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Water–energy nexus of the Eastern Route of China's South-to-North Water Transfer Project

Dan Chen[a,b], Di Zhang[a], Zhaohui Luo[c], Michael Webber[d]
and Sarah Rogers[e]

[a] *College of Agricultural Engineering, Hohai University, Nanjing 210098, China*
[b] *Department of Agricultural and Biological Engineering, The University of Florida, Gainesville 32611, USA*
[c] *Corresponding author. College of Resources and Environmental Sciences, Nanjing Agricultural University, Nanjing 210095, China. E-mail: lzhui@njau.edu.cn*
[d] *School of Geography, The University of Melbourne, Victoria 3053, Australia*
[e] *Centre for Contemporary Chinese Studies, The University of Melbourne, Victoria 3053, Australia*

Abstract

This article investigates the energy intensity and related impacts of the Eastern Route of China's South-North Water Transfer Project, based on the concept of the water–energy nexus. It finds that from November 2013 to May 2017 a total of 2.35 billion kWh of energy was consumed to transfer 15.5 billion m^3 water driven by a large-scale system of pumping stations. This energy production required 7.4 million m^3 of virtual water and emitted 1.93 $MtCO_{2e}$ of carbon. An average water–energy nexus ratio of 0.05% indicates that transferring 100 m^3 of water consumes 0.05 m^3 of virtual water due to the electricity consumption of the Eastern Route's pumping stations. It is estimated that to transfer 7.3 billion m^3 water by 2030, this mega project will consume 1.35 billion kWh of energy, 4.6 million m^3 of virtual water and emit 0.94 $MtCO_{2e}$ of carbon. These findings and scenario analysis demonstrate that strategies are needed for mitigating the energy intensity of the Eastern Route, such as improved pumping efficiency, reduced water loss during water delivery, decreased water quotas, and promotion of other, less carbon-intensive water sources in destination provinces.

Keywords: Eastern Route; Energy intensity; South-to-North Water Transfer Project (SNWTP); Water–energy nexus

Introduction

The inextricable link between water and energy, known as the water–energy nexus, has received increased attention in the theoretical and empirical work concerned with achieving and sustaining water and energy security (Griggs *et al.*, 2013; Wakeel *et al.*, 2016; Endo *et al.*, 2017; Inas *et al.*,

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2017). While there is no formal definition of the concept, it refers to the relationship between the water used for energy production, including fuel extraction and processing and electricity generation, and the energy consumed to extract, purify, deliver, heat or cool, treat, and dispose of water (Spang *et al.*, 2014; Hamiche *et al.*, 2016; Lee *et al.*, 2017). Since the water used for energy production need not be the same water that is processed using that energy, this relationship is not truly a closed loop; nonetheless, all forms of energy production require some input of water (Ackerman & Fisher, 2013; Tsolas *et al.*, 2018). A lack of understanding of the interdependence between these two resources within a system can result in misuse and mismanagement of resources (Scott *et al.*, 2011). Many variables influence the water–energy nexus, including the governance and availability of natural resources, the potential for climate change, economic globalization, and increased urbanization and demands (Radcliffe, 2018). Some studies also considered the correlation between the water–energy nexus and greenhouse gas (GHG) emissions responsible for global climate change (Reffold *et al.*, 2008; Plappally, 2012; Shrestha *et al.*, 2012; Wang *et al.*, 2012; Fang & Chen, 2017). Greater focus on the energy requirements and carbon emissions of water systems has become crucial to the sustainable management of these systems (Lee *et al.*, 2017).

China has become the world's largest energy consumer, accounting for around 23% of global energy consumption (Dale, 2017). Accordingly, China is the largest emitter of energy-related carbon dioxide. It emitted 10.4 billion tons, accounting for around 29% of global CO_2 emissions in 2015 (Le Quéré *et al.*, 2018). The development of energy conservation and emissions reductions policies has become an urgent and tough task for China. Since water and energy are governed by different state institutions, principally the Ministry of Water Resources and the National Energy Administration, there is even more need to enhance our understanding of the water–energy nexus in China. Increased attention is being paid to the energy consumption and carbon dioxide emissions of hydropower and hydraulic projects; however, few studies have examined large-scale water diversions (Rothausen & Conway, 2011; Nair *et al.*, 2014; Li *et al.*, 2016; Dai *et al.*, 2017; Lin & Chen, 2017; Zhao *et al.*, 2017). Like other large-scale construction projects, China's South–North Water Transfer Project (SNWTP) is high in energy consumption and carbon emissions, both in its construction and operation. It appears that the project's impact assessments neglected, underestimated, or perhaps downplayed energy consumption and carbon emissions at the demonstration and planning stages, even though unlike the Middle Route which is gravity fed, the Eastern Route relies on a large-scale system of pumping stations to lift water over 65 m from the Yangtze River to its destinations. Further, cities and provinces along the Eastern Route are highly reliant on energy imports. For instance, Jiangsu Province, the starting point of the Eastern Route, is among the top energy importing provinces of China with an energy self-sufficiency rate of 20%, compared to that of Shandong which is 37% (Chu, 2017). There are a number of rationales, therefore, for undertaking in-depth analysis of the Eastern Route's water–energy nexus: to better understand the possible mismatch between location and energy resources (and any risk of energy shortages), and to better understand the energy intensity and therefore broader environmental sustainability of this mega, strategically important project.

This article raises two questions about the SNTWP's Eastern Route framed by the concept of a water–energy nexus: (1) What is the total energy consumption, virtual water, and carbon emissions required to transfer water along the Eastern Route; and, (2) What are the implications of this water–energy nexus in the planning and management of interbasin water transfers? This article argues that the water–energy nexus should be embedded into impact and efficiency analysis of mega water transfer projects, going beyond conventional environmental impact assessment. To this end, it has two objectives. First, by estimating the energy consumption, virtual water and carbon emissions of the Eastern Route and discussing the potential impacts and countermeasures, the article presents a water–energy nexus-based understanding of mega water transfer projects. Second, the article emphasizes the importance of the water–energy nexus concept to research, training, and policy advocacy that can potentially advance nexus-oriented strategies in planning, design, operation, and management of mega water transfer projects. The article is structured as follows. The next section presents a brief overview of the Eastern Route, the methods of estimation and the data sources followed by a section describing the estimation results and discussing impacts and countermeasures. The final section concludes with the article's main findings and implications.

