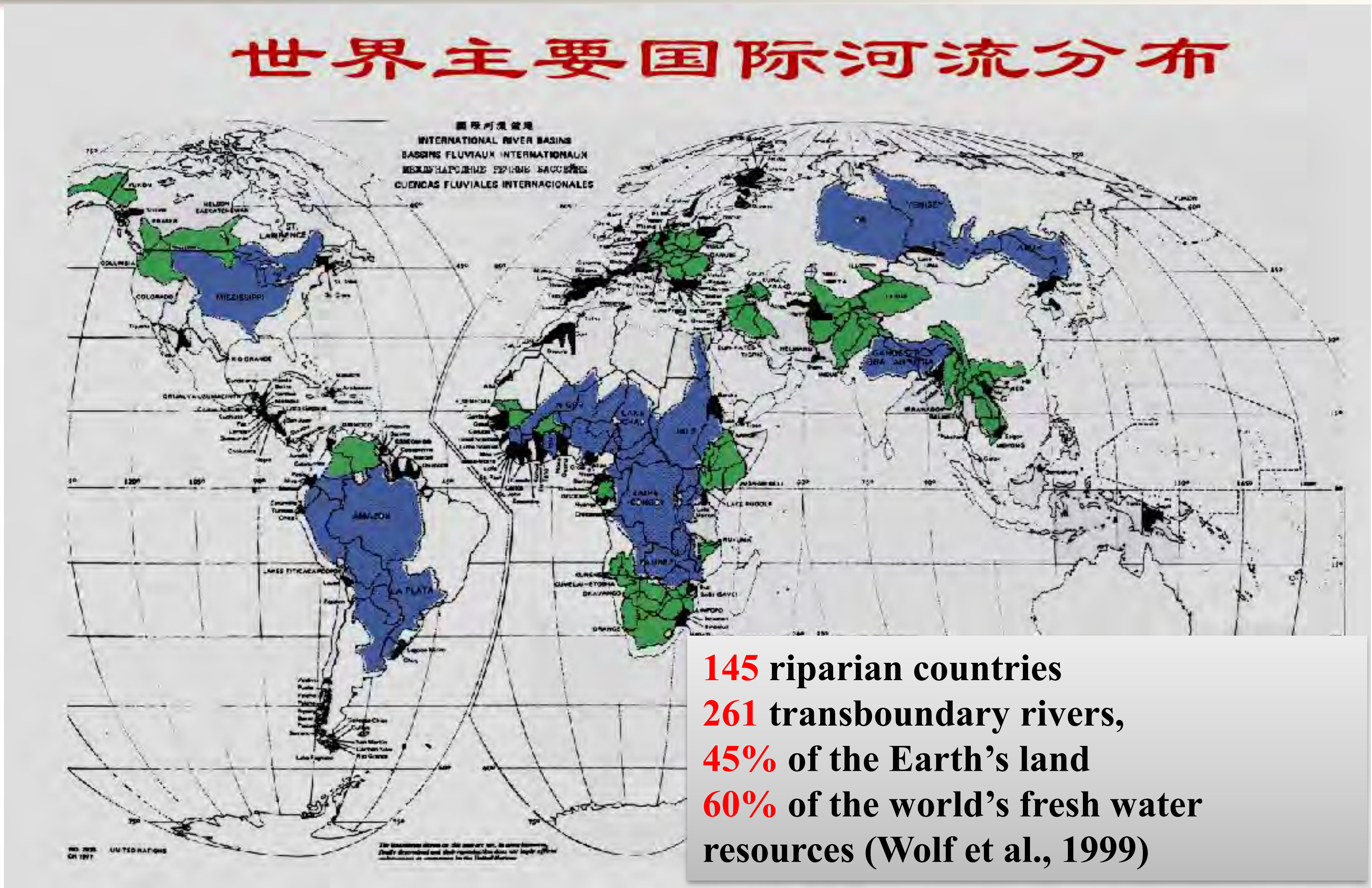
Multi-objective optimization

⇩

Maximize benefits of the system

(Labadie, 2004; Loucks and Beek, 2005；Zhao and Zhao, 2014；Madani, 2014)

Introduction



145 riparian countries
261 transboundary rivers,
45% of the Earth's land
60% of the world's fresh water resources (Wolf et al., 1999)

Introduction

Emergency water supply for the Mekong Delta in 2016

Mekong River Commission, China discuss joint study

... 2016 – Expert teams of the Mekong River Commission Secretariat, representatives from some of its member countries, and China met from 4 to 5 May in Vientiane to discuss and explore a possibility to conduct a joint observation and evaluation of China's emergency water supplement to the Mekong River and a future joint research project. This initiative is to allow the MRC and China, our Dialogue Partner since 1996, to evaluate jointly the effect of the emergency water supplement from China for...

WHY?
HOW?
STABIE?

The questions of why and how stakeholders achieve cooperation and in what cases the cooperation is stable are worthy of research attention.

