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Research article

Modeling the carbon-energy-water nexus in a rapidly urbanizing catchment: A general equilibrium assessment

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ABSTRACT

Energy and water systems are interdependent and have complex dynamic interactions with the socio-economic system and climate change. Few tools exist to aid decision-making regarding the management of water and energy resources at a watershed level. In this study, a Computable General Equilibrium (CGE) model and System Dynamics and Water Environmental Model (SyDWEM) were integrated (CGE-SyDWEM) to predict future energy use, CO_2 emissions, economic growth, water resource stress, and water quality change in a rapidly urbanizing catchment in China. The effects of both the CO_2 mitigation strategies and water engineering measures were evaluated. CO_2 mitigation strategies have the potential to reduce 46% CO_2 emissions and 41% energy use in 2025 compared with reference scenario. CO_2 mitigation strategies are also found to be effective in promoting industrial structure adjustment by decreasing the output of energy- and water-intensive industries. Accordingly, it can alleviate local water stress and improve water environment, including a 4.1% reduction in both domestic water use and pollutant emissions, a 16.8% water demand reduction in the labor-intensive industry sector, and 4.2% and 4.4% decrease in BOD_5 and NH_3-N loads in all industrial sectors, respectively. It is necessary to implement water engineering measures to further alleviate water resource stress and improve water quality. This study improves the understanding of the feedbacks of CO_2 abatement on water demand, pollutant discharges, and water quality improvement. The integrated model developed in this study can be used to aid energy, carbon, and water policy makers to understand the complicated synergistic effects of proposed CO_2 mitigation strategies on water demand and pollution emissions, and to design more effective policies and measures to ensure energy and water security in the future.

1. Introduction

Providing reliable and sustainable energy and water service faces multiple challenges, including increasing demand due to population growth and economic development, water resources degradation, fossil energy resource depletion as well as climate change (Liu et al., 2016; WWAP, 2014). To ensure energy and water security as well as the adaptation to climate change, the Chinese government has implemented a series of CO_2 mitigation, energy and water saving, and pollutant emission reductions policies and measures. Recently, the Nationally Determined Contributions (NDC) in the Paris Agreement was announced to reduce CO_2 emission intensity (CO_2 emissions per unit of GDP) by 60%–65% in 2030 on the base of 2005 level (UNFCCC, 2015). At the same time, the 13th *Five-Year Plan for economic and social development* (NPC, 2016) proposes that energy and water use efficiency (energy and water use per unit of GDP) should be improved by 30% and 18% in 2020, respectively, compared with 2015 level. In addition, two main water pollutant control targets are set to improve surface water quality, including a 10% reduction of industrial chemical oxygen demand (COD) and ammonia nitrogen (NH_3-N) discharge in 2020 compared with 2015 level. Water and energy systems are interdependent, and thus policies and measures designed to increase the efficiency in one system might significantly affect another (Hussey and Pittock, 2012; Li et al., 2017; Rothausen and Conway, 2011). To aid decision-makers to meet these goals efficiently, there is a need to integrate CO_2 mitigation strategies with water resources management. The integrated approach helps better understand the links between energy and water systems and their dynamic interactions with socio-economic

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development and CO_2 emissions.

The impacts of CO_2 mitigation strategies on long-term economic and energy use have been widely studied (Dai et al., 2011; Dong et al., 2015; Wang et al., 2015; Wu et al., 2016). In China, several studies found that the implement of China's NDC can reduce CO_2 emission and energy consumption, and have adverse effects on economic output and employment in energy- and carbon-intensive industries (Dai et al., 2011; Dong et al., 2015; Wang et al., 2015; Wu et al., 2016). Furthermore, its co-benefits on air pollutant reduction (Dong et al., 2015) and health effects (Wu et al., 2017; Xie et al., 2016) have gained much attention recently. Recently, some energy-water nexus studies have been carried out to analyze the impacts of CO_2 mitigation strategies on energy use and water consumption in the power generation sector (Arent et al., 2014; Cameron et al., 2014; Chandel et al., 2011; Huang et al., 2017; Talati et al., 2016). These studies investigated water saving and CO_2 emission reduction under different CO_2 mitigation strategies and indicate that these strategies may increase or decrease water consumption due to the wide range of water use intensity of low-carbon emissions technologies choices (Kyle et al., 2013; Liu et al., 2015; Talati et al., 2016). Also, there are increasingly integrated modeling tools considering the broader nexus of water, energy, and food system for CO_2 mitigation and climate adaptation purposes (Ermolieva et al., 2015; Howells et al., 2013; Kraucunas et al., 2015; Martinez-Hernandez et al., 2017). CO_2 mitigation strategies involving a carbon price can also promote the adjustment of industry structure to a low-carbon, high energy efficient one (Dong et al., 2015; Dong and Liang, 2014; Xing et al., 2011), which have extensive impacts on the water consumption and pollutant discharge in the economic system (Cooper and Sehlke, 2012). However, these cross-sector feedbacks have not been fully considered in current water-energy nexus studies. In addition, a whole economic-wide assessment of the impacts of CO_2 mitigation on water pollutant emission reduction is in lacking. Some studies have assessed energy conservation and pollutant reduction using a technology-based bottom-up model in China's pulp and paper (Wen et al., 2015) and steel sectors (Wang et al., 2017). There are few studies integrating energy use, CO_2 emissions, economic and population growth, water resource stress and water quality change. An integrated model capturing the feedbacks among socio-economic, energy, and water systems is needed to help policymakers identify the possible co-benefits across these systems and formulate more effective policies and measures.