Materials and methods

The South-North Water Transfer's Eastern Route

The completed Eastern Route has the capacity to supply 14.8 billion m^3 per year from the Yangtze River to northern China through a system of pumps, rivers, lakes, reservoirs and canals, including the Grand Canal, itself more than 2500 years old (Webber *et al.*, 2017) (Figure 1). Its construction consisted of three stages. The first stage began operating in 2013, providing 15.5 billion m^3 water for the provinces of Jiangsu, Anhui and Shandong between November 2013 and May 2017. The second and third stages are not yet operational. The Eastern Route consists of a trunk line and many local branch lines with complicated ancillary works: this study focuses on the water pumped by the stations along the trunk line. Although energy consumption and carbon emissions are generated in both construction and operation, due to data availability, this study mainly considers the route's operation between 2013 and 2017.

Estimation methods

A conceptual framework for understanding the water–energy nexus of the Eastern Route is presented in Figure 2. Figure 2(a) depicts the links between water and energy in the Eastern Route. Energy is required in many processes, including water engineering construction, water source pollution treatment and control, water pumping and conveying, water distribution and treatment, end use, reclamation, and disposal at local levels. Conversely, water is required in many processes associated with energy, including production and transportation of construction materials, energy used during project construction, and electricity generation and delivery for project operation. Further, energy production as well as its utilization creates carbon emissions, which contribute to climate change. The role of hydroelectric reservoirs in emitting carbon is the subject of increased attention in the climate science and policy community (Barros *et al.*, 2011), while specific studies of the water–energy–carbon nexus have been conducted, especially for cities (Venkatesh *et al.*, 2014; Valdez *et al.*, 2016; Chhipi-Shrestha *et al.*, 2017). This study integrates the amount of water diverted, energy consumption, virtual water flows, and carbon emissions into a quantitative analysis of the sustainability of the Eastern Route.

Our method consists of the steps outlined in Figure 2(b). First, the amount of water pumped by stations in different sections of the route was calculated from actual water diversions into different provinces from 2013 to 2017, and the planned water allocations. Second, the electricity consumption for pumping water was estimated using an equation with hydraulic heads for pumping, the efficiency of

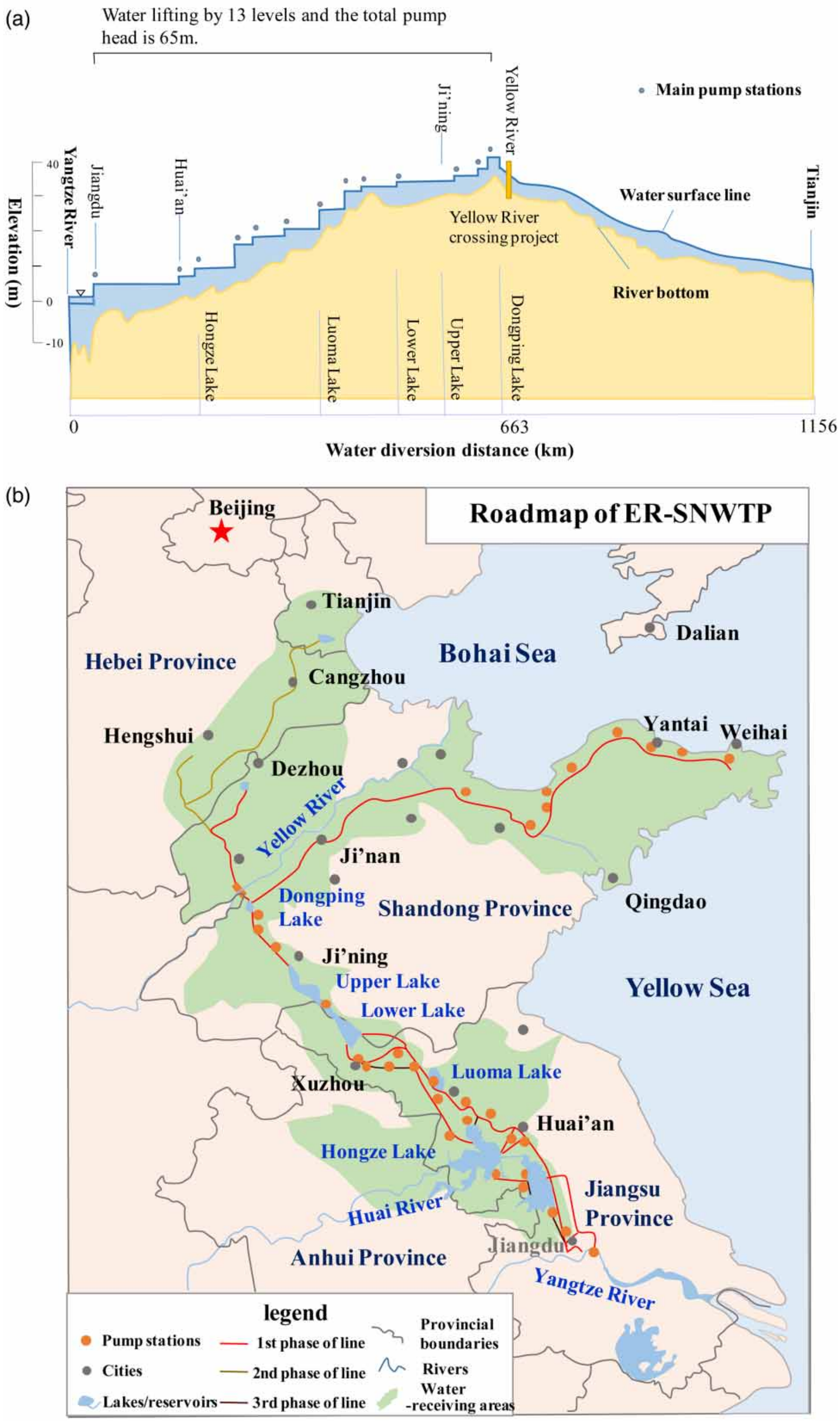

Fig. 1. View of the vertical section and roadmap of the ER-SNWTP. (a) Vertical section of the main channel; (b) roadmap of ER-SNWTP.

Fig. 2. A conceptual framework for water–energy nexus of the Eastern Route. (a) Linkage between water and energy in the Eastern Route; (b) methodological steps and data input for the estimations.

pumping stations, and the amount of water pumped by each station. Third, virtual water for electricity generation was estimated using data on China's power industry, water demand quotas of different generation methods, and water diversions and energy consumption in different sections of the Eastern Route. In addition, the ratios of virtual water to total water pumped were calculated. Finally, carbon emissions for electricity generation were estimated using conversion factors for different generation methods. The methods and data sources for each step are each described in more detail.

Electricity consumption. Theoretically, electricity consumption by pumping water along the trunk line of the Eastern Route could be calculated directly by adding up the electricity consumed by each station.

However, in China, detailed data on operation costs, electricity consumption, and water pumped by each station are not available to the public or even to local water conservancy departments. However, the annual quantities of water diversion into different provinces from 2013 to 2017 are published on the SNWTP's official website (www.nsbd.gov.cn/), so we estimated electricity consumption using the following method:

1. Basic theory: A basic theoretical physical relationship was applied to estimate the electricity consumption of pumping stations. Equation (1) shows this relationship: the energy required to lift 1 m^3 of water (with a density of 1,000 kg m^3) up 1 m at 100% efficiency is 0.0027 kWh (Rothausen & Conway, 2011; Wang *et al.*, 2012). The average efficiency of pumping stations from 2013 to 2017 is 75% and the predicted value for 2030 is 80% (Zhang, 2009).

$$\text{Electricity consumption (kWh)} = \frac{9.8\,\text{m}\,\text{s}^{-2} \times \text{Lift (m)} \times \text{Mass (kg)}}{3.6 \times 10^6 \times \text{Efficiency (\%)}} \tag{1}$$

2. Pump head: The actual hydraulic head (lift in Equation (1)) is an important indicator of the electricity consumption for each pumping station. Rather than searching for the data for each station, we simplified the calculation by dividing the trunk line of the Eastern Route into five sections and using the average pump head of each section. These sections were bounded by the water intake of Yangtze River, Hongze Lake (Hongze Station), Luoma Lake (Zaohe Station), the Lower Lake (Hanzhuang Station), the Upper Lake (Secondary Dam Station) and Dongping Lake (Baliwan Station).
3. Water pumped by different stations: The public data about water transferred into different provinces (Jiangsu, Anhui and Shandong) from 2013 to 2017 were allocated to the above sections with definite pumping stations using partition coefficients. These coefficients were based on the data of the planned water transfers to different cities in the General Report on Feasibility Study of the First Stage of South-North Water Transfer Project (CWHPDR, 2016).

Virtual water and water–energy nexus ratio. Since the Eastern Route consumes large amounts of electricity for pumping, this water transfer project can paradoxically also be considered a water consumer. Here we use the term 'virtual water' to refer to the hidden flows of water for electricity generation and transmission from other places. Since different forms of electricity generation consume different amounts of water, the production structures of China's power in each year were considered in the calculations, which indicate that China's electricity production was still dominated by thermal power sources (coal, oil and gas-fired generation), supplemented by hydropower and nuclear power (Department of Energy Statistics, 2017). In terms of water consumption by different electricity generation methods, the following quotas were used: 0.0016 m^3/kWh for oil-fired power generation and 0.0023 m^3/kWh for nuclear power generation (Saidur *et al.*, 2011); 0.0026 m^3/kWh for coal-fired and 0.0023 m^3/kWh for gas-fired power generation (Burkhardt *et al.*, 2011); 0.0098 m^3/kWh for hydroelectric power generation (Bakken *et al.*, 2013). Then, Equation (2) was used for calculating the virtual water for electricity consumed by pumping stations:

$$VW_i = \sum_j E_i \times \eta_j \times q_j \tag{2}$$

where VW_i denotes the quantity of virtual water (m^3) and E_i the electricity consumption (kWh) for the section i; η_j and q_j denote the percentage of electricity generation by method j in China's total electricity production (%) and the quota of virtual water from electricity generation method j (m^3/kWh).

A new index was developed to assess the water–energy nexus of the Eastern Route, named the water–energy nexus ratio (R), shown in Equation (3). This index synthesizes the effects of both the energy (E) for pumping water (W) and the virtual water (VW) for electric power generation. R is the ratio of the virtual water (VW) to the total water pumped in the period of water diversion (W). This index can also scale the virtual water input of energy use for pumping electricity consumption. The higher the ratio, the higher the energy intensity of the Eastern Route:

$$R = \frac{E}{W} \times \frac{VW}{E} = \frac{VW}{W} \tag{3}$$

Carbon emissions. Electricity generation accounted for 50% of China's emissions in 2010 (Kehua, 2014). Since pumping water consumes electricity, the Eastern Route indirectly emits carbon dioxide. We use Equation (4) to calculate the emissions associated with pumping water. The conversion factor in Equation (4) is the emissions per energy use for the main types of electricity generation: 975.2 g/kWh for coal-fired, 742.1 g/kWh for oil-fired, 607.6 g/kWh for gas-fired, 24.2 g/kWh for nuclear, and 11.3 g/kWh for hydroelectric power generation (Hondo, 2005):

$$CE_i = \sum_j E_i \times \eta_j \times \varphi_j \tag{4}$$

where CE_i, denotes carbon emissions by pumping water for section i ($MtCO_2e$); and φ_j is the conversion factor of electricity generation method j ($MtCO_2e$/kWh).

An index named the carbon emissions rate (CER) is used to quantify the energy intensity of the Eastern Route. CER ($MtCO_2e/m^3$) is the carbon emissions (CE) divided by the water pumped (W). The higher this indicator is, the greater the energy intensity for water pumping:

$$CER = \frac{CE}{W} \tag{5}$$

Overall estimation and scenario analysis. The electricity consumption, virtual water, and carbon emissions of the Eastern Route can be estimated for 2030 using data on planned water transfers. First, the data of hydraulic heads, efficiency of pumping stations and water pumped by stations for 2030 were input into Equation (1) to estimate the energy consumption for pumping water. The efficiency of pumping stations is assumed to be 80% for 2030 (Zhang, 2009). Second, data on estimated electricity consumption, projected electricity production structure (Yu & Wei, 2012), and water demand quotas of different generation methods (Xiang & Jia, 2016) were input into Equation (2) to estimate the virtual water input of energy use for pumping electricity consumption for 2030. The ratios of virtual water to water transferred were calculated using Equation (3) correspondingly, and using conversion factors, the total carbon emissions and the ratios to water transferred were estimated using Equations (4) and (5). To mitigate the energy intensity of the Eastern Route, we will discuss the strategies and their corresponding impacts using the scenario analysis method. The changes in the electricity consumption, virtual water and carbon emissions in the Eastern Route in the planned 2030 will be estimated under different management scenarios by changing the related parameters, such as the efficiency of pumping stations, the rate of water loss and changes in the planned water quotas.

Results and discussion

Estimation of electricity consumption

The estimates of electricity consumption for the Eastern Route are presented in Table 1 and Figure 3, which show that the Eastern Route has been consuming large amounts of energy by pumping water

Table 1. Electricity consumption of the Eastern Route.

Period	Water-receiving province	Quantity of water transferred (W) (10^8 m^3)	Electricity consumption (E) (10^8 kWh)	Electricity consumption (E) (kWh/m^3)
Nov. 2013–June 2014	Jiangsu	7.63	1.10	0.14
	Anhui	1.28	0.11	0.09
	Shandong	1.7	0.43	0.25
	Total	10.61	1.64	0.16
Oct. 2014–June 2015	Jiangsu	19.25	2.77	0.14
	Anhui	3.23	0.28	0.09
	Shandong	3.28	0.83	0.25
	Total	25.76	3.88	0.15
Dec. 2015–May 2016	Jiangsu	35.33	5.09	0.14
	Anhui	5.93	0.51	0.09
	Shandong	6.02	1.53	0.25
	Total	47.28	7.13	0.15
Dec. 2016–May 2017	Jiangsu	53.99	7.77	0.14
	Anhui	9.06	0.78	0.09
	Shandong	8.89	2.26	0.25
	Total	71.94	10.81	0.15
Total (Nov. 2013–May 2017)	Jiangsu	116.2	16.73	0.14
	Anhui	19.5	1.68	0.09
	Shandong	19.89	5.05	0.25
	Total	155.59	23.46	0.15
2030 (Planned)	Jiangsu	30.42	4.11	0.13
	Anhui	5.42	0.44	0.08
	Shandong	37.34	8.91	0.24
	Total	73.18	13.45	0.18

Note: As benchmarks, the energy consumption of various water sources in the UK is as follows: 0.05 kWh/m^3 (from reservoirs), 0.09 kWh/m^3 (groundwater), 0.12 kWh/m^3 (rivers), 0.49 kWh/m^3 (wastewater reuse) and 0.26 kWh/m^3 (water diversions) (Reffold *et al.*, 2008). The average for groundwater irrigation in China is 0.47 kWh/m^3 (Wang *et al.*, 2012).

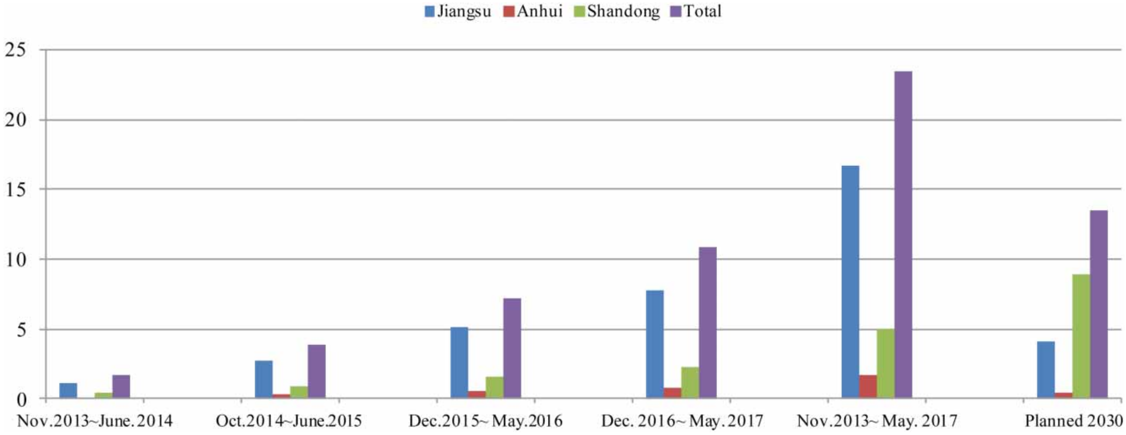

Fig. 3. Electricity consumption of the Eastern Route (10^8 kWh).

from the Yangtze River to the north. A total of 2.35 billion kWh was consumed during the period November 2013 to May 2017. The route's electricity consumption increased from 0.164 billion kWh in the period November 2013 to June 2014 to 1.082 billion kWh during December 2016 to May 2017. That 1.082 billion kWh accounted for around 0.21, 0.60 and 0.26% of total electricity consumption in Jiangsu, Anhui and Shandong provinces respectively in 2016. Importantly, these water-receiving provinces are located in eastern China, a region that is a major consumer and importer of electricity from China's west. The estimates raise questions about the project's intensive energy use in what is an energy-deficient region. Electricity consumption for transferring water into each province in different periods is mainly determined by the amount of water transferred and the pump heads. The value for Jiangsu was usually the highest, followed by Shandong, while Anhui had the lowest value in every period from 2013 to 2017. However, the value for Shandong is forecast to become the highest by 2030 as it will by then receive the greatest quantities of water.

The average electricity consumption of the Eastern Route was around 0.15 kWh/m^3 during 2013–2017. Of the three water-receiving provinces, Shandong had the highest values (0.24–0.25 kWh/m^3), followed by Jiangsu (0.14–0.15 kWh/m^3) and Anhui (0.08–0.09 kWh/m^3), due to their different pump heads. When compared to the energy consumption of various water sources in the UK, the values in Table 1 are higher than those of water sourced from reservoirs (0.05 kWh/m^3), groundwater (0.09 kWh/m^3) and rivers (0.12 kWh/m^3), but lower than the average for wastewater reuse (indirect) (0.49 kWh/m^3) and water diversions (0.26 kWh/m^3) (Reffold *et al.*, 2008). They are also lower than the average for groundwater irrigation in China (0.47 kWh/m^3) (Wang *et al.*, 2012). However, our estimates are only for conveying water along the canal; they do not include energy used for purification, distribution or wastewater treatment at the local level, all of which require additional energy inputs.

Table 1 also shows electricity consumption of the Eastern Route in 2030. The planned quantity of water to be transferred (7.318 billion m^3) is slightly higher than the period 2016–2017, with total electricity consumption rising from 1.082 billion kWh to 1.345 billion kWh. Even assuming there is a 5% increase in the efficiency of pumping stations by 2030, the average electricity consumption of water pumped (0.18 kWh/m^3) is nonetheless higher than that of 2016–2017 (0.15 kWh/m^3), due to the different water distributions among the three provinces. The quantity of water transferred into Shandong in

2030 would be about four times that during 2016–2017, and the total electricity consumption would increase from 0.226 billion kWh (2016–2017) to 0.891 billion kWh (2030), accompanied by a slight decrease of 0.01 kWh/m^3 in the electricity consumption rate. Meanwhile, the quantity of water transferred to Jiangsu would drop from 5.399 billion m^3 (2016–2017) to the planned 3.042 billion m^3 (2030), and the electricity consumption would decline from 0.777 billion kWh (2016–2017) to 0.411 billion kWh (2030), accompanied by a slight decrease from 0.14 kWh/m^3 (2016–2017) to 0.13 kWh/m^3 (2030) in the electricity consumption rate.

Estimation of virtual water and carbon emissions

Estimates of the Eastern Route's virtual water and carbon emissions are presented in Table 2 and Figure 4. The results show that the SNWTP's Eastern Route used 7.4 million m^3 of virtual water and emitted 1.93 MtCO$_2$e of carbon to transfer water from the Yangtze River during the period November 2013 to May 2017. Virtual water consumption has increased as the quantities of water transferred along

Table 2. Virtual water and carbon emissions for water pumping electricity consumption in the Eastern Route.

Period	Water-receiving province	Virtual water (*VW*) (10^6 m^3)	Ratio of virtual water to transferred water (*R*) (%)	Carbon emissions (MtCO$_2$e)	Carbon emissions rates (MtCO$_2$e km^{-3})
Nov. 2013–June 2014	Jiangsu	0.33	0.04	0.09	0.12
	Anhui	0.03	0.03	0.01	0.07
	Shandong	0.13	0.08	0.04	0.22
	Total	0.50	0.05	0.14	0.14
Oct. 2014–June 2015	Jiangsu	0.86	0.04	0.23	0.12
	Anhui	0.09	0.03	0.02	0.07
	Shandong	0.26	0.08	0.07	0.21
	Total	1.21	0.05	0.32	0.13
Dec. 2015–May 2016	Jiangsu	1.59	0.05	0.42	0.12
	Anhui	0.16	0.03	0.04	0.07
	Shandong	0.48	0.08	0.13	0.21
	Total	2.23	0.05	0.59	0.12
Dec. 2016–May 2017	Jiangsu	2.49	0.05	0.63	0.12
	Anhui	0.2	0.03	0.06	0.07
	Shandong	0.72	0.08	0.18	0.21
	Total	3.46	0.05	0.88	0.12
Total (Nov. 2013–May 2017)	Jiangsu	5.27	0.05	1.37	0.12
	Anhui	0.53	0.03	0.13	0.07
	Shandong	1.59	0.08	0.42	0.21
	Total	7.4	0.05	1.93	0.13
2030 (Planned)	Jiangsu	1.41	0.05	0.29	0.09
	Anhui	0.15	0.03	0.03	0.06
	Shandong	3.06	0.08	0.62	0.17
	Total	4.62	0.06	0.94	0.13

Note: As a benchmark, in China, the carbon emissions from groundwater pumping for irrigation were 33.1 MtCO$_2$ equivalent nationally in the mid-2000s (Wang *et al.*, 2012). The carbon emissions rates in the mid-2000s were 0.35 MtCO$_2$e km^{-3} nationally (Wang *et al.*, 2012).

