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Selection of sustainable municipal water reuse applications by multi-stakeholders using game theory

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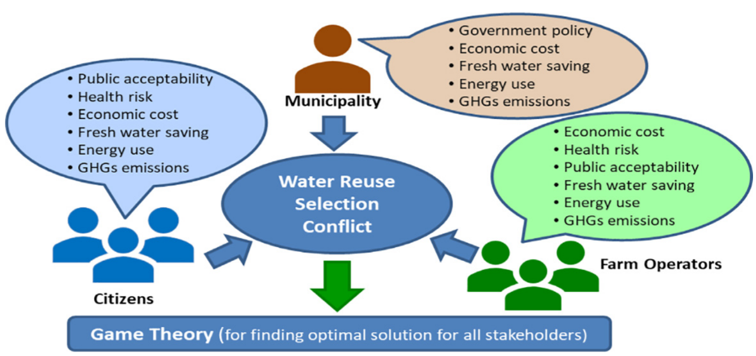
HIGHLIGHTS

- Water reuse decision is complex having conflicting criteria and multi-stakeholders.
- Multicriteria decision analysis and game theory are combined and applied.
- Game theory efficiently gives solutions in water reuse decision conflict.
- Estimated expenses for water reuse are within the willingness to pay by citizens.
- The framework can be adapted to other applications involving multi-stakeholders.

GRAPHICAL ABSTRACT



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ABSTRACT

Globally the trend of water reuse has been increasing. The public perception and government regulations are supportive for reclaimed water use in Canada. Reclaimed water can be used in variety of applications that may have different performance in economic, environmental and social dimensions for various stakeholders, indicating decision on water reuse selection is complex. This research proposes a multi-criteria multi-decision-makers framework combining multicriteria decision analysis (MCDA) and game theory for a selection of a sustainable water reuse application. The proposed framework is applied to the City of Penticton, BC, Canada. The evaluation criteria included were environmental: fresh water saving, energy use, and carbon emissions; economic: annualized life cycle cost; and social: government policy, public perception, and human health risk for three stakeholders: municipality, citizens, and farm operators. The game theory is applied to eight water reuse options considering a cooperative game. The result shows that lawn, golf course and public park irrigation and toilet flushing with an equal sharing of municipal benefits between the municipality and citizens is the optimal solution. By using the solution, the municipality can have an additional saving of approximately $35/household/year and the citizens have to spend an additional amount of approximately $100/household/year for dual plumbing of toilet and lawn for reclaimed water use. The additional expenditure for the citizens is within Canada's public willingness to pay an additional charge for reclaimed water use. The scenario analysis shows that the weights of sustainability criteria are important in decision-making. Also, the sensitivity analysis shows that the change in the amount of reclaimed water availability can affect water reuse sustainability performance. The proposed framework can also be used in other applications by changing the number of evaluation criteria and stakeholders as required.

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1. Introduction

1.1. Background to water reuse

Reclaimed water use is an alternative in water supply management in the condition of water shortage. Reclaimed water is treated municipal wastewater that has gone through various treatment processes to meet specific water quality criteria, which is specially intended for beneficial uses. Water reuse refers to the use of treated wastewater for a beneficial purpose (Asano et al., 2007). Reclaimed water is an on-site water resource that can be generated at or near the same location of water consumption throughout the year. The major factors triggering reclaimed water use are water shortage, drought impact management, fresh water saving, production of cheaper water sources, water reuse as low cost disposal of wastewater, and environmental water restoration (EU, 2016; Jiménez Cisneros, 2014). Moreover, increased use of safe reclaimed water globally is one of the targets of the "Sustainable Development Goals 6: Ensure availability and sustainable management of water and sanitation for all" (United Nations, 2018).

Globally, the trend of reclaimed water use has been increasing and Global Water Intelligence estimated that the world market of water reuse is expected to be larger than desalination in the future (EU, 2016). More than 60 countries have been using reclaimed water for different purposes (Angelakis and Gikas, 2014). Non-potable water reuse is common although potable reuse has been in practice since a long time in Namibia and Singapore (Asano et al., 2007). Technically, reclaimed water can be applied to many water use activities after proper treatment. Regulatory and public acceptability are also equally import for reclaimed water use (Chhipi-Shrestha et al., 2017a).

In Canada, the federal government endorsed the reclaimed water quality guidelines: Canadian guidelines for domestic reclaimed water for use in toilet and urinal flushing (Health Canada, 2010). Although the guidelines are prescribed only for toilet and urinal flushing, the federal government aims to develop reclaimed water use guidelines for many other beneficial uses (Health Canada, 2010). However, British Columbia provincial government implemented Municipal Wastewater Regulation in 2012 for allowing reclaimed water use in potable and non-potable purposes with the approval of local health authority (MWR, 2012). The public acceptability of reclaimed water use was studied in Canada-wide survey by Dupont (2013). Based on the survey results, 80% or more of people are willing to use reclaimed water for toilet flushing and irrigating garden grass, flowers, public parks, and golf courses. Moreover, 75% and 64% of people are willing to use reclaimed water to irrigate agriculture crops and garden vegetables, respectively. In addition, the people have willingness to pay an additional charge of $142 to $155 per year per household for reclaimed water use to avoid water restrictions. The amount is about 33% higher than their yearly water bills. The survey results are in line with another study in Ontario, which investigated public perception on reclaimed water use in different cities in the Lake Simcoe Region (LSRCA, 2010). These evidences and regulations show the possibility of reclaimed use at least in non-potable purposes.