Available energy models and water system models assess CO_2 mitigation strategies and water engineering measures independently. In energy system, Long-range Energy Alternatives Planning (LEAP) (Heaps, 2016) and The Integrated MARKAL-EFOM System (TIMES) (Loulou et al., 2005) have been used to predict long-term energy planning and CO_2 mitigation. Compared with these methods, Computable General Equilibrium (CGE) model has been widely used to simulate the full range of future economic system (e.g. industry output, domestic and international trade) and energy system (e.g. energy supply, consumption and trade) (Cheng et al., 2016; Dai et al., 2011, 2016, 2012; Dong et al., 2015; Xie et al., 2016). In water system, many integrated water management models such as Water Evaluation And Planning (WEAP) (Hollermann et al., 2010; Illich, 2006; Li et al., 2015; Yates et al., 2005), Elbe-DSS (de Kok et al., 2009; Hahn et al., 2009; Lautenbach et al., 2009), System Dynamics and Water Environmental Model (SyDWEM) (Qin et al., 2011, 2013) are developed to evaluate effects of series of socio-economic and water engineering measures on water environment management. These integrated water models have been coupled with currently available energy models (e.g., the integration of LEAP and WEAP) to support planning for both water and energy system (Howells et al., 2013). However, the socio-economic components (e.g., population and economic growth rate) in these studies are regarded as external scenarios and fixed, and thus the feedbacks between different socio-economic components and between energy and water system cannot be effectively captured (de Kok et al., 2009; Lautenbach et al., 2009; Qin et al., 2013). The SyDWEM (Qin et al., 2011) model developed in our previous studies provides a useful tool to better understand the interactions among socioeconomic, water infrastructure, and receiving water systems by treating the socio-economic dynamics as an internal sub-module. The SyDWEM model has been successfully applied to a rapidly urbanizing coastal region (Qin et al., 2011, 2013).

In this study, a CGE model was integrated with the upgraded version of SyDWEM (CGE-SyDWEM) to simulate energy and water systems simultaneously and support the decision-making regarding management of energy and water resources and carbon reduction policy. Using this integrated model, planners from water and energy sectors could examine the cross-sectoral feedbacks, especially the impacts of CO_2 mitigation strategies on water demand and pollutant discharges as well as water quality. In this study, water demand, or water withdrawal, is defined as the amount of water withdrawn from all water resources, including local groundwater and surface water resources, water transfer from other catchment, and reclaimed wastewater reuse. The Shenzhen River Estuary catchment located in a rapidly urbanizing coastal region of Southeast China (Fig. A.1) was chosen as the study area. With rapid economic and population growth, the Shenzhen River Estuary catchment is facing challenges to meet the increasing water and energy demand. This study aims (1) to examine the performance of the integrated CGE-SyDWEM in simulating the interactions among socioeconomic, energy, carbon and water environmental systems; (2) to evaluate the co-benefit of CO_2 mitigation strategies on water use saving and pollutant emission reduction; and (3) to assess if the current water engineering measures can satisfy water demand, water pollutant reduction, and water environmental targets.

2. Methodology

2.1. IMED|CGE model

The IMED|CGE (**I**ntegrated **M**odel of **E**nergy, **E**nvironment and **E**conomy for Sustainable **D**evelopment | **C**omputable **G**eneral **E**quilibrium) model applied in this study can be classified as a 25-sector (Table A.1), 1-region, recursive dynamic CGE model developed for Shenzhen City by the Laboratory of Energy & Environmental Economics and Policy (LEEEP) at Peking University. The 2007 input and output table and 2007 energy balance table for Shenzhen are used for the base year calibration. The major features of the model are similar to the one-region version (Dai et al., 2012), including a production block, government and household incomes and expenditures blocks, and a market block with domestic and international transactions. The activity output for each sector follows a nested constant elasticity of substitution (CES) production function. Inputs are categorized into material commodities, energy commodities, labor, capital and resources. More technical descriptions can be found in Appendix B or available at http://scholar.pku.edu.cn/hanchengdai/imedcge.

2.2. SyDWEM

SyDWEM was developed to describe the socio-economic, water infrastructure, and the change of receiving water system in the Shenzhen River catchment during 1990–2020 (Qin et al., 2011, 2013) (equations and parameters are accessed at the webpage of http://see.szpku.edu.cn/qhp_sydwem.aspx.) The model is upgraded to meet our requirements in this study in the following five aspects: (1) The simulation period was extended to the year 2025. The simulations results of labor productivity for each industry in 2025 have been compared with the corresponding data in Japan (JPC, 2016) and Hong Kong (Census and statistics department of Hong Kong, 2016) to guarantee the projection for each industry falling in a reasonable range; (2) Previous industrial structure was considered as a decision variable, and its effect on GRP and population growth was evaluated using scenario analysis. However, in the updated SyDWEM, the industrial structure is predicted by