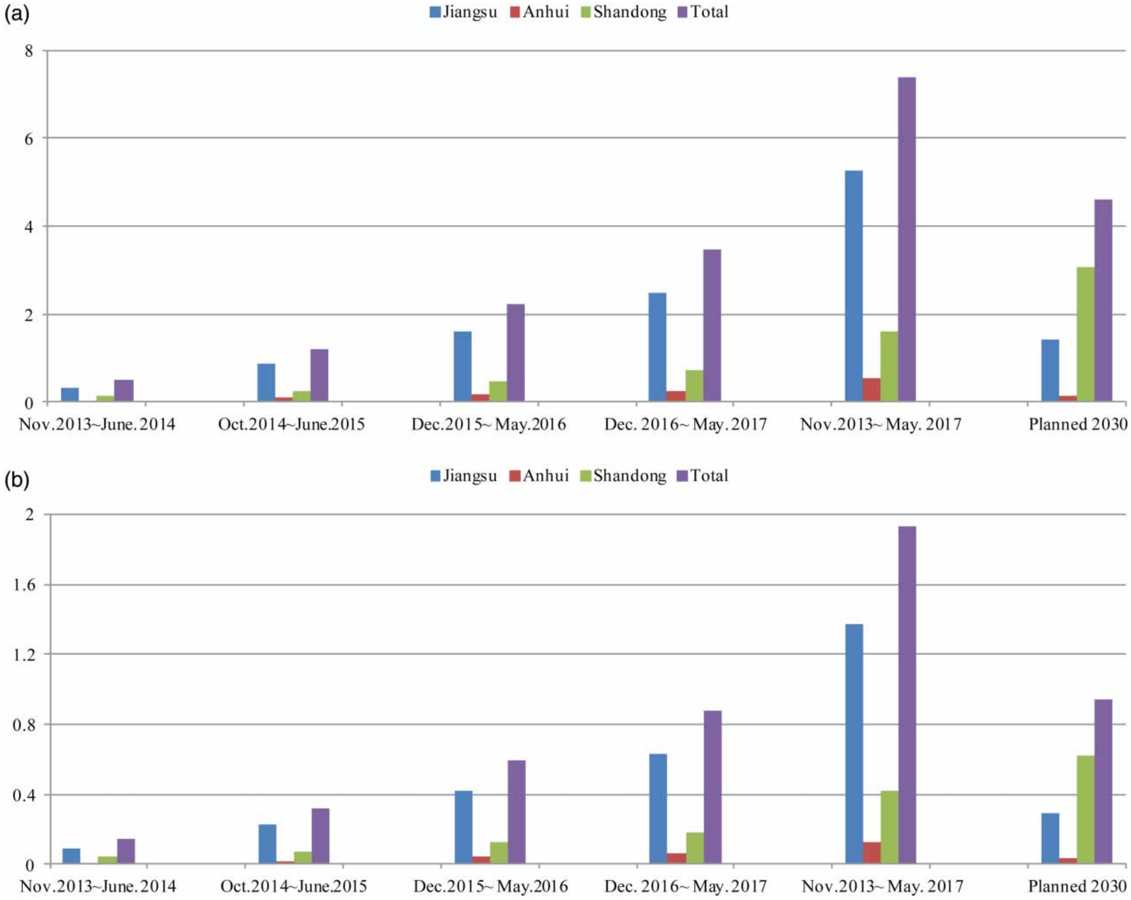

Fig. 4. Virtual water and carbon emissions for water pumping electricity consumption in the Eastern Route. (a) Virtual water (10^6 m^3); (b) carbon emissions ($MtCO_2e$).

the Eastern Route have increased, with the lowest value (0.50 million m^3) in 2013–2014 and the highest (3.46 million m^3) in 2016–2017. Total virtual water consumption will reach 4.62 million m^3 by 2030. The calculated water–energy nexus ratio (R) is also shown in Table 2. Its average ratio was 0.05% during the period November 2013 to May 2017. It has a range of 0.05–0.06%, which indicates that to transfer 100 m^3 water consumes 0.05–0.06 m^3 of virtual water.

Of the four water transfer periods, the estimated carbon emissions of the Eastern Route were the largest in 2016–2017 (0.88 $MtCO_{2e}$), and the lowest in 2013–2014 (0.14 $MtCO_{2e}$). Emissions are projected to rise to 0.94 $MtCO_{2e}$ by 2030. These emissions by the Eastern Route are mostly lower than the estimates of annual emissions from groundwater pumping for irrigation by Wang *et al.* (2012): 0.13 $MtCO_2$ equivalent in Jiangsu, 0.16 $MtCO_2$ equivalent in Anhui, 3.84 $MtCO_2$ equivalent in Shandong, and 33.1 $MtCO_2$ equivalent nationally. Yet the total emissions from water transfers in 2016–2017 account for 0.015% of the national total emissions (5,670 $MtCO_{2e}$) (Wang *et al.*, 2012). The estimated GHG emission rates of the Eastern Route (around 0.13 $MtCO_2e\ km^{-3}$) were less than those from groundwater pumping for irrigation by Wang *et al.* (2012), with 0.29 $MtCO_{2e}\ km^{-3}$ for

Jiangsu, 0.25 $MtCO_{2e}\ km^{-3}$ for Anhui, 0.26 $MtCO_{2e}\ km^{-3}$ for Shandong, and 0.35 $MtCO_{2e}\ km^{-3}$ for China in the mid-2000s. From this perspective, using more transferred water than groundwater should have a positive effect on reducing GHG emissions, especially for Shandong, which has large groundwater abstractions.

Discussion and policy implications

Because of its high lifts and large pumping stations, the Eastern Route has high operating costs which are passed on to consumers. Elsewhere it has been estimated that the Eastern Route's total annual electricity expenditure on water pumping is around 1 billion RMB (Li & Zhuan, 2016). Using a water–energy nexus framework, our analysis shows that the Eastern Route is associated with not only high economic costs but also high embodied water, energy consumption, and carbon emissions, which have broader environmental and social costs. These 'invisible' impacts and costs are similar to the concept of a virtual water trade (Hoekstra & Hung, 2002). When Yangtze water is pumped and transferred from South China to North China along the Eastern Route, there are hidden flows of energy, water, and carbon. Our estimates indicate that it took 2.35 billion kWh of electricity, 7.4 million m^3 of virtual water, and 1.93 $MtCO_{2e}$ of carbon to transfer 15.5 billion m^3 water along the Eastern Route during November 2013–May 2017. These potential impacts and costs have not been considered in project-level assessments; as such, energy-intensive water projects have expanded into energy-deficient areas. As actions to reduce carbon emissions are being conducted in a wide range of sectors in response to climate change, it is important that we recognize these impacts and develop solutions for optimizing the operations of the Eastern Route. Since the first stage of the Eastern Route has been already implemented, the concept of water–energy nexus could contribute to improving the tools and methodologies for decision making in its second and third stages.

Reducing the energy intensity of the Eastern Route can be achieved by improving the efficiency of pumping stations. This would include optimal design and operation of pumping stations, that is, the selection of pump type, capacity, and number of units, as well as scheduling their operation (Moradi-Jalal *et al.*, 2003). Many studies have been conducted of the optimal design and operation of pumping stations along the Eastern Route (Zhang & Zhuan, 2017). Some officials from the Eastern Route predicted that a 5% increase of the average efficiency of pumping stations on the present 75% would be reached by 2020, which was previously planned by 2030. The improvement in the efficiency of pumping stations will be accompanied by decreases in the electricity consumption, virtual water and carbon emissions in the Eastern Route. Table 3 shows these changes in the planned 2030 under scenario (A1) (from 80 to 85%) and scenario (A2) from 80 to 90%. However, from a water–energy nexus perspective, this goal is not just a technical question but raises questions about the economic efficiency and environmental impacts of the Eastern Route. Additionally, the related assessments should be integrated into a sustainability analysis for the Eastern Route as a whole.

Another major factor contributing to the energy intensity of large-scale and long-distance water transfer projects is water loss, mainly through evaporation, seepage, lake storage, hydraulic loss, and extractions from uncontrolled outlets. For instance, water loss of the Central Arizona Water Transfer Project in USA accounted for 4% of the total aqueduct diversion in 2012, with 85% of this water loss resulting from evaporation (Ma *et al.*, 2016). A study of the Eastern Route showed that water loss by evaporation accounted for 17.46% of the total water diverted in Jiangsu, resulting in a decrease of 10.33% of water conveyance efficiency (Qiu *et al.*, 2011). An estimate for the Middle Route indicated

Table 3. Electricity consumption, virtual water and carbon emissions in the Eastern Route in the planned 2030 under different management scenarios.

Scenarios		Electricity consumption (E) (10^8 kWh)	Electricity consumption (E) (kWh/m^3)	Virtual water (VW) (10^6 m^3)	Ratio of virtual water to transferred water (R) (%)	Carbon emissions ($MtCO_2e$)	Carbon emissions rates ($MtCO_2e$ km^{-3})
Baseline		13.45	0.18	4.62	0.06	0.94	0.13
Scenario (A)	(A1): 85%	12.66	0.17	4.35	0.06	0.88	0.12
	(A2): 90%	11.96	0.16	4.11	0.05	0.84	0.12
Scenario (B)	14%	11.57	0.15	3.97	0.05	0.81	0.11
Scenario (C)	(C1):5%	12.78	0.17	4.39	0.06	0.89	0.12
	(C2):10%	12.11	0.16	4.16	0.05	0.85	0.12
	(C3):15%	11.43	0.15	3.93	0.05	0.80	0.11
Scenario (D)	(A2) + (B) + (C3)	9.25	0.12	3.18	0.04	0.65	0.09

Note: Scenario (A1) is to improve the efficiency of pumping stations from 80 to 85%; Scenario (A2) from 80 to 90%. Scenario (B) is to reduce water loss with a rate of 14%. Scenario (C1) is to decrease the planned water quotas with a rate of 5%; scenario (C2) with 10% and scenario (C3) with 15%. Scenario (D) refers to an integrated measure including scenario (A2), scenario (B) and scenario (C3).

that evaporative loss accounted for 8.57% of the actual total diversion in 2015, its first operational year (Ma *et al.*, 2016). An investigation of Beijing-Shijiazhuang Emergency Water Diversion Section Project of the SNWTP also showed that water conveyance losses in the four periods from September 2008 to June 2013 ranged from 1.66 to 11.13% of total water diverted, shaped by weather conditions, canal construction quality and water flows (Tian *et al.*, 2015). A study of the hydraulic loss by pumping stations in the section from Nansi Lake to Dongping Lake along the Eastern Route in Shandong Province calculated the loss as 4% (Li *et al.*, 2017). The *Overall Plan on the South-North Water Diversion Project* by the Ministry of Water Resources of China in 2002 also showed that the potential annual losses for the Eastern Route accounted for around 14.6% of total diversions (MWRC, 2002). Table 3 indicates the potential deceases in the electricity consumption, virtual water and carbon emissions in the Eastern Route in the planned 2030, under scenario (B) reducing water loss with a rate of 14%. Yet affecting water loss is the many outlets (tributaries, sluice, and water intake facilities) along the line that are not controlled by the Eastern Route authorities. Since these outlets are owned by different stakeholders (e.g. Jiangsu or Shandong office of the SNWTP, Water Resources Department of Jiangsu or Shandong Province, the Huaihe River Commission, the Yellow River Commission, local water authorities or private water users), it is difficult to prevent someone from abstracting water without permission. However, while the problem of water loss for the SNWTP has been widely discussed, the energy loss resulting from this water loss has been given little attention. Integrated activities are needed that both reduce energy loss and improve the efficiency of water conveyance.

Reducing the quantity of diverted water is also an effective way of mitigating the energy intensity of the Eastern Route. Table 3 indicates the impacts in the estimated electricity consumption, virtual water and carbon emissions in the Eastern Route in the planned 2030, under scenario (C1) decreasing the planned water quotas with a rate of 5%, scenario (C2) with 10% and scenario (C3) with 15%. The planned quantity of diverted water could be reduced even after the project approaches full-scale operation. The relationship between water supply and demand is complicated and nonlinear (Zheng *et al.*, 2014; Dong *et al.*, 2018), which creates uncertainty about the volume of water that needs to be diverted to meet changing water demands in water-receiving areas. Recent data show that water consumption structures and water utilization efficiencies in water-receiving areas have improved since the implementation of SNWTP, mainly due to China's Strict Water Resources Management policy (Zhu *et al.*, 2017). The use of recycled water and desalinated water is also increasing in many water-receiving cities. For instance, the use of recycled water in Beijing has sharply increased, from 0.72% of total water supply in 1999 to 25.77% in 2016, according to the Beijing Water Resources Bulletin (1999–2016) (BWA, 2017). The 13th Five-Year Plan for water sources developed by Qingdao's government indicates that the daily supply capacity of desalinated water in Qingdao will increase from 132,000 m^3/d in 2017 to 600,000 m^3/d in 2020 (PGQM, 2017). Related evidence indicates that water conservation practices have raised water use efficiencies in many water-receiving areas and further, that many measures are planned to increase local water supply capacity. Hence it is possible that some water-receiving cities will not need as much SNWTP water as anticipated. The scope for water-saving is considerable and may be even greater than the prospective gains from water transfer projects (Chu, 2017). Additionally, it is estimated that southern China imports 52 billion m^3 of virtual water through food production from northern China, which is more than the maximum water transfer volume of the three routes of the SNWTP (Ma *et al.*, 2006). Many scholars have suggested that instead of diverting water, northern China should import water-intensive products and export commodities that require little water (Zhao *et al.*, 2015). To reduce the planning quotas of water diversion may cause political consequences for the central government, since it may show that the project would not reach its target of water supply. However, the demand for water transfer in water-receiving areas could not be constant, which determines that it is a dynamic process for allocating water quotas to different water-receiving areas. A reasonable adjustment mechanism on the water transferring quotas is needed to adapt to the demand changes in water-receiving areas.

The SNWTP will also be challenged by the increased probability of concurrent droughts in water source and destination regions (Liu *et al.*, 2015; Yuan *et al.*, 2017; Liang, 2018). Significant changes in the hydrological cycle and the need for climate change adaptation will challenge the somewhat static assumptions of water planning and management, and affect the reliability of planned diversions through the SNWTP. In a changing climate there is great urgency to re-evaluate the planned volume of water to be diverted and to develop adaptive measures to ensure the long-term sustainability of the SNWTP. Further, inter-basin water transfer may be one solution to chronic water crises, but may also be a fix that backfires (Gohari *et al.*, 2013; Chu, 2017). Both physical and virtual water flows may exacerbate water stress for water-exporting regions (Zhao *et al.*, 2015). As such, better demand management and the development of local water sources should be a priority in both water source and destination regions.

To summarize, this article answered two fundamental questions about the SNWTP's water–energy nexus. First, during the operation period from November 2013 to May 2017, a total of 2.35 billion kWh of energy was consumed to transfer 15.5 billion m^3 water; 7.4 million m^3 of virtual water was required for this energy production, which in turn emitted 1.93 $MtCO_{2e}$ of carbon. An average water–energy nexus ratio of 0.05% indicates that transferring 100 m^3 water consumes 0.05 m^3 of virtual water. Estimates of energy consumption, virtual water and carbon emissions increase sharply with the annual growth of water transferred, and differ in the water-receiving provinces. By 2030, this mega project will require 1.35 billion kWh of energy, 4.6 million m^3 of virtual water and 0.94 $MtCO_{2e}$ of carbon emissions to transfer 7.3 billion m^3 water. Our findings show that the SNWTP project has high energy intensity with implications for GHG emissions.

Second, by characterizing the SNWTP's water–energy nexus as energy intense, with large flows of virtual water and high carbon emissions, this study shows that strategies are needed to mitigate the

SNWTP's energy intensity. This may include improving pumping efficiency, reducing water loss during water delivery, decreasing the planned water quotas, and promoting other water sources with fewer carbon emissions. Table 3 shows the potential decreases in the estimated electricity consumption, virtual water and carbon emissions in the Eastern Route in the planned 2030, under different management scenarios. Clearly, long-distance water transfer projects present resource tradeoffs at multiple scales. The Eastern Route faces changing water demand and supply at the local level, a changing social and economic environment, and a changing climate. Our estimates and analyses demonstrate that the concept of water–energy nexus offers a good framework for understanding the sustainability of such mega projects and for developing methodologies for taking into account overlooked impacts. Direct measurement and reporting of energy requirements in feasibility studies for inter-basin water transfers will provide a more appropriate basis for planning and management. The nexus between water and energy policies needs to be considered to both improve existing transfers and promote sustainable development.

Overall, our analysis has a number of macro-level policy implications. First, the structure of China's electricity production could be improved by reducing the high dependence on thermal power, which consumes much more water and emits more carbon than other methods. Second, more effort needs to be made to incorporate the nexus concept into energy and water management. Rather than being regarded simply as inputs, the integrated management of water and energy would require cross-institutional and cross-jurisdictional collaboration, data sharing, and the synchronization of development targets. Third, to address the mismatch of water transfers and energy availability in eastern China, reductions in the quantity of planned diversions are a direct way to reduce the energy consumed by pumping water. We recognize, of course, that this would involve a complex and politically charged re-evaluation of water allocation decisions. This study's results suggest that further research into the water–energy nexus of mega water transfer projects should be conducted. In particular, energy consumption, virtual water flows and carbon emissions during project construction should be further accounted for. We also recognize the limitations of this study's estimated results due to a combination of data from various sources and calculation parameters in the equations. Further data collection in the form of field surveys is needed to support in-depth comparative analysis. Sensitivity analysis could also be used to test the robustness of results from the variations in parameters.

Conclusions

This article has examined the energy intensity of transferred water along the Eastern Route of the SNWTP within the framework of the energy–water nexus. The results fill a knowledge gap in our understanding of energy consumption, virtual water flows, and carbon emissions in the world's largest water transfer project. They are of critical importance for decision-making about the next two stages of the project, as well as for the sustainable operation and management of the first stage of the Eastern Route. The nexus-based analysis could also help to improve the methodologies of sustainable planning and management of water resources in China. The key findings of this study are:

1. The Eastern Route of SNWTP, driven by a system of pumping stations, has a large impact on the intensity of energy use in eastern China. It consumed electricity at a rate of 0.15 kWh/m^3 during its operation from November 2013 to May 2017. Energy consumption for transferring water into different provinces accounted for 0.2–0.6% of the total electricity consumption in the water-receiving provinces of Jiangsu, Anhui, and Shandong.

2. The Eastern Route consumed 7.4 million m^3 of virtual water during the operation period of November 2013–May 2017, amounting to 0.05% of the total water transferred. Transferring 100 m^3 of water from the Yangtze River consumes 0.05 m^3 virtual water due to energy consumed through pumping. Since power in eastern China is mainly imported from western China, the Eastern Route also consumes virtual water from these water-deficient areas.
3. The Eastern Route was an indirect emitter of carbon dioxide due to its massive electricity consumption: total emissions of 1.93 $\mathrm{MtCO_{2e}}$ during 2013–2017 accounted for 0.034% of the total national emissions (5670 $\mathrm{MtCO_{2e}}$). However, the Eastern Route's average emission rate of 0.13 $\mathrm{MtCO_{2e}\,km^{-3}}$ is less than those from groundwater pumping for irrigation, which indicates that emissions will fall if transferred water replaces groundwater, especially in Shandong. The estimated data invite further analyses of the relative energy intensity and carbon emissions of various sources of water supply.
4. By 2030, this mega project will consume 1.35 billion kWh of energy, 4.6 million m^3 of virtual water and 0.94 $\mathrm{MtCO_{2e}}$ of carbon emissions in order to transfer 7.3 billion m^3 of water. Estimates of energy consumption, virtual water flow and carbon emissions sharply increase with the annual growth of water transferred. Scenarios analysis show that the potential decreases in the estimated electricity consumption, virtual water and carbon emissions in the planned 2030 under different management strategies.
5. The above impacts of the Eastern Route have not been considered in decision making for project-level assessments. The concept of water–energy nexus therefore offers a better understanding of the sustainability of this mega project. Strategies are needed to address the energy intensity of the Eastern Route, such as improving pumping efficiency, reducing water loss during water delivery, decreasing the quantity of water transferred through local water conservation, and selecting less carbon-intensive sources of water in water-receiving areas.

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Conflicts of interest

The authors declare no conflict of interest.

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