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Calculation of carbon footprints for water diversion and desalination projects

Jiahong Liu,[a,b*] Silan Chen,[a] Hao Wang,[a,b] Xiangdong Chen,[a,b]

[a] *State Key Laboratory of Simulation and Regulation of Water Cycle in River Basin, China Institute of Water Resources and Hydropower Research, Beijing 100038, China*
[b] *Engineering and Technology Research Center for Water resources and Hydroecology of the Ministry of Water Resources, Beijing 100038, China*

Abstract

As greenhouse gas emissions that contribute to global warming increase, it is becoming more important to consider the "carbon footprints" of engineering projects; however, the carbon footprints of water resource projects are often overlooked during environmental impact assessments. Notably, carbon releases occur when water is extracted and transported to industrial, agricultural, and residential areas for use, which consumes energy and materials. For different water extracting and transporting processes, the carbon footprints can be very different. This paper defines the carbon footprint concept in relation to water resources—the carbon emissions generated by acquiring one cubic meter of water—and estimates the carbon footprints for several water resource projects including China's south-to-north water diversion project and desalination plants in the UAE. The results show that the carbon footprint of China's south-to-north water diversion project decreased as the number of operating years increased. When the operation period reaches 30 years, the carbon footprint of China's south-to-north water diversion project will be about 0.179 kg CO_2. The carbon footprints for UAE desalination plants were 2.988 kg CO_2 for the multi-stage flash (MSF) method, 1.280 kg CO_2 for the multiple effect distillation (MED) method, and 2.562 kg $CO_2$for the reverse osmosis (RO) method. Overall, the results of this study demonstrate that the calculation of carbon footprints for water resource projects can be a valuable source of information for decision-making involving water utilization and conservation.

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Key words: water resources, carbon footprint, China's south-to-north water diversion project, desalination.

1. Introduction

Energy and water resources are the basic resources that support economic and social development. With concerns growing over the effects of rising carbon dioxide emissions from energy consumption and water shortage problems, developments that can achieve "low carbon" and "water conservation" outcomes are becoming socially and politically desirable. Energy and water are closely related. Energy production and utilization processes require the use of water. Similarly, water acquisition, allocation, and utilization stages are accompanied by energy consumption.

"Carbon footprints," which emerged from the ecological footprint concept, are an important indicator

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of the impact that human activities may have on the environment [1–4]. Specifically, a carbon footprint (CF) is a measure of the total quantity of greenhouse gasses, expressed as carbon dioxide equivalents, that directly and indirectly result from an activity or that accumulate over the life stages of a project [5, 6]. Research on carbon footprints covers a diverse array of both large-scale and small-scale areas of interest. For example, large-scale studies have looked at the carbon footprint of urban life, the carbon footprint of industrial production, and the carbon footprint of agricultural activities, whereas small-scale studies have explored topics such as the carbon footprint of individual behavior and the carbon footprint of specific industrial processes. Currently, many cities would like to implement low carbon development projects; therefore, the calculation and assessment of carbon footprints represent very important research issues [7–9]. For the calculation of carbon footprints for individual behavior, there are many methods and models [10–12], and some methods have been proposed for large-scale projects as well. However, the implementation of reliable methods can be difficult because the concept of the carbon footprint still lacks a consistent definition [13]. Calculation methods mainly include techniques such as life cycle assessment (LCA) [14–19], input–output analysis (IOA) [20–23], and hybrid life cycle assessment (hybrid LCA) [24–27]. On the basis of the LCA method, this paper provides a definition for the concept of carbon footprints in relation to water resources and estimates the carbon footprints for several water resource projects including China's south-to-north water diversion project and the operation of desalination plants in the UAE.

2. Definition for the carbon footprint of water resources

Carbon releases occur when water is extracted and transported to industrial, agricultural, and residential areas for use, which consumes energy and materials and results in a carbon footprint [28]. Different water resource projects can have different carbon footprints. For example, an artesian water diversion project near a river that requires only small amounts of construction and does not use much energy during the water transportation process will have a low carbon footprint. In contrast, a large-scale inter-basin water diversion project that requires large amounts construction and high amounts of energy during the water transportation process (e.g., for pressurization) will have a high carbon footprint. While many countries around the world have established water resources engineering organizations, there have been only a few studies on the carbon footprints of water resource projects. Currently, carbon footprint studies have been carried out for drinking water supply systems [29–31], water transportation systems [32, 33], and different types of dams [34].