Introduction

Cooperative game theory

Water rights
(Frisvold and Caswell, 2000)

Water allocation
(Kilgour and Dinar, 2001)

Benefits allocation
(Mckinney and Teasley, 2007; Teasley, 2009; Wu and Whittington, 2006)

Fishery
(Do et al., 2008)

Hydropower license
(Bhagabati et al., 2014)

。。。

The impacts of hydrologic conditions and reservoir system operation are not full discussed

2. The Lancang-Mekong Case

Materials and Methods

Understanding cooperative game

	Company A	Company B	Company C	
Annual Revenue (Non-Cooperative)	$ 70 Million	$25 Million	$5 Million	$100 Million
Annual Revenue (Cooperative)	$ 95 Million	$20 Million	$0 Million	$115 Million

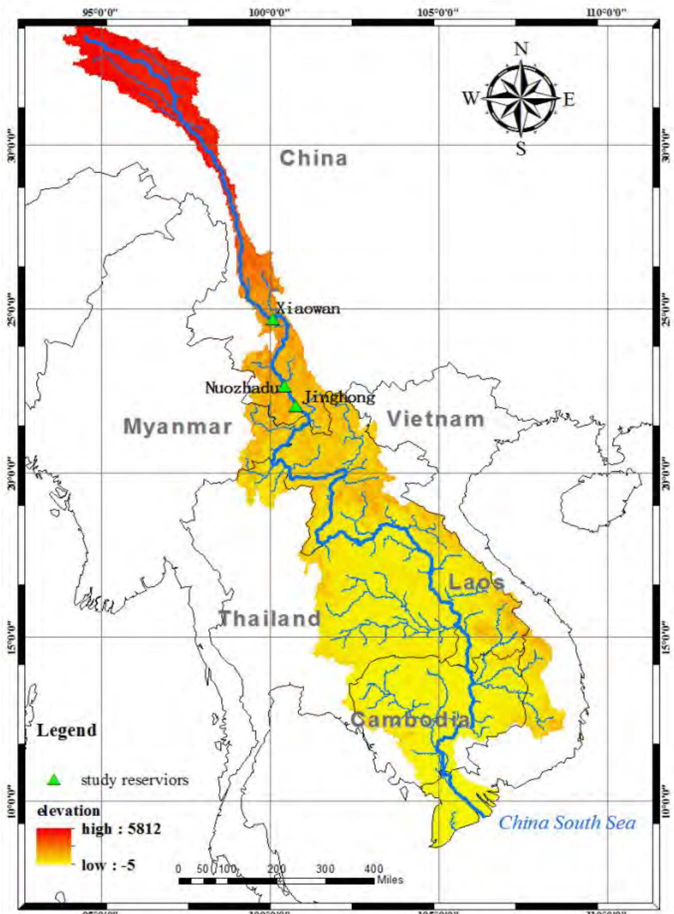
How to persuade the B & C to cooperate?

Sharing Solution	$ 75 Million	$30 Million	$10 Million	$115 Million

（Madani, 2014）

Materials and Methods

■ Lancang-Mekong River



Overview of the Lancang-Mekong River Basin

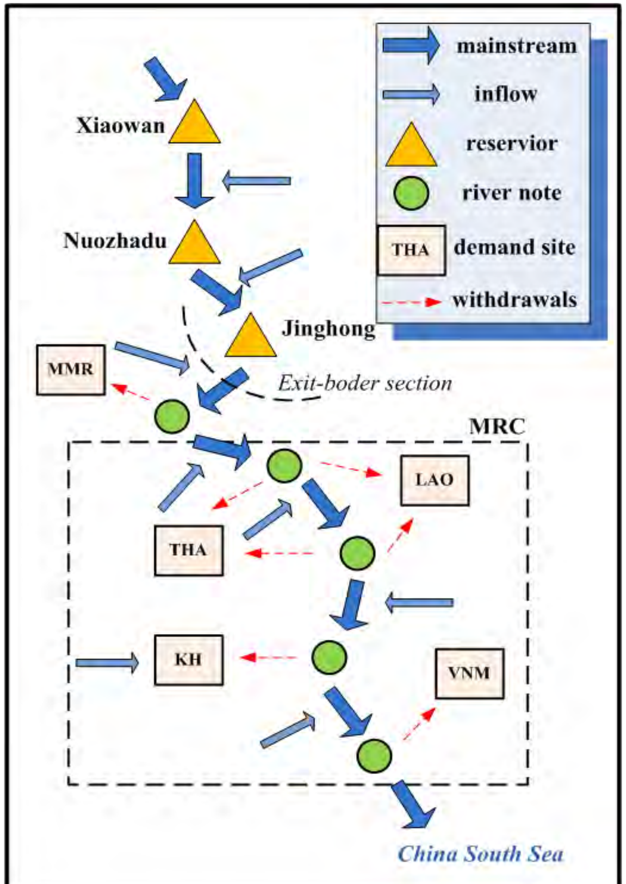
International transboundary river in Asia, flows through 6 countries, i.e., China, Myanmar, Laos, Thailand, Cambodia, and Vietnam

Provides hydropower, irrigation, fisheries, wetlands, navigation, and other resources to the riparian countries it flows through。

Upstream: hydropower
Downstream: Irrigation/fishery/ecosystem

Materials and Methods

■ Model for the basin



Conceptual representation of the Lancang-Mekong Optimization Model

Three major cascade hydropower reservoirs: Xiaowan , Nuozhadu and Jinghong

In the Mekong River:
irrigation, fishery, and wetland water demands of the riparian stakeholders.

divide the six riparian countries into three representative stakeholders:

- China (CHN)
- Myanmar (MMR)
- MRC countries: Laos, Thailand, Cambodia, and Vietnam

Materials and Methods

Optimization Model for multiple stakeholders

Objectives: $$MAX\left(\sum_{n=1}^{tn} V_g, \sum_{n=1}^{tn} V_a, \sum_{n=1}^{tn} V_f, \sum_{n=1}^{tn} V_w\right)$$

