Fair and efficient freshwater allocation based on bankruptcy rules with cooperative game approaches

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Objectives

Achieving fair and efficient allocation of freshwater resources ;
Exploring the possibility and highlighting the necessity of water rights trading in water-rich regions;
Quantifying the incremental economic benefits generated by water resource allocation at different levels of cooperation;
Promoting the intensive and economical utilization of water resources in water-rich regions;
Enriching the application of various interdisciplinary and theoretical technologies in the field of water resource allocation.
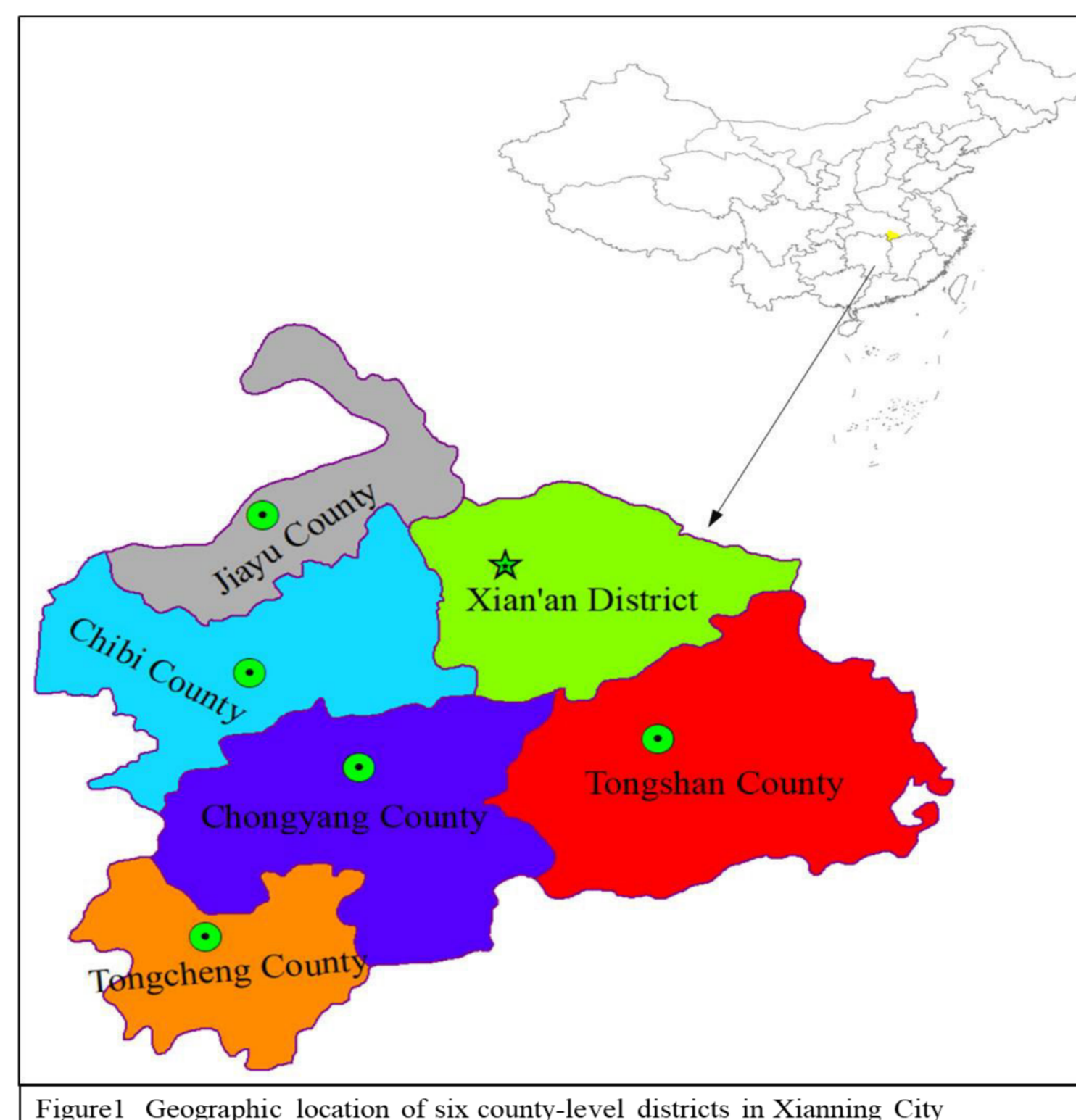

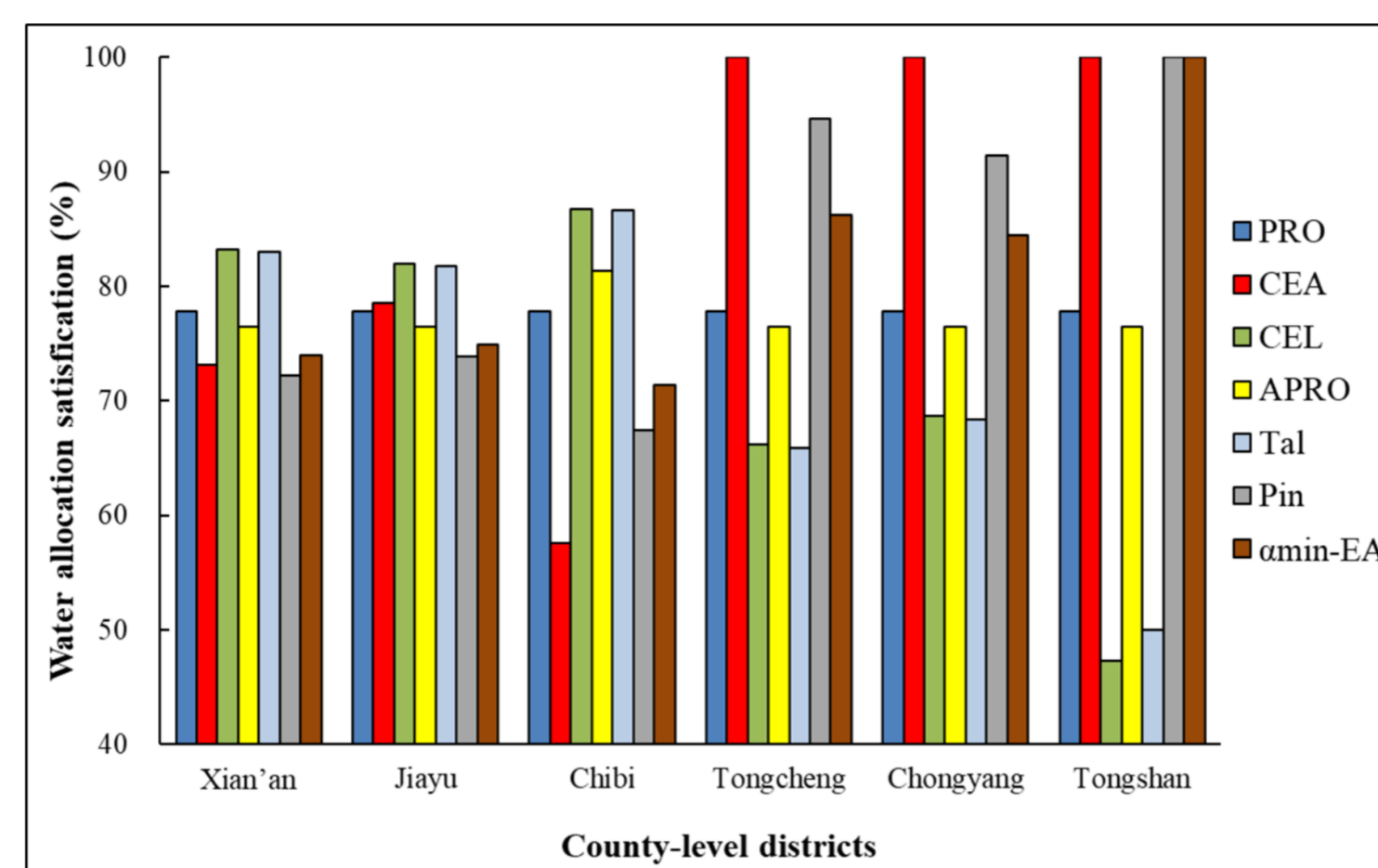Figure1 Geographic location of six county-level districts in Xianning City

Figure3 Water allocation satisfactions (%) of six county-level districts in Xianning City under seven bankruptcy solutions

County-level district	Water-use sectors				Total
	Domesticity	Industry	Agriculture	Eco-environment	
Xian'an	7,099	15,765	22,789	260	45,912
Jiayu	3,940	14,613	24,049	151	42,753
Chibi	6,295	25,098	26,770	149	58,312
Tongcheng	5,237	5,750	11,670	171	22,828
Chongyang	4,577	3,868	16,024	157	24,626
Tongshan	4,720	3,527	6,248	123	14,618
Total	31,868	68,622	107,550	1,010	209,050

Figure2 Water demand prediction results of six county-level districts in Xianning city

County-level districts	PRO	CEA	CEL	APRO	Tal	Pin	αmin-EA
Xian'an	0.69	8.03	7.11	0.25	5.44	8.03	1.36
Jiayu	0.03	0.03	7.11	0.25	5.44	8.03	4.69
Chibi	0.03	14.69	7.11	2.25	5.44	3.36	1.36
Tongcheng	0.03	4.69	5.44	0.25	7.11	4.69	0.69
Chongyang	0.03	4.69	5.44	0.25	7.11	4.69	0.69
Tongshan	0.03	4.69	11.11	0.25	2.78	10.03	8.03
Priority index value	0.14	6.14	7.22	0.58	5.56	6.47	2.81

Figure4 Priority vectors and priority index values of seven bankruptcy rule-based water allocation solutions

Methods

An integrated allocation framework is proposed to implement fair and efficient freshwater allocation;
Bankruptcy theoretical rules are examined to divide the total water permits;
Priority index method is adopted to identify the most appropriate and fair allocation solution;
Hydro-economic optimization models are established to obtain the economic benefits of all possible coalitions by redistributing the initial water rights;
Cooperative game approaches are employed to perform economic benefit compensations among the involved agents;
Sustainability of cooperation regarding various benefit compensation solutions are investigated using the Shapley-Shubik power index.

Results

Proportional is the fairest rule to divide the total water permits in Xianning City, while it is not the most economically efficient;
Compared with unilateral actions taken by six regions according to the Proportional rule, the fully cooperative strategy can generate an incremental benefit of 2.77 billion Chinese yuan;
As the level of cooperation deepens, the incremental benefit generated by the coalition increases;
To materialize most efficient use of water resources, Xian'an, Tongcheng and Chongyang should transfer water volume of 83.98, 66.20 and 105.76 million cubic meters, respectively, to other three regions, and simultaneously their obtained corresponding economic compensation should not be less than 2.01, 1.28 and 2.17 billion Chinese yuan.

Conclusions

Four cooperative game-based benefit compensation solutions all can ensure that the water usage benefits of six regions raise compared with those of their unilateral actions;
Shapley solution is identified as the most long-term stable since it allows the most equitable distribution of internal power among agents;
The proposed allocation framework not only contributes to facilitate water conflict resolution among regions, but also has the potential to improve the economic efficiency of water usage by conducting water rights transfer.
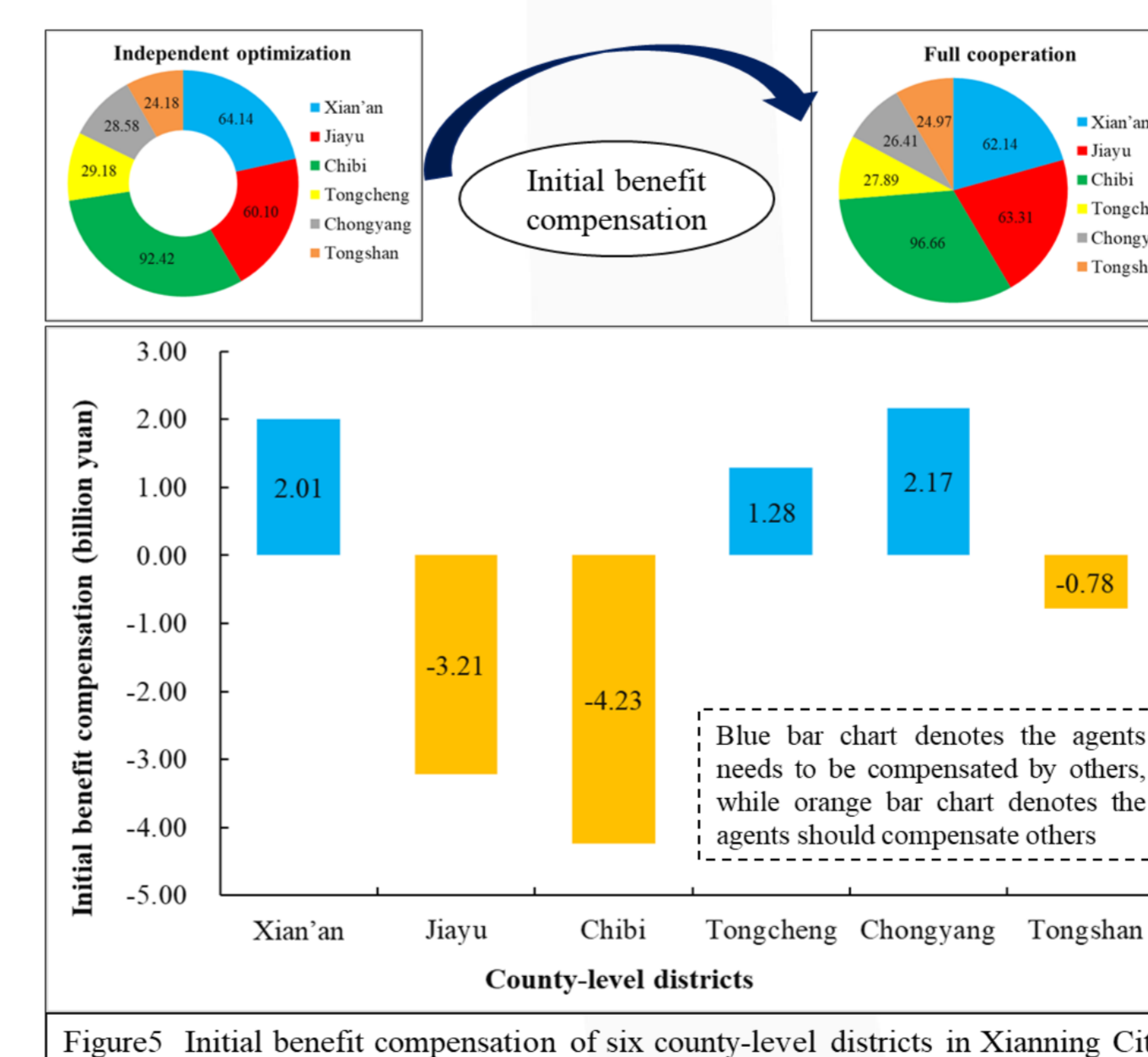

