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Optimality versus stability in water resource allocation

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ABSTRACT

Water allocation is a growing concern in a developing world where limited resources like fresh water are in greater demand by more parties. Negotiations over allocations often involve multiple groups with disparate social, economic, and political status and needs, who are seeking a management solution for a wide range of demands. Optimization techniques for identifying the Pareto-optimal (social planner solution) to multi-criteria multi-participant problems are commonly implemented, although often reaching agreement for this solution is difficult. In negotiations with multiple-decision makers, parties who base decisions on individual rationality may find the social planner solution to be unfair, thus creating a need to evaluate the willingness to cooperate and practicality of a cooperative allocation solution, i.e., the solution's stability. This paper suggests seeking solutions for multi-participant resource allocation problems through an economics-based power index allocation method. This method can inform on allocation schemes that quantify a party's willingness to participate in a negotiation rather than opt for no agreement. Through comparison of the suggested method with a range of distance-based multi-criteria decision making rules, namely, least squares, MAXIMIN, MINIMAX, and compromise programming, this paper shows that optimality and stability can produce different allocation solutions. The mismatch between the socially-optimal alternative and the most stable alternative can potentially result in parties leaving the negotiation as they may be too dissatisfied with their resource share. This finding has important policy implications as it justifies why stakeholders may not accept the socially optimal solution in practice, and underlies the necessity of considering stability where it may be more appropriate to give up an unstable Pareto-optimal solution for an inferior stable one. Authors suggest assessing the stability of an allocation solution as an additional component to an analysis that seeks to distribute water in a negotiated process.

1. Introduction

Water resource planning problems are multi-dimensional by nature, as they involve synthesizing hydrological, environmental, and socio-economic data for successful management of the system. Madani and Lund (2011) assert that water resource decision-making problems are multi-criteria (MC) and fall into two categories: single decision-maker (MC-SDM) and multiple decision-maker (MC-MDM), classified based on if a single entity acts as the decision maker or if decisions are to be made by multiple parties. Water resource management is increasingly grappling with adding stakeholders to its decision-making collective as supplies become more limited, demands increase, and water users rely more heavily on shared resources. Managers should be well informed on the complexity of water systems and the interests and needs of their stakeholders to be able to implement their plans. Multi-party negotiations over water resource allocation problems are complicated by inherent differences in political, social, and economic status among the parties involved in the negotiation.

Hajkowicz and Collins (2007) provide a review of the extensive applications of multi-criteria decision-making (MCDM) methods to water resource management problems. Conventional methods for assessing MCDM problems involve aggregating the multiple stakeholders into a single decision-maker, a process that lumps the parties' perspectives and behavior into a homogeneous entity and assumes unanimous agreement. In other words, these methods convert an MC-MDM problem to a MC-SDM problem in order to prescribe an optimal (efficient) solution to decision-making problems. This effectively omits the self-optimizing behavior that can be

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an important barrier to reaching an agreement over the system's optimal solution (Cardenas and Ostrom, 2004; Madani, 2010).

To improve upon convention, conflict resolution methods have been applied to facilitate water negotiations with increasing popularity in recent years (Madani, 2010; Bourget, 2011). These methods seek collaboration among parties to develop cooperative decision rules, sometimes using optimization methods from operations research (Lund and Palmer, 1997; Madani, 2010). In these works, finding the Pareto-optimal solution, or the one that provides the best solution for each user without compromising the benefits of another, is the primary objective. However, achieving Pareto-optimal (efficient) solutions in practice in a negotiation may not be feasible due to the complex external power dynamics that exist between decision makers (DMs) and the different reactions and strategies that DMs can adopt (Madani, 2013). In the water resources management context, factors such as lack of trust, information, and communication can result in tragedy of the commons (Hardin, 1968), as parties prefer to act based on individual-rationality as opposed to group-rationality (Madani and Dinar, 2012a). As long as parties have strong incentives for acting based on self-interest, even regulations and intervention by governments may be subject to failure (Madani and Dinar, 2013). On the other hand, "environmental policy and governance" researchers such as Ostrom (1998) and Lubell et al. (2002) have provided strong evidence for circumstances under which water resource stakeholders are more likely to develop cooperative institutions (Madani and Dinar, 2012b), rather than working individually to maximize their gains.