V_g is the profit from hydropower ($US million, only in CHN)
V_a is the profit from irrigation($US million)
V_f is the profit from fisheries ($US million)
V_w is the profit from wetlands ($US million)
n is the number of countries in the Mekong river basin, and *tn* is the total number of countries represented by each stakeholder

Water balance:

$$f_{up} + f_{in} = f_{down} + w + E_{loss}$$

Materials and Methods

Multi-objective Cascade Reservoir System Operation Optimization Model

Hydropower:

$$V_g = p_0 \sum_{i=1}^{3} \sum_{t=1}^{T} 9.81 \eta_i \Delta h_{(i,t)} \cdot rf_{(i,t)} \cdot ga_{(i,t)}$$

$$Q_{(i,t)} + S_{(i,t)} = S_{(i,t+1)} + Q_{s(i,t)}$$

$$Q_{s(i,t)} = T_1 \cdot rf_{(i,t)} \cdot a_{(i,t)} + T_2 \cdot rg_{(i,t)}$$

$$S_{d(i)} \le S_{(i,t)} \le S_{u(i)}$$

$$0 \le a_{(i,t)} \le 24$$

$$H_{d(i)} \le \sum_{t=1}^{T} a_{(i,t)} \le H_{u(i)}$$

$$P_{c(i)} \le 9.81 \eta_i \cdot h_{(i,t)} \cdot rf_{(i,t)} \le P_{t(i)}$$

$$r_{(i,t)} = rf_{(i,t)} + rg_{(i,t)}$$

$$r_{(i,t)} \ge base_{(i,m)}$$

Materials and Methods

Irrigation： $$V_a = \frac{\omega}{\mu}\left(1 - e^{-\mu w}\right) - A_{cos}$$ **(Li, 2010)**

$$w_{n,min} \le w_n \le w_{n,max}$$

Fishery： $$V_f = f_{pro} \cdot \alpha \cdot (f_{pri} - f_{cos}) \cdot iff \cdot glf$$ **（Ringler and Cai , 2006）**

$$iff = \min\left\{\arctan\left(\frac{flow_{act(m)} - flow_{min}}{flow_{max}}\right) \cdot \left[1 - b\left(\frac{flow_{act(m)} - flow_{min}}{flow_{max}} - c\right)^2\right]\right\}$$

$$glf = \min\left\{\arctan\left(\frac{stroge_{act}}{stroge_{max}}\right) \cdot \left[1 - d\left(\frac{stroge_{act}}{stroge_{max}} - e\right)^2\right]\right\}$$

Wetlands： **（Ringler and Cai , 2006）**

$$V_w = wet_{area} \cdot wet_{yield} \cdot f - \sum_{m}^{m=12} [\left(flow_{act(m)} - flow_{ave(m)}\right) \cdot dmf_m]$$

Materials and Methods

Data

A historical streamflow series from 1961-1995 is used as the hydrologic input. 50 groups of synthetic streamflow series are generated for uncertainty analysis.

The economic data used in the model are mostly from the MRC and related literature (MRC, 2010; Ringler, 2001).

The model is coded with the General Algebraic Modeling System (GAMS).

Materials and Methods

Cooperative game theory methods

Cooperation conditions:

Individual rationality : $V_n^* \geq V_n \quad \forall n \in N$

Group rationality : $\sum_{n \in S} V_n^* \geq V(S) \; \forall S \subseteq N$

Efficiency : $\sum_{n \in N} V_n^* = V(N)$

The core is defined as the set of all allocations in which no coalition of stakeholders has an incentive to secede to obtain better benefits (Myerson, 1991).

Materials and Methods

Cooperative game theory methods

Incremental benefit allocations in the core:

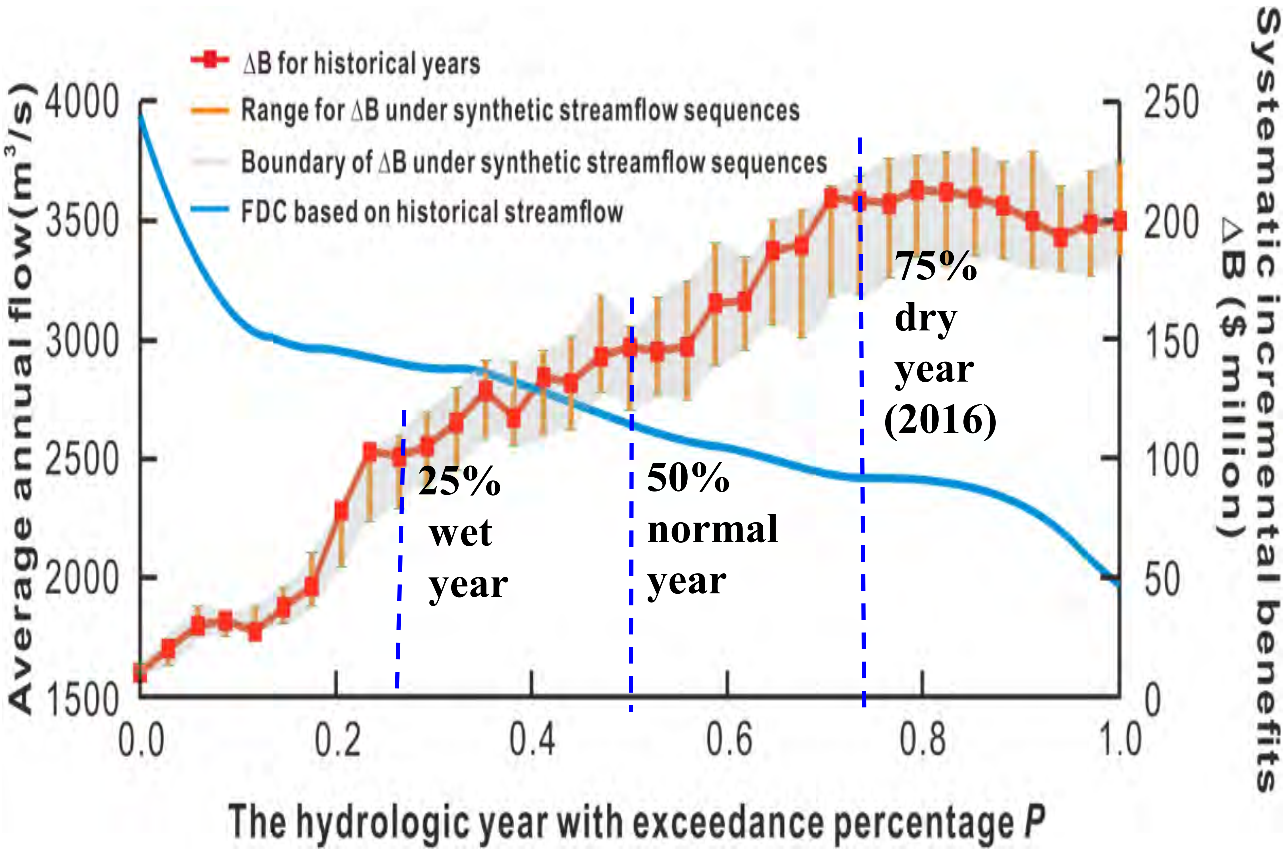
Shapley value： $$V_n^* = \sum_{S \subseteq N} \frac{(tn - |s|)!(|s| - 1)!}{tn!}(V(S) - V(S - \{n\}))$$

Nucleolus： $$Min\left\{ Max \left[V(S) - \sum_{n \in S} V_n \right] \right\}$$

Nash-Harsanyi： $$Max \prod_{n=1}^{tn} \left(V_n^* - V_n \right)$$

Results and Discussion

- Relationship between the systematic incremental benefit of cooperation and the FDC at Chiang Sean station



$$\Delta B_n = V_n^{'} - V_n$$

$$\Delta B = \sum_{n=1}^{tn} \Delta B_n$$

*The difference between the benefits of the grand cooperation and non-cooperation in the system is defined as the systematic incremental benefit of cooperation

Results and Discussion

- Incremental benefits to stakeholders and systematic incremental benefit under different hydrological conditions ($US million)

Hydrological Regime	Coalitions	CHN(1)	MMR(2)	MRC(3)	Total
P=0.25 high flow year	{1},{2},{3}	1526.56	388.21	1392.74	3303.51
	{1,2,3}	1498.52	421.16	1486.68	3406.36
	ΔB_n and ΔB	-28.04	32.95	93.94	**102.85**
P=0.50 normal flow year	{1},{2},{3}	1496.76	383.25	1356.85	3236.86
	{1,2,3}	1483.52	417.16	1482.68	3383.36
	ΔB_n and ΔB	-13.24	33.91	125.83	**146.50**
P=0.75 low flow year	{1},{2},{3}	1460.66	378.56	1295.40	3134.62
	{1,2,3}	1450.95	421.14	1479.19	3351.28
	ΔB_n and ΔB	-9.71	42.58	183.79	**216.66**

Results and Discussion

- Obtainable benefits for each stakeholder in different cooperation scenarios in a dry year ($ million)

Scenarios	Coalitions	CHN(1)	MMR(2)	MRC(3)	Total
A	{1},{2},{3}	1460.66	378.56	1295.40	3134.62
B	{1,2},{3}	1458.15	421.16	1296.75	3176.06
C	{1,3},{2}	1446.19	379.66	1478.65	3304.50
D	{2,3},{1}	1460.66	378.56	1296.70	3136.02
E	{1,2,3}	1450.95	421.14	1479.19	3351.28

The importance of CHN in coalitions

Results and Discussion

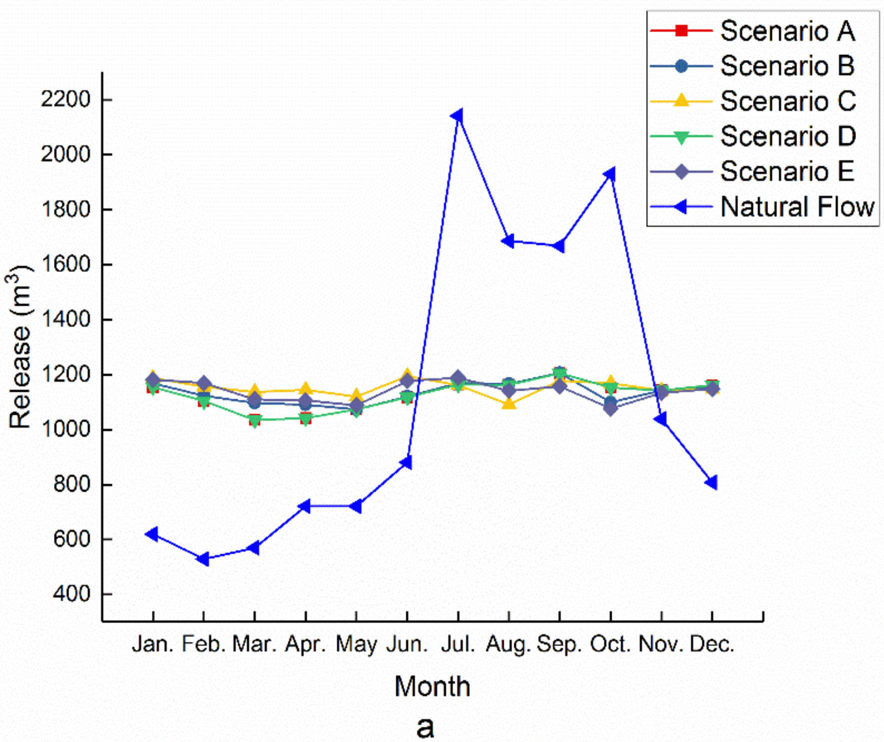
- Obtainable benefits for each stakeholder in different cooperation scenarios in a dry year ($ million)

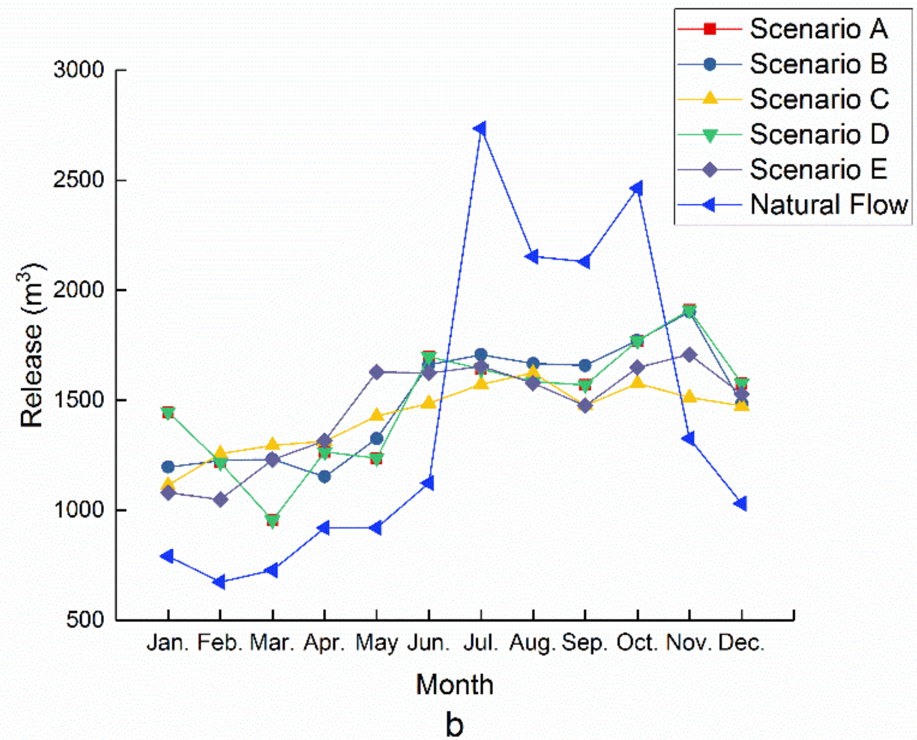
Scenarios	Coalitions	CHN(1)	MMR(2)	MRC(3)	Total
A	{1},{2},{3}	1460.66	378.56	1295.40	3134.62
B	{1,2},{3}	1458.15	421.16	1296.75	3176.06
C	{1,3},{2}	1446.19	379.66	1478.65	3304.50
D	{2,3},{1}	1460.66	378.56	1296.70	3136.02
E	{1,2,3}	1450.95	421.14	1479.19	3351.28

Free-ride of non-cooperative stakeholders

Results and Discussion

- Release flows from the reservoirs for different cooperation scenarios in a dry year (*P*=0.75).