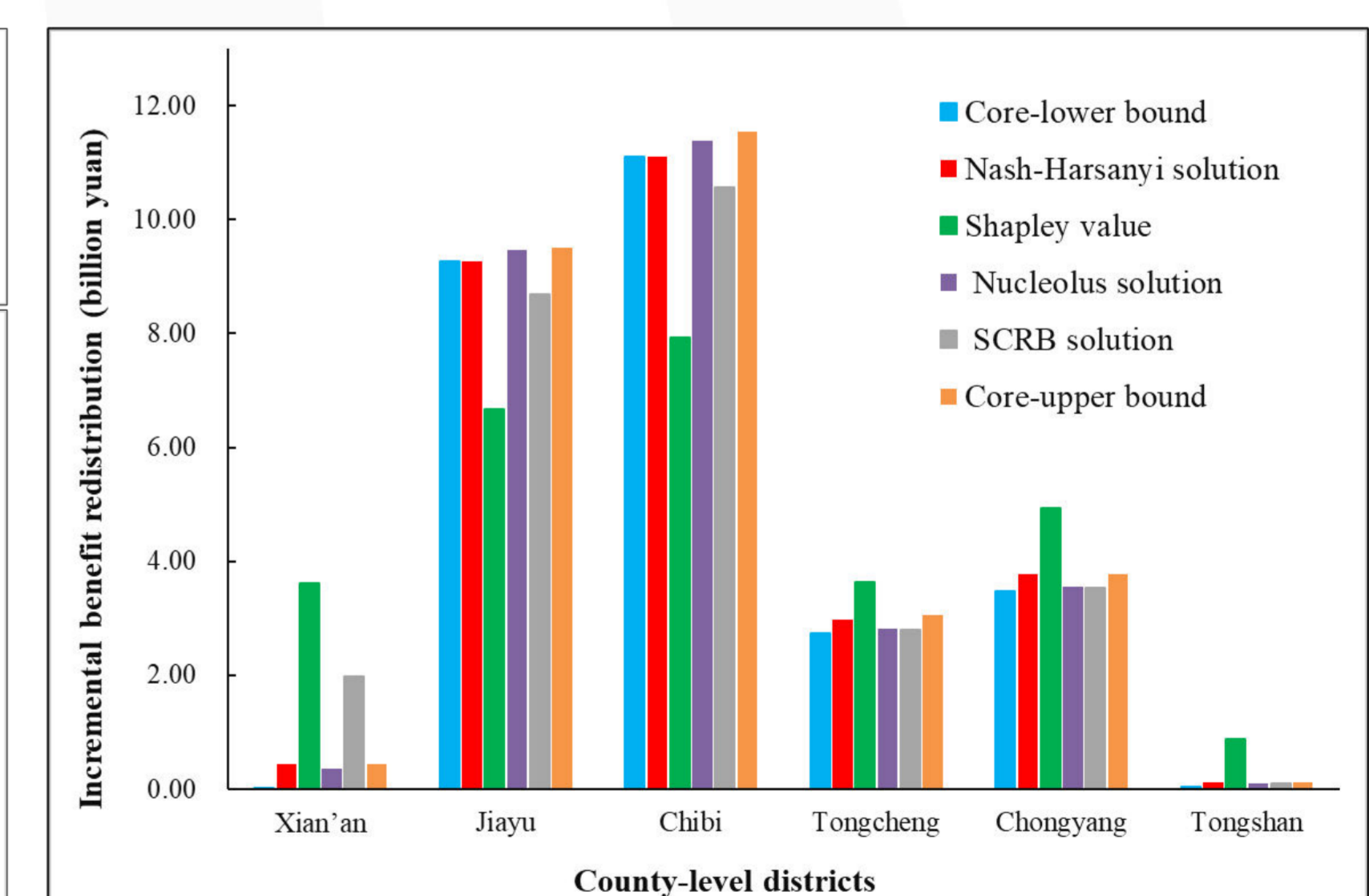Figure5 Initial benefit compensation of six county-level districts in Xianning City

Figure6 Incremental benefit redistributions of full cooperation among six county-level districts in Xianning City under four cooperative game solutions

County-level districts	Nash-Harsanyi solution	Shapley value	Nucleolus solution	SCRB solution
Xian'an	0.02	0.13	0.01	0.07
Jiayu	0.34	0.24	0.34	0.31
Chibi	0.40	0.29	0.41	0.38
Tongcheng	0.11	0.13	0.10	0.10
Chongyang	0.14	0.18	0.13	0.13
Tongshan	0.00	0.03	0.00	0.00
Stability index	0.99	0.54	1.03	0.89

Figure7 Stability evaluation results of various cooperative game benefit compensation solutions

XVIII
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