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Life cycle assessment of water supply alternatives in water-receiving areas of the South-to-North Water Diversion Project in China

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ABSTRACT

To alleviate the water shortage in northern China, the Chinese government launched the world's largest water diversion project, the South-to-North Water Diversion Project (SNWDP), which delivers water from water-sufficient southern China to water-deficient northern China. However, an up-to-date study has not been conducted to determine whether the project is a favorable option to augment the water supply from an environmental perspective. The life cycle assessment (LCA) methodology integrated with a freshwater withdrawal category (FWI) was adopted to compare water supply alternatives in the water-receiving areas of the SNWDP, i.e., water diversion, wastewater reclamation and seawater desalination. Beijing, Tianjin, Jinan and Qingdao were studied as representative cities because they are the primary water-receiving areas of the SNWDP. The results revealed that the operation phase played the dominant role in all but one of the life cycle impact categories considered and contributed to more than 70% of their scores. For Beijing and Tianjin, receiving water through the SNWDP is the most sustainable option to augment the water supply. The result can be drawn in all of the water-receiving areas of the middle route of the SNWDP. For Jinan and Qingdao, the most sustainable option is the wastewater reclamation system. The seawater desalination system obtains the highest score of the standard impact indicators in all of the study areas, whereas it is the most favorable water supply option when considering the freshwater withdrawal impact. Although the most sustainable water supply alternative was recommended through an LCA analysis, multi-water resources should be integrated into the region's water supply from the perspective of water sustainability. The results of this study provide a useful recommendation on the management of water resources for China.

1. Introduction

Water shortages and water scarcity have threatened many parts of the world, particularly in China (Liu and Yang, 2012). China's per capita water resources are only 25% of the world average (Cheng et al., 2009), whereas the water consumption per unit of Gross Domestic Product (GDP) is three times the world average (Liu and Yang, 2012). Moreover, the heterogeneous distribution of freshwater, both spatially and temporally, further aggravates the water shortage, especially for northern China (Gu et al., 2012; Li et al., 2011). Northern China (approximately 1,920,000 km^2) contains only 19.1% of the total national water resources (Ministry of Water Resources (2012)), whereas it holds 45% of the total cultivated land and 36% of the total population and generates half of the national percentage of GDP (Cheng et al., 2009). The water shortage in this region poses a huge risk to food security and economic development.

To relieve the water shortage that has been plaguing northern China, the location of sustainable complementary water resources is an important task. The South-to-North Water Diversion Project (SNWDP) is an infrastructure project with an investment of over 500 billion yuan (U.S. $80.5 billion) to divert water from water-sufficient southern China to water-deficient northern China. After undergoing a 50-year feasibility study, the project was launched in 2002. It has been driven by its favorable functions such as diminishing the adverse impact of extreme hydrologic events and ensuring food production and economic development. The three-route water transfer project (i.e., East, Middle and West route)

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links the nation's four major rivers (i.e., the Yangtze River, Yellow River, Huai River and Hai River) that stretch more than 2000 km. Until now, it has been the largest water diversion project ever developed (Li et al., 2015). By 2050, the project will be fully implemented. Forty to fifty billion cubic meters of water are supposed to be delivered to northern China every year and benefit 300 to 325 million people (Lin et al., 2012; Zhang, 2009). During the construction of the SNWDP, various solutions to alleviate water scarcity have been introduced in northern China such as wastewater reclamation, seawater desalination and rainwater harvesting. Seawater is an unlimited water resource; meanwhile, wastewater reclamation can simultaneously resolve quantity-related and quality-related water scarcity (Jiang, 2009). Both of these solutions are considered the most promising strategies and have been widely implemented.

While all water supply alternatives are potentially feasible strategies to augment water supply, each of them presents costs and benefits in terms of environmental impacts (Mo et al., 2014). For example, the SNWDP has sparked a grievous controversy in environmental implication. On the one hand, it is not regarded as a reliable water supply system because of its extensive energy demand, which is currently supplied to a large extent by fossil fuel. On the other hand, it has potential impacts on water supply areas such as potential water shortage (Chen et al., 2013; Gu et al., 2012) and saltwater intrusion in the Yangtze River Estuary (Xu et al., 2012). Wastewater reclamation and seawater desalination usually require additional chemicals and energy consumption and emit air pollutants (Tong et al., 2013).

To promote more sustainable water supply decisions, there is a need to systematically evaluate the environmental impacts of water supply alternatives. Life Cycle Assessment (LCA) is a methodological tool that has proven its strengths to provide a quantitative environmental analysis by using a “cradle-to-grave” approach (Lundie et al., 2004; Muñoz and Fernandez-Alba, 2008). In the past 10 years, it has been widely applied to evaluate existing water systems and to propose alternative and environmentally sound practices (Pasqualino et al., 2011). The literature contains studies on potable water production (Vince et al., 2008; Godskesen et al., 2012), wastewater reuse systems (Meneses et al., 2010; Ortiz et al., 2007; Tong et al., 2013; Zhang et al., 2010), seawater desalination systems (Raluy et al., 2006; Tarnacki et al., 2012) and the environmental assessment of the urban water cycle (Amores et al., 2013; Lundie et al., 2004). LCA has also been used for the comparison of water supply systems. Previous studies have shown that seawater desalination systems have 2–18 times more emissions than importation or recycling (Lyons et al., 2009; Stokes and Horvath, 2005; Raluy et al., 2005). However, the environmental impact of seawater desalination can be decreased by approximately 65–70 times when the electricity production model is shifted from traditional fossil fuel to renewable energy (Raluy et al., 2006). Recently, taking into account the increased awareness of water scarcity, the LCA methodology has been extended with the addition of a freshwater withdrawal category (FWI) in a number of papers to determine the optimal water supply option (Godskesen et al., 2013; Muñoz et al., 2010).

By December 12th, 2014, the first phase of the east and middle route of the SNWDP was completed and placed into operation. The data of the material consumption and energy requirements are available and offer an opportunity for evaluating the environmental impacts of the SNWDP. Therefore, the aim of this study was to conduct a comparative LCA of various promising water supply alternatives in the water-receiving areas of the SNWDP including water diversion, wastewater reclamation and seawater desalination. Because the different water supply systems draw water from different regions, we adopted the method of Godskesen et al. (2013) for integrating FWI into the LCA methodology to compare the three water supply alternatives. To the best of our knowledge, this is the first study comparing the environmental impacts of SNWDP with other water supply alternatives from an LCA perspective. The results of this study provide general recommendations on water resource management in water-receiving areas of the SNWDP.

2. Methods

2.1. Study areas

Beijing, Tianjin, Jinan and Qingdao were chosen as study areas because they are typical water-receiving areas of the SNWDP. These four cities primarily rely on local groundwater and surface water sources that together constitute more than 70% of the total water supply (Table 1). However, these groundwater and surface water sources are becoming restricted. According to the Water Resources Bulletin 2012, the per capita freshwater resources in these four cities are much lower than the threshold of water scarcity in the world (i.e., 500 m^3 p.a.). A variety of unconventional water resources have been increasingly implemented in these regions to augment the existing water supply.

2.2. Description of water supply alternatives

We considered three supplementary water supply scenarios in the four study areas (Table 2) as outlined in the following subsections.

2.2.1. Imported water supply scenario

The imported water supply scenario (S1) in the four study areas attained water through the SNWDP. Beijing and Tianjin are the main water-receiving areas of the middle route of the SNWDP. The canal of the middle route of the SNWDP runs 1432 km from Danjiangkou reservoir at the Han River to Beijing and Tianjin (Fig. 1). The total volume of water abstraction is 9.5 billion m^3 per year, of which 1.24 billion m^3 and 1.02 billion m^3 of water is expected to be delivered to Beijing and Tianjin, respectively (Dong and Wang, 2011). Jinan and Qingdao are the east route of the SNWDP which draws water from the lower reach of the Yangtze River (Fig. 1). A total of 100 and 146 million m^3/year of water is supposed to be received by Jinan and Qingdao, respectively. This route consists of 1467 km canal and 54 pumping stations, which are applied to lift water 65 m over the Yellow River. Imported water is treated to meet the customers' water quality requirements before it reaches the distribution network.

2.2.2. Reclaimed water supply scenario

In the reclaimed water supply scenario (S2), reclaimed water is utilized to replace an equivalent volume of freshwater withdrawal. The scenario was based on the representative wastewater reclamation technologies applied in the four study areas (Table 2). For instance, the Qinghe reclaimed water treatment plant in Beijing is the largest reclaimed water treatment plant in China with a production capacity of 80,000 m^3/day. In Tianjin, the Jizhuangzi reclaimed water treatment plant is the largest wastewater reclamation treatment plant with a production capacity of 70,000 m^3/day. In this scenario, it was assumed that reclaimed water would be utilized for non-potable use. Processes associated with sewer pumping, primary treatment, secondary treatment and tertiary treatment were included in the LCA analysis.

2.2.3. Desalinated seawater supply scenario

In the desalinated seawater supply scenario (S3), representative seawater desalination projects were chosen as case studies