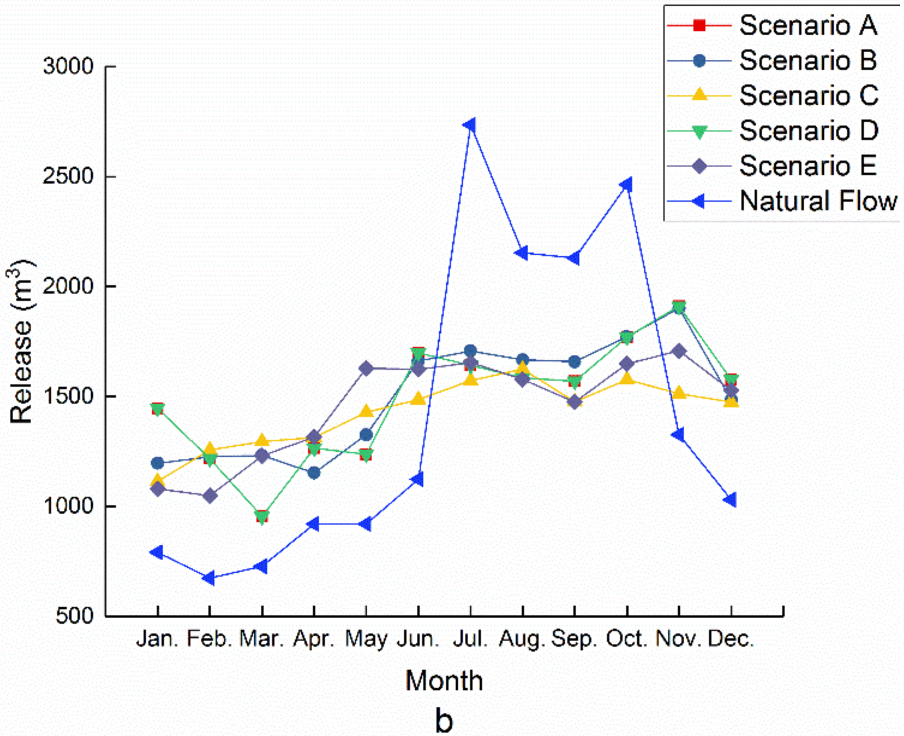




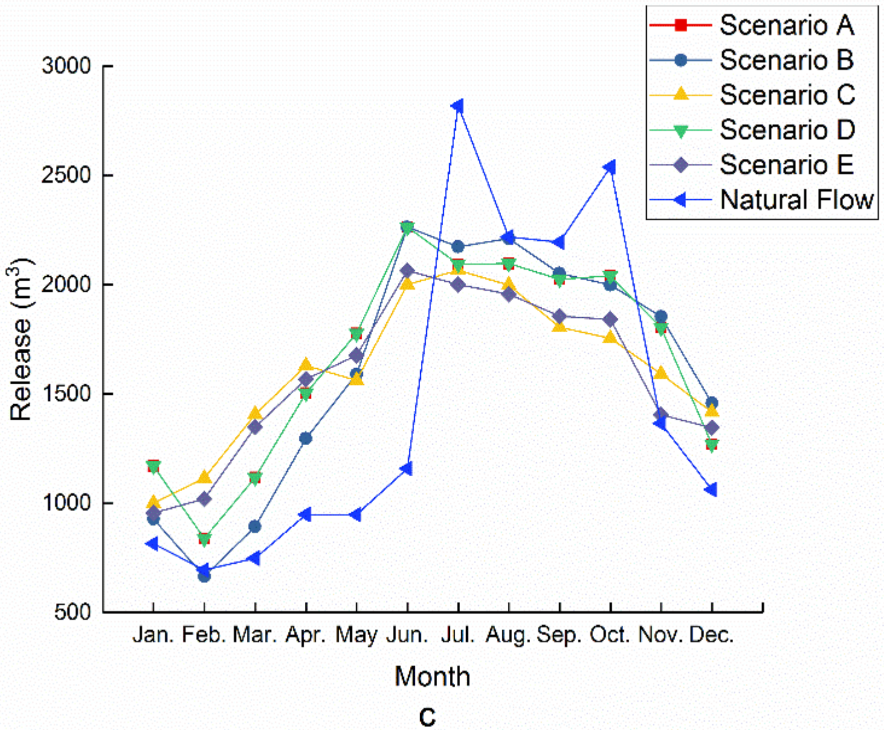
Xiaowan **Nuozhadu**

Results and Discussion

- Release flows from the reservoirs for different cooperation scenarios in a dry year (P=0.75).



Nuozhadu

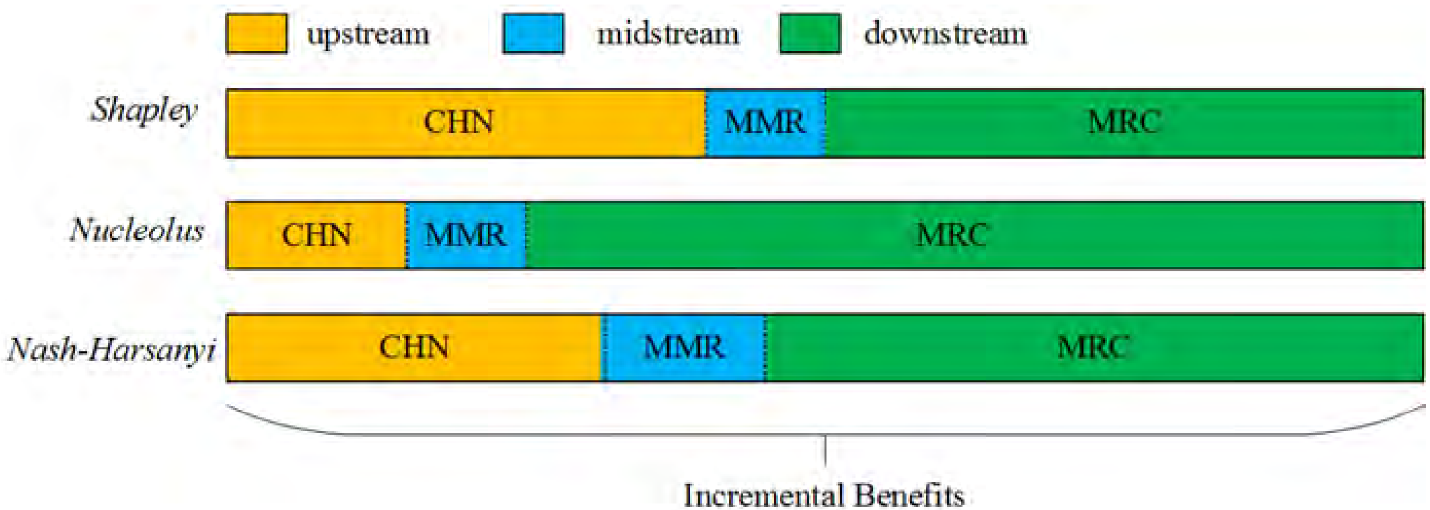


Jinghong

Results and Discussion

- Stakeholders’ final benefits after compensation under the grand coalition based on the Shapley, Nucleolus, and Nash-Harsanyi methods ($ million)

Method	CHN(1)	MMR(2)	MRC(3)	Total
Shapley	1567.30(+)	401.41(-)	1382.57(-)	3351.28
Nucleolus	1500.75(+)	402.50(-)	1448.03(-)	3351.28
Nash-Harsanyi	1545.05(+)	426.44(+)	1379.79(-)	3351.28



Stability of the cooperation

Stability of the cooperation/allocations

1. **Plurality** ——dictates that each stakeholder prefers the allocation solution that results in a higher gain

2. **Power index**

$$PI_n = \frac{V_n^* - V_n}{\sum_{z=1}^{N}\left(V_z^* - V_z\right)}$$

—— the ratio of the loss to stakeholder n from leaving the grand coalition to the summation of the loss to the other stakeholders when they leave the grand coalition

3. **Propensity to disrupt**

$$PTD_n = \frac{\sum_{z \neq n} V_z^* - V\left(N - \{n\}\right)}{V_n^* - V_n}$$

——the ratio the loss to the other beneficiaries if stakeholder n were to leave the grand coalition and refuse to cooperate to how much that stakeholder would lose by refusing to cooperate

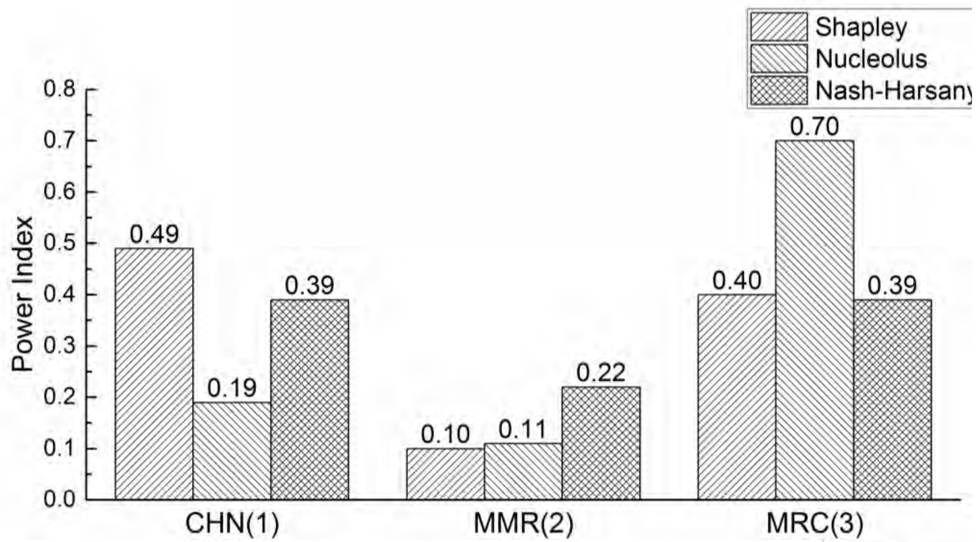
Stability of the cooperation

- Application of the plurality rule to the cooperative allocation solutions

Player	Allocation method	Gain($ million)	Rank
CHN(1)	Shapley	1567.30	1
	Nucleolus	1500.75	3
	Nash-Harsanyi	1545.05	2
MMR(2)	Shapley	401.41	3
	Nucleolus	402.50	2
	Nash-Harsanyi	426.44	1
MRC(3)	Shapley	1382.57	2
	Nucleolus	1448.03	1
	Nash-Harsanyi	1379.79	3

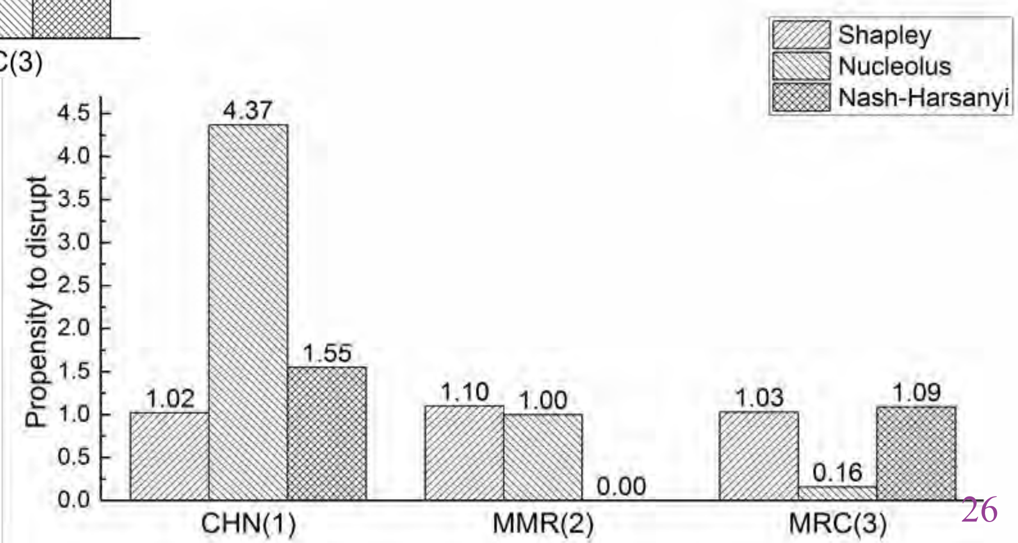
Stability of the cooperation

- PI and PTD for each player in the different allocation scenarios



a lower power index indicates a lower tendency for cooperation

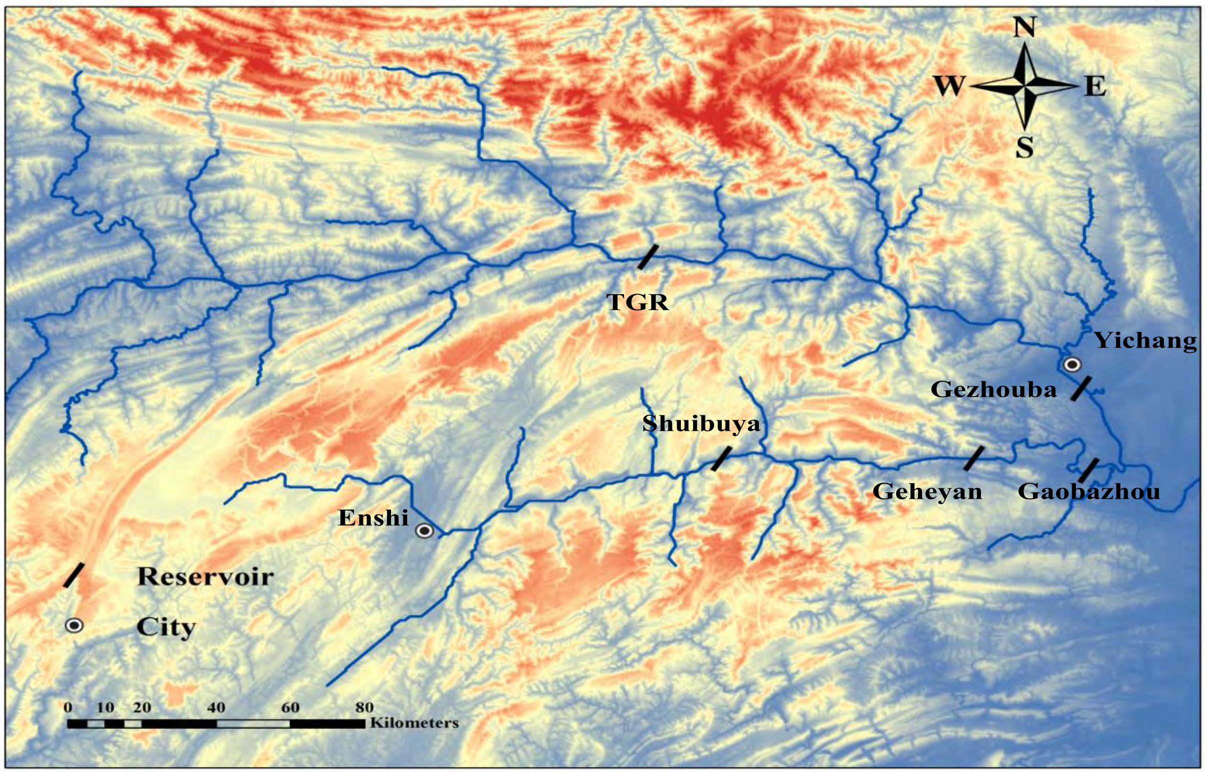
a lower PTD indicates higher willingness for cooperation



3. The Three Gorges Case

Materials and Methods

Qing River and Three Gorges cascade reservoirs in China



Two stakeholders

- the China Yangtze Power Company (CYPC) controls Three Gorges and Gezhouba reservoirs
- Qing River Hydroelectric Development Company (QHDC) controls Shuibuya, Geheyan, and Gaobazhou reservoirs

Materials and Methods

Multi-objective Cascade Reservoir System Operation Optimization Model

Additional fairness objective:

$$min\sum_{a=1}^{k}(\sum_{b=1}^{k}(\frac{E_{increase,a}}{E_{base,a}} - \frac{E_{increase,b}}{E_{base,b}})^2)$$

$E_{base,a}$ is the optimal individual hydropower generation or agent a.

$E_{increase,a}$ is the incremental hydropower generation, which is the difference between the joint and individual optimal operation for agent a.

The fairness measurement addresses the fact that the more hydropower a stakeholder generates in a non-cooperative situation, the larger proportion of incremental benefits the stakeholder shares in a cooperative situation (Shen et al., 2018).

Results and Discussion

- Comparison of different scenarios

Scenarios	Average annual hydropower generation (billion kWh)						Increasing rate of each agent (%)	
	Qing River reservoirs			Three Gorges cascade reservoirs		Total		
	Shuibuya	Geheyan	Gaobazhou	TGR	Gezhouba		QHDC	CYPC
Conventional operating rules	3.62	2.95	0.86	81.38	14.52	103.32	/	/
Optimal individual operating rules for each agent	3.61	2.95	0.87	81.29	15.00	103.72	/	/
Optimal joint operating rules	3.58	3.01	0.85	82.42	15.13	104.99	0.1	1.3
Optimal joint operating rules with fairness	3.63	3.01	0.86	82.29	14.96	104.75	1.0	1.0

4.Conclusions

Conclusions

- The economic gains from cooperation are greater than for non-cooperation, implying there is a huge potential for cooperation, particularly in dry years. Because the dryer the basin is, the more benefits cooperation can yield。

- The operation of the cascade reservoir system in CHN can provide substantial economic benefits to the downstream stakeholders in coalitions. Three reservoirs need to release more water in the dry seasons, leading to hydropower losses upstream but extra gains at the system level.

Conclusions

- Game theory methods can help to identify cooperative solutions for the river basins with multiple stakeholders. It is clear that the shares of benefit for each stakeholder vary with the different methods.

- The stakeholders may have different solution preferences, thus the key to achieving cooperation is to establish a fair scheme that ensures that all stakeholders have sufficient incentive to participate in the cooperation.

Thank you!