In primitive society, human communities were often located near the water and the extraction and transportation of water was mostly performed by human labor, whose "carbon footprint" was negligible. Then, people started using livestock to transport water so that the water could be sent to distant regions. In this situation, water use had an indirect carbon footprint, which represents the carbon releases associated with the raising of livestock. However, prior to mechanized production, the overall water carbon footprint was still relatively low. When society entered the industrial age, an increasing number of machines were applied to production and transportation processes for water. Additionally, the mechanical power sources changed from sources such as steam to fossil fuels. In the current construction and operation processes of water resource projects, fossil energy consumption typically accounts for a large proportion of the total energy used. Construction methods have evolved as well and now high dams of more than one hundred meters and power stations are becoming more common. Furthermore, engineering materials have changed from rock and clay-like materials drawn from the site of construction

to non-local concrete and steel. Coincident with these changes in energy sources, construction methods, and building materials, carbon emissions of water resource projects have increased significantly.

A useful way to conceptualize the carbon footprint of water resources is to analyze the carbon emissions generated by acquiring one cubic meter of water. For a unit volume of water, earlier methods used to access one cubic meter of water were associated with almost no carbon emissions, but now, access to one cubic meter of water for industrial, agricultural, and domestic uses has a large carbon footprint. For the sustainable development and utilization of water resources, attention must be paid not only to the water itself and the effects of obtaining water on the environment, but also to the carbon emissions generated by water resource projects.

In this paper, we calculate the carbon footprints for several water resource projects by analyzing the carbon emissions generated by acquiring one cubic meter of water. We hope that our results will provide useful information to the decision-making processes regarding these specific projects and that our proposed method will facilitate additional studies of water resource carbon footprints elsewhere.

3. Calculation method for the carbon footprint of water resources

To obtain the carbon footprints for recent water resource development projects, this paper first collects basic construction and operation data for China's south-to-north water diversion project and desalination projects in the UAE and then determines the energy consumption associated with these projects. Next, the calculation method for obtaining the carbon footprints is presented according to the definition for the carbon footprint of water resources presented above, and it is then applied to the projects in China and the UAE.

3.1 Water diversion project

As a result of limited water resources or water shortages, many cities need to get water from water-rich regions located hundreds or thousands of miles away [35–37]. Long-distance water diversion projects require the construction of large amounts of production infrastructure; meanwhile, the extraction, processing, and transport of water consume large amounts of energy [38]. Consequently, these processes will produce large amounts of carbon emissions that should not be ignored.

China's south-to-north water diversion project (the middle line) is a diversion from the east bank of the Danjiangkou reservoir, which is located in the upper reaches of the Yangtze River's largest tributary—the Hanjiang River. The diversion is being implemented through the excavation of several channels and tunnels, and ultimately it will deliver water to arid areas in northern China. Water supply coverage will mainly be to the Tangbaihe Plain and the Huanghuaihai Plain. The aim of the project is to provide water to three provinces (Henan, Hebei, and Hubei) and 20 cities along the middle line including Beijing and Tianjin. The project will annually transfer 9.5 billion cubic meters of water. China's south-to-north water diversion project will involve both water source area engineering work and water transportation engineering work. Water source area engineering work encompasses the Danjiangkou reservoir rehabilitation project and the Hanjiang River compensation project; water transportation engineering work encompasses the construction of the Hanjiang Main Canal (total length of 1241.2 km) and the Tianjin Canal (total length of 142 km) [39, 40].

3.2 Desalination project

In some coastal arid areas, desalination is a common way to gain access to water. Currently, desalination has been used in many parts of the world including the Middle East, North Africa, the United States, and

Europe [45]. Desalination largely alleviates the pressure on freshwater resources in these areas. However, the operation of desalination plants requires large quantities of energy and can have adverse impacts on the environment.

Environmental impact assessments and research on desalination plants have been carried out [46, 47]. Because of their high amounts of energy consumption, water desalination plants release large amounts of CO_2 during the production process. When these carbon emissions are accounted for, the carbon footprint for desalination plants can be quite high. Hence, it would of great value to have methods that can evaluate the carbon footprints of specific production processes in desalination plants to see which ones are the most efficient.

There are many desalination plants in the Arabian Gulf region, and they have the capacity to produce ten million cubic meters of freshwater per day, which accounts for about half of the world's daily desalination capacity. The UAE is the most important desalination country in the Gulf region, and it alone accounts for about 14% of the world's daily desalination capacity [42, 43].

3.3 Method

The core idea of this paper is to track the activities of water-related projects and estimate their carbon footprints using the LCA method. Based on deep analyses of China's south-to-north water diversion project and desalination projects in the UAE, the energy consumption processes were divided into four main stages: materials production, materials transportation, construction, and operation and maintenance. Carbon emissions of these four stages were then calculated. Taking into account the function apportionment factors, the carbon emissions were allocated to each cubic meter of water. Finally, the carbon emissions of each cubic meter of water in all stages were added together to obtain the carbon footprints of the water resource projects.