Lubell et al. (2002) identifies the presence of three factors – problem severity, institutional opportunities, and political incentives, in determining whether parties in negotiation are likely to form partnerships toward cooperative solutions or work for individual interests. Since behavioral and institutional factors can influence a negotiation and potentially destabilize otherwise ideal or optimal solutions, alternative solutions that address stability (feasibility) in addition to optimality in MC-MDM problems can provide additional insight. Fairness is another factor that contributes to the emergence of solutions which may differ from those identified by the Pareto-frontier. That is, sub-optimal (Pareto-inefficient) solutions exist that may be perceived as fair according to all parties, and will emerge as more stable. In these cases, parties will prefer a fairer allocation to an allocation which is not acceptable based on individual-rationality (Dinar and Howitt, 1997).

Game theory methods provide an appropriate framework for analyzing MC-MDM problems (Madani and Lund, 2011), as these methods can incorporate the individuality of players' strategies and behaviors in MC-MDM, provide valuable insights into real water resource conflicts (Rogers, 1969; Dinar and Alemu, 2000; Fisher and Huber-Lee, 2008; Wang et al., 2008; Teasley and McKinney, 2011; Madani and Lund, 2012) and offer different solutions from conventional systems methods in selecting the outcome. A classic example for highlighting the difference between Pareto-optimality (conventional solution) and stability (game theoretic solution) is the prisoner's dilemma, for which the outcome between the two players is not the one with the highest payoff for the system (Pareto-optimal), but is instead the one that emerges through simultaneous maximization of individuals' utilities. Thus, in the context of MC-MDMs, a stability analysis can form a different feasible solution set than an optimality analysis, since DMs are unlikely to reject a solution which they all find stable, i.e., an equilibrium (Madani and Hipel, 2011).

Systems engineering methods such as goal programming, least squares analysis, compromise programming, and Pareto-based optimality have been largely used to solve water resources allocation problems (Draper et al., 2003; Loucks & van Beek, 2005; Hollinshead and Lund, 2006; Zoltay et al., 2010). This discussion shows the breadth of optimization to solve water and resource problems, and also highlights a need to include stability analysis in MC-MDM issues. Optimality as a sole analysis is better suited for MC-SDM problems where an algorithm to optimize based on multiple criteria can be employed, and the relative dissatisfaction of parties is not preventive of implementing the optimal solution in practice (Madani and Lund, 2011). Conversely, MC-MDM problems can benefit from a mathematical formulation that includes stability as an evaluation metric, such as the power index method presented in this work. Stable solutions can provide important insight in practical MC-MDM cases where it is often difficult to reach consensus on the system's optimal solutions, since 'optimality' from a systems (social planner's) view does not consider stakeholders' perceptions of fairness and acceptability.

Generally defined, power may reflect decision makers' relative willingness to cooperate in the negotiation process. Rooted in economics literature (Shapley and Shubik, 1954; Gately, 1974; Loehman et al., 1979; Straffin and Heaney, 1981), power-based approaches rely on the premise that the most stable (feasible) solution is that which distributes powers equally. Mainly applied in the cooperative game theory literature, power index (Loehman et al., 1979) is considered to be an appropriate method for selecting the most stable or fair method to allocate the incremental benefits of cooperation (Dinar and Howitt, 1997; Teasley and McKinney, 2011; Madani and Dinar, 2012b). While this method has not been originally developed for applications in assessing the stability of water and resource allocation solutions, this paper adapts the power index method to develop discrete and continuous solutions for water resource allocation problems with multiple DMs. The main objectives of this work are: (1) to present a method for determining the relative stability (feasibility) of allocation solutions with multiple DMs, and provide a comparison to those calculated via socially optimal methods; (2) to characterize the relative satisfaction of DMs in a negotiation under socially optimal and stable methods in a continuous space; (3) to provide a case study for illustrating the practical significance of conducting a stability analysis through the power index method.

The paper is structured as follows. The next section presents the MC-MDM formulations of distance-based methods and compares them to applying a stability metric via the power index. Section three presents background on the Caspian Sea case study; and section four discusses the allocation results from using discrete predefined division rules to divide the Caspian Sea when all players have equal power in the negotiation. Section five presents a new allocation method based on the power index to calculate continuous solutions for MC-MDM problems, and presents results for the Caspian Sea case study. Section six discusses how external negotiator weights influence the allocation results for continuous and discrete formulations; the paper closes with a discussion of policy implications and concluding remarks.

2. Water allocation methods

In allocation problems, highly dissatisfied parties may find certain solutions unfair and resist implementing them (Dinar and Howitt, 1997; Madani and Dinar, 2012b). Therefore, several allocation methods in the literature focus on fair distribution of dissatisfaction among parties. Generally in the water resources literature these are distance-based allocation methods, which try to minimize the distance of the allocation solution from the ideal solutions of the stakeholders. To highlight the major differences between the operations research (OR) allocation methods and the economic method introduced in this study, i.e., power index, four commonly used distance-based methods are reviewed here.