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Research article

A decision-making framework for river water quality management under uncertainty: Application of social choice rules

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ABSTRACT

An important issue in river water quality management is taking into account the role played by wastewater dischargers in the decision-making process and in the implementation of any proposed waste load allocation program in a given region. In this study, a new decision-making methodology, called ‘stochastic social choice rules’ (SSCR), was developed for modeling the bargaining process among different wastewater dischargers into shared environments. For this purpose, the costs associated with each treatment strategy were initially calculated as the sum of treatment cost and the fines incurred due to violation of water quality standards. The qualitative simulation model (QUAL2Kw) was then used to determine the penalty function. The uncertainty associated with the implementation of strategies under the economic costs (i.e., the sum of treatment and penalty costs) was dealt with by a Monte-Carlo selection method. This method was coupled with different social choice methods to identify the best solution for the waste load allocation problem. Finally, using the extended trading-ratio system (ETRS), the most preferred treatment strategy was exchanged among dischargers as the initial set of discharge permits aimed at reducing the costs and encouraging dischargers to participate in the river water quality protection scheme. The proposed model was finally applied to the Zarjoub River in Gilan Province, northern Iran, as a case study. Results showed the efficiency of the proposed model in developing waste load allocation strategies for rivers.

1. Introduction

Rivers are one of the most important water resources that are exploited not only to meet the different industrial, agricultural, and domestic needs at the local level but also to transfer water to neighboring areas with water shortage. The assimilative capacities of rivers have also been exploited to discharge both point and non-point sources of pollution into them. In such cases, river water quality is degraded and human health and environment are adversely affected when the wastewater discharged exceeds the assimilative capacity of the receiving water. Waste load allocation is, hence, an important concern in river water quality management.

Effluent trading is one method commonly proposed for maintaining river water quality within predetermined standards. The method is a cost-effective means used in pollution control programs. In this method, unused discharge permits are bought, as commodities, by dischargers with higher treatment costs. This allows not only for environmental goals to be achieved but also for both stakeholder buyers and sellers to benefit maximally from the available resources (Crocker, 1966; Dales, 1968). A brief description of the various aspects of effluent trading as reported in the literature follows.

Previous studies have extensively dealt with efficient pollution control programs (Montgomery, 1972), monitoring changes in river water quality under effluent trading programs (Eheart, 1980; Brill et al., 1984; Eheart and Ng, 2004), trading with time (Eheart et al., 1987), trading with the flow variable (O'Neil, 1983; Noss and Gladstone, 1987), trading based on multiple pollutants (Lence et al., 1988; Lence, 1991; Letson, 1992; Sarang et al., 2008), and trading between point sources of pollution such as municipal wastewater and non-point sources of pollution such as agricultural drainage (Malik et al., 1993; Horan et al., 2002). Some studies have also been devoted to trading based on a Mean-Value First-Order Second-Moment (MFOSM) method (Ng and Eheart, 2005; Ning and Chang, 2007), examination of the role of pollution trading in river water quality management (Nishizawa, 2003; Shortle and Horan, 2006), concurrent use of treatment and trading methods (Lopez-

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Villarreal et al., 2011, 2014), development of the structure of artificial market using the agent-based model (Zhang et al., 2013), development of the trading-ratio system (Hung and Shaw, 2005; Mesbah et al., 2009), and the use of real time operating rules for trading (Mesbah et al., 2009). Among other lines of research, one can refer to trading with uncertainty about treatment costs (Mesbah et al., 2010; Nguyen et al., 2013), fair reallocation of treatment costs using cooperative game theory (Niksokhan et al., 2009b), and conflict resolution in trading programs (Niksokhan et al., 2009a; Mahjouri and Bizhani-Manzar, 2013).

Iran Department of Environment (IDEO) is responsible for the control and monitoring of river water quality through its monitoring stations along river bodies, ensuring pollution in rivers does not exceed recommended limits, alleviating the destructive environmental effects due to waste discharge into rivers, and conservation of the local ecosystem and the indigenous flora and fauna. The Organization reports directly to the President and its Director is also appointed by the President.

The regulatory responsibility for adopting decisions and selecting appropriate waste load allocation policies for river water quality management in Iran is left to the hands of Iran Department of Environment (IDOE) which somewhat mirrors the American Environmental Protection Agency in structure and legal status. In addition to such environmental considerations and provisions as might be deemed necessary by IDOE, waste load allocation policies must also meet cost efficiency requirements and acceptability of water quality protection schemes to all or most dischargers. A major drawback with the policies so far adopted, however, is that less attention has been paid to their applicability to real-life conditions on the ground. It is, thus, mandatory to revisit such proposed waste load allocation programs in order to ensure their applicability. The means that may be exploited to this end include appropriate decision-making approaches and the effluent trading system, among others.

It is not uncommon for water resources management and environmental problems to be stated as multi-criteria decision-making problems (MCDM) due to their various environmental, economic, social, and technical aspects. Such problems may be classified into two general categories (Madani and Lund, 2011): 1) multi-criteria single-decision maker (MC-SDM), and 2) multi-criteria multi-decision maker (MC-MDM). The first category of problems usually involves a single decision-maker who has the responsibility of adopting the best solution in the context of predetermined criteria. MC-MDM problems, on the other hand, should take into account and integrate the views of a number of decision-makers toward a sustainable decision which is not necessarily an optimal solution (Madani et al., 2014). This inherent difference makes MC-MDM-based solutions more preferable and appropriate for environmental and water resources management problems. However, this important advantage is usually ignored in favor of MC-SDM approaches and MC-MDM problems are usually tackled through translating the different views of different decision-makers into different criteria.

Adopting an MC-SDM method for solving problems of an MC-MDM nature always presupposes perfect cooperation among the decision-makers; otherwise, a sustainable solution can only be sought through non-cooperative game theories or bargaining methods. Only a slight likelihood of full cooperation can be expected among the stakeholders in cases where there are many stakeholders with varied interests so that no optimal solution may be expected to emerge.

An important decision-making approach developed over the years for partial cooperation in decision making problems is the social choice rules (SCR) approach (De Borda, 1781; Condorcet, 1785; Dodgson, 1876; Nanson, 1882; Thurstone, 1927; Black, 1948; Arrow, 1951; Brams and Fishburn, 1978; Bassett and Persky, 1999; Sertel and Yilmaz, 1999; Nurmi, 1999, 2010).

When faced with decision-making problems in which stakeholders exhibit both cooperative and non-cooperative attitudes, one can adopt an optimistic (MCDM) approach or a pessimistic (non-cooperative and bargaining) one. However, the voting methods may be adopted in cases where stakeholders exhibit a partial cooperation among themselves. Thus, solutions that emerge from the social selection approaches and that seem to be socially optimal fall somewhere between those emerging the absolutely optimistic and the absolutely pessimistic approaches. They are, therefore, more sustainable than the pessimistic (non-cooperative) ones but more sustainable when compared with the optimistic (MCDM) ones.

In addition to their applicability to group decision-making problems with partial stakeholders' cooperation, the other advantages of social selection rules that encourage managers and planners involved in the environmental and water resources management may be summarized as follows:

1) The simplicity and ease of understanding have made social selection methods applicable to group decision-making problems.
2) The rapid and transparent decision making process that relies on no precise or detailed quantitative data have made especially appealing.
3) Given the fact that these methods are based on prioritized desirable options to stakeholders have made them insensitive to uncertainties in input data.

According to the voting approach, each voter only votes for his/her priority options. This property ignores differences between different performance levels in the decision-making process. In this situation, some of the stakeholders might withdraw from or ignore their priorities in order to reach a final agreement with drastically adverse consequences.

However, applications of this method to decision-making problems in water resources management have remained highly limited (Martin et al., 1996; D'Angelo et al., 1998; Laukkanen et al., 2002, 2004; Kant and Lee, 2004; Kangas et al., 2006; Srdjevic, 2007; Goetz et al., 2008; Sheikhmohammady et al., 2010; Morais and Almedia, 2012; Srdjevic and Srdjevic, 2013; Madani et al., 2014; Mehrparvar et al., 2015).

As for recent studies of applications of the social choice approach in the area of water quality management, reference may be made to one the qualitative and quantitative urban runoff management (Ghodsi et al., 2016). The study used NSGA-II to determine different management scenarios by considering a variety of objectives such as minimizing runoff volume, runoff pollution load, and costs of implementing the best management practices. The different social choice methods were then employed to select the superior scenario for implementation. Malakpour et al. (2016) used a fuzzy social choice method to identify the superior option for the water quality management of an urban lake. Mahjouri and Abbasi (2015) used different social choice methods to determine the optimum treatment percentages based on trade-off curve which included such objectives as minimizing the risks associated with violating quality standards and minimizing total treatment costs.

Clearly, the social choice approach has won special attention in water quality management, but in the waste load allocation problems with a view to the inherent uncertainties are less considered. The present study also used the same approach to determine socially sustainable wastewater treatment strategies in an attempt to encourage dischargers to participate in river water quality improvement schemes.

Given the special social and political situation in Iran which

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