3.3.1 The main calculated items

For the water diversion project, the carbon footprint calculation methods used for the four energy consumption stages are as follows.

(1) Material production (concrete, steel, etc.)

$$CF_m = \sum_i \beta_i \times C_i \tag{1}$$

where CF_m represents the carbon emissions of material production; β_i is the emission factor for the production of the material; C_i is the consumption of construction materials.

(2) Material transportation

$$CF_t = \sum_i \beta_d \alpha_d \times \frac{Q_i}{L} \times \frac{s_i}{v} \tag{2}$$

where CF_t represents the carbon emissions of material transportation; β_d is the emission factor for the burning of diesel fuel; α_d is the amount of diesel consumed by one truck per hour; Q_i represents the transported quantities of the material; L is the capacity of one truck; s_i is the transported distance; v is the speed of the trunk.

(3) Construction (earth and rock excavation, filling, etc.)

$$CF_c = \sum_i (\beta_d C_{di} + \beta_e C_{ei}) \tag{3}$$

where CF_c represents the carbon emissions of construction; C_{di} is the consumption of diesel in the construction project; C_{ei} the consumption of electricity in the construction project; β_e is the emission factor of electricity.

Carbon emissions during the construction period are apportioned according to the operation period. Assuming the operation period is α years and the annual transportation of water amounts to Q_w, the carbon footprint CF_{w1} of water resources during the construction period can be calculated by the following formula:

$$CF_{w1} = \frac{CF_m + CF_t + CF_c}{a \times Q_w} \tag{4}$$

(4) Operation and maintenance

The operation stage mainly includes the carbon emissions CF_o from the consumption of electricity, while the maintenance stage mainly includes the carbon emissions CF_{ma} from the replacement and repair of materials and equipment. The carbon footprint CF_{w2} of water resources in the operation and maintenance period is calculated by the following formula:

$$CF_{w2} = \frac{CF_o + CF_{ma}}{Q_w} \tag{5}$$

The carbon footprint CF_w of the water diversion project is then calculated by the following formula:

$$CF_w = CF_{w1} + CF_{w2} \tag{6}$$

3.3.2 Exclusions

The emissions from the construction of the residential site were not considered here because they were insignificant. Emissions related to the production of construction machinery were also not considered. Other exclusions were related to the emissions arising from the production of residential goods and materials, as well as employee transportation [34, 41].

4. Results

4.1 China's south-to-north water diversion project (the middle line)

4.1.1 Material production

Carbon emissions for material production were calculated by multiplying the material consumption by the material emission factors. The total amounts of principal engineering materials used in China's south-

to-north water diversion project are: 950 Gm3 of soil-rock, 15.37 Mm3 of concrete, 0.7 Mt of steel, and 7.18 Mm3 of soil cement [39]. The emission factors were obtained from various resources including the ELCD, CIAE, CAE, and CLCD. The emissions generated during the material production stage are shown in Table 1.

Table 1 Emissions for material production

Materials	Total amount	Emission factor	Total emissions (Mt CO_2)
Soil-rock	950 Mm3	0.006 t CO_2/m3	5.70
Concrete	15.37 Mm3	0.300 t CO_2/m3	4.611
Steel	0.7 Mt	2.2 t CO_2/t	1.54
Soil cement	7.18 Mm3	1.25 t CO_2/m3	8.975
Total	---	---	20.286

4.1.2 Material transportation

The carbon emissions for the material transportation stage are mainly due to fuel combustion during vehicle use. Carbon emissions are related to both the transport quantities and distances. Most of the materials were transported via diesel trucks with a capacity of 20 tons and a speed of 50 km per hour. The diesel consumed by one truck was approximately 20.75 kg/hour according to the Hydraulic Construction Mechanical Quota 2004. The emission factor used for the burning of diesel fuel was 3.06 t CO_2/t. Similarly, carbon emissions for material transportation were calculated by multiplying the diesel consumption by the emission factor. Because the specific material transport distances were not exactly equal, based on a statistical analysis of the site transport routes of China's south-to-north water diversion project, this paper estimated the average transport distance of each material used; the results are shown in Table 2.

Table 2 Emissions for material transportation

Materials	Transport distance (km)	Transport quantities (Mt)	Total emissions (Mt CO_2)
Soil-rock	60	2850	10.857
Concrete	100	38.43	0.244
Steel	350	0.7	0.016
Soil cement	150	21.54	0.205
Total	---	---	11.322

4.1.3 Construction

The carbon emissions for the construction stage were mainly calculated by multiplying the consumption of diