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Research article

Joint pollution control in the Lake Tai Basin and the stabilities of the cost allocation schemes

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ABSTRACT

This paper provides insights into the allocation of benefits derived from joint wastewater treatment in the Lake Tai Basin of China and the acceptability and stability of different cost allocation schemes in a trans-jurisdictional water system context. First, the wastewater treatment cost function is estimated and coalition costs are compared to the cost of stand-alone wastewater treatment in each province. Second, two standard and five game theoretical cost allocation schemes are applied to the grand coalition. Results suggest that a cost savings of US $46.46 million can be obtained by forming a grand coalition. All allocation schemes were found to be acceptable. Results also suggest that both Shanghai and Jiangsu Province would prefer a proportional allocation scheme based on pollutant discharge, because it would offer them the largest cost savings. But this allocation scheme is the least stable one. Based on the criterion of stability, the Nash-Harsanyi scheme emerges as providing the optimal allocation. Finally, calculation of power and stability indexes suggests Jiangsu Province as an agent is critical to the success of grand coalition formation.

1. Introduction

Reusing wastewater is a heated topic nowadays as it improves the resource efficiency and it is in line with the concept of circular economy. In order to reuse wastewater, wastewater needs to be purified to a certain level to guarantee the safety. Wastewater treatment plants are a key facility for water pollution abatement. Building such plants, however, requires large initial investments and high operation and maintenance outlays. Many areas of the developing world therefore still lack sufficient wastewater treatment capacity. Indeed, more than 80% of the wastewater in developing countries is discharged into water bodies without treatment (Corcoran, 2010). This undermines local sanitation, public health, and ecosystem sustainability.

Various studies have found free-riding behaviour and pollution spillovers in transboundary water systems, including in the USA, Brazil, and China (Helland and Whitford, 2003; Sigman, 2005; Lipscomb and Mobarak, 2011; Deng et al., 2012). Water quality is often lower close to jurisdictional boundaries. In Brazil, Lipscomb and Mobarak (2011) concluded that pollution rose at an increasing rate as the river system they studied approached its downstream exit border. Examining 2005 data from 249 Chinese cities, Deng et al. (2012) found that municipalities behaved strategically when allocating resources to environmental protection. City governments appeared to cut their own spending on environmental protection in response to increased spending on environmental protection by neighbours. Hence, environmental protection was often underprovided. Based on these findings, we might conclude that centralising environmental protection responsibility to a higher level of government might help mitigate pollution.

A recurring issue in centralised wastewater management in transboundary water systems is an equitable allocation of costs and benefits. Several authors have discussed this theme with an emphasis on property rights and on the stability of cooperation (Ni and Wang, 2007; Gengenbach et al., 2010; Van der Laan and Moes, 2012). Some authors have found decentralised wastewater treatment facilities to be in fact more reliable and cost-effective than centralised systems under certain conditions (Wilderer and Schreff, 2000; Massoud et al., 2009). However, where population density is high, such as in the Lake Tai Basin region discussed in this paper, centralised wastewater treatment may be preferred. Centralised facilities can achieve economies of scale, thereby reducing the unit

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cost of environmental control, while in joint action externalities can be internalised (Dinar and Howitt, 1997).

Whether centralised or decentralised, pollution mitigation strategies must always be region specific and tailor made. Agents in a water system are heterogeneous. Their levels of economic development differ, and each has its own reasons for joining or not joining a joint pollution control effort. Each agent, furthermore, gravitates towards economically rational behaviour, seeking to minimise the costs it incurs for pollution control. Each agent will have its own preferred cost allocation scheme as well. Ultimately, the way environmental costs are allocated among partners in a joint effort will therefore be the result of a negotiation process conducted by the agents.

Currently, China uses the command-and-control approach to alleviate trans-jurisdictional lake basin pollution, under which the central government regulates the maximum sewage level through compulsory administrative intervention. The current study explores an alternative pollution control paradigm by treating the local governments in the trans-jurisdictional lake basin as individual agents, and each agent gives priority of its own economic objective, rather than the whole basin system's objective. It looks at the potential of regional cooperation for mitigating trans-jurisdictional water pollution. It also examines ways in which the costs of joint pollution mitigation might be allocated. Furthermore, the preferences and stabilities of different allocation schemes are also tested. Most of the previous studies on cost and benefit allocation issues did not analyse the stability and acceptance of the allocation schemes. (e.g. Loehman et al., 1979; Zhao, 2009a,b; Fernandez, 2009). The stability and acceptance are crucial for a sustainable cooperation, especially in the context of a trans-jurisdictional lake basin. This study is an extension of current work in this field, as it compares both non-game-theoretic and game theoretical allocation schemes, and empirically examines their acceptances and stabilities in a representative trans-jurisdictional lake basin in China.

2. Cost allocation schemes

We aim at comparing different allocation schemes to evaluate their stabilities and preferences by the agents. In reality, agents tend to select the schemes that guarantee that they achieve the least costs. This principle affects the stabilities of the coalition. By comparing different cost allocation schemes, insights into the stabilities and preferences of these schemes can be provided. Therefore, this section presents two non-game-theoretical schemes (proportional allocation based on pollutant discharge, separable costs–remaining benefits (SCRB) method) and five game-theoretical schemes (the core, the least core, the nucleolus, the Shapley value and the Nash-Harsanyi method). Fig. 1 depicts our theoretical framework.

2.1. Standard allocation schemes

2.1.1. Proportional allocation based on pollutant discharge

The proportional allocation method implies that each agent in a cooperative wastewater treatment effort will be charged in relation to the discharged pollutant quantity. Thus, the cost to agent i is

$$Y_i = C_N \cdot \frac{Q_i}{\sum_{i \in N} Q_i}, \tag{1}$$

where Y_i is the cost allocated to agent i; C_N is the total pollution abatement cost of all N agents; and Q_i is the pollutant quantity discharged by agent i.

2.1.2. Separable Costs–Remaining benefits (SCRB)

The SCRB method is based on the premise that each party pays its own separable costs, with the non-separable costs then allocated in proportion to the remaining benefits, assuming that all remaining benefits are non-negative for each agent (Young, 1985). The separable cost of agent $i \in N$ is the incremental cost $C_i^s = C_N - C_{(N-i)}$. The alternative cost for agent i is indicated by C_i, which is the cost incurred when acting alone, and the remaining benefit to agent i (after deducting the separable cost) is $r_i = C_i - C_i^s$. The SCRB method allocates the cost by Eq. (2) (Young, 1985):

$$Y_i = C_i^s + \frac{r_i}{\sum_{i \in N} r_i} \cdot \left(C_N - \sum_{i \in N} C_i^s \right), \tag{2}$$

where $i = 1, 2, \ldots, N$; Y_i is the cost allocated to agent i; C_i^s is the separable cost of agent i; C_N is the total pollution abatement cost; and r_i is the remaining benefit to agent i.

This scheme allocates the costs to each agent by dividing the costs into two parts, which are separable costs and non-separable costs. The separable costs are costs of including an agent into a subcoalition and thus forming a grand coalition. Usually separable costs of all agents that participate in the grand coalition are less than the total joint costs. Therefore, the non-separable costs are the difference between the joint costs and cumulative separable costs of all the participating agents.

2.2. Game theoretical allocation schemes

Water resources are a classic public good characterized by non-excludability. This characteristic creates a free-rider problem that leads to the tragedy of the commons. Game theory is generally employed to study such problems. It is an effective method to analyse the cost and benefit allocation issues such as the allocation of pollution control cost to incentivize the stakeholders to cooperate. It allows the analysis of the strategies and behaviours of different agents. Game theory can be classified into cooperative and non-cooperative game theory. As proved in many practical experiences all over the world, cooperation is an economic way to implement the pollution control. In this paper, we are interested in looking into a potential cooperation of pollution control in a trans-jurisdictional lake basin. Therefore, we use cooperative game theory.

To describe the collective water pollution control issue in game theory terms, we define each agent in the trans-jurisdictional water system region as a player i. N is the set of all players in the region. Each player can choose to cooperate with other players to control water pollution together, or they can choose not to cooperate. A player choosing not to cooperate must bear the cost of water pollution abatement individually, and meet the requirements set by local regulations. Regulations are assumed to be implemented and monitored strictly with no possibility for players to violate them. The benefit side of cooperation is that the abatement cost function is usually concave with respect to capacity in environmental control practice. Therefore, economies of scale can be achieved by treating pollution cooperatively. An increase of the total welfare in the region is obtained through the cost savings generated by cooperation. For each agent, the payoff of the game is the cost savings obtained from joining a coalition. S ($S \subseteq N$) is defined as the set of all feasible coalitions in the game, and s ($s \in S$) as one feasible coalition in the game. The non-cooperation case is denoted by $\{i\}, i = 1, 2, \ldots, n$. The grand coalition is $\{N\}$.

This cost savings game assumes each player to be economically rational. They choose different strategies, here cooperation or non-cooperation, in order to maximise their own cost savings. X_i denotes the cost savings achieved by player i in coalition s ($s \in S$). A