The key barriers and challenges for universal acceptance of water reuse are potentially larger costs than conventional water, human health risk, and public perception (EU, 2016; Maimon et al., 2014). These factors are relevant for the sustainability of water reuse. Broadly, the sustainability of water reuse applications is affected by three dimensions: environment, economic, and social. Specifically, the sustainability assessment of a water reuse application requires an evaluation of indicators, such as available quantity of reclaimed water, energy use, cost, human health risk, public perception, and government policy (Dupont, 2013; Nasiri et al., 2013; Pan et al., 2018). In such decisions there can be more than one stakeholder, e.g., municipality and water consumers. On one hand, these stakeholders may have their own preferences. On the other hand, sustainability indicators can be conflicting. Both aspects should be considered while selecting a sustainable water reuse application. In such a situation, multi-criteria decision analysis (MCDA) and game theory can be combined (Soltani et al., 2016). MCDA is a method that aggregates various criteria together, in which criteria can be conflicting and have different units of measurement. This aggregation assists decision-makers to compare one alternative over another, whereas game theory can solve problems involving multiple decision-makers.

1.2. Game theory and water reuse applications

Game theory studies the outcomes of interaction between self-interested agents. "Self-interest" indicates that each agent has his own description of preferences and acts in an attempt to achieve the preferences (Leyton-Brown and Shovan, 2008). An agent's interests are commonly modelled using *utility theory* that quantifies an agent's degree of preference over a set of available alternatives. The theory also explains the change in preferences due to the uncertainty about alternative an agent faces (Leyton-Brown and Shovan, 2008). Games can be noncooperative and cooperative game. The basic modeling unit is the individual in a noncooperative game in which each player plays individually concerning only his/her benefits and do not make binding commitments to coordinate their strategies (Chew et al., 2009; Leyton-Brown and Shovan, 2008; Ma et al., 2015). A cooperative game, also called coalitional game has a group as the basic modeling unit and players form a coalition to improve their collective payoff (Leyton-Brown and Shovan, 2008; Ma et al., 2015). Game theory was developed by von Neumann and Morgenstern in 1944 with the publication of "Theory of Games and Economic Behavior" book (Madani, 2010; Nash, 1951).

The strategic interactions in game theory are commonly represented in a normal form, also known as the strategic or matrix form.

A (finite, n-person) normal-form game is a tuple (N, A, u), where N is a finite set of n players, indexed by i (Leyton-Brown and Shovan, 2008);

$A = A_i \times \cdots \times A_n$, where A_i is a finite set of actions available to player i.

Each vector

$a = (a_i, \ldots\ldots, a_n) \in A$ is called an action profile;

$u = (u_i, \ldots\ldots\ldots, u_n)$ where u_i: $A \rightarrow R$ is a real-valued utility (or payoff) function for player i.

Games can be represented by an n-dimensional matrix or tree. In a matrix, each row contains a possible action for Player 1, each column contains a possible action for Player 2, and each cell corresponds to one possible outcome. In the cell, each player's utility for an outcome is written with Player 1's utility in the first, Player 2's utility in the second and so on (Soltani et al., 2016). Game theory problems are solved by identifying certain subsets of outcomes, called *solution concepts*. The most fundamental solution concepts are Pareto optimality and Nash equilibrium (Leyton-Brown and Shovan, 2008).

a) *Pareto optimality*: Strategy profile "s" is Pareto optimal, or strictly Pareto efficient, if there does not exist another strategy profile $s' \in S$ that Pareto dominates s. Also, strategy profile s Pareto dominates strategy profile s' if for all $i \in N$, $u_i(s) \geq u_i(s')$, and there exists some $j \in N$ for which $u_j(s) > u_j(s')$.

where u_i and u_j are real-valued utility (or payoff) functions for player i and j, respectively.

N is a finite set of n players, indexed by i.

b) *Nash equilibrium*: A strategy profile $s = (s_1, \ldots.., s_n)$ is a Nash equilibrium if, for all agents i, s_i is a best response to s_{-i}. Also, player i's best response to the strategy profile s_{-i} is a mixed strategy $s^*_i \in Si$ such that $u_i(s^*_i, s_{-i}) \geq u_i(s_i, s_{-i})$ for all strategies $s_i \in S_i$.

where $s_{-i} = (s_1, \ldots, s_{i-1}, s_{i+1}, \ldots, s_n)$, a strategy profile "s" without agent i's strategy, i.e. "s" $= (s_i, s_{-i})$ and agents other than i is -i.

Nash equilibrium in any non-cooperative game is a solution from which no player can unilaterally deviate to improve his payoff (Chew et al., 2011; Nash, 1950, 1951). On the other hand, Pareto optimal is the best solution in a cooperative game in which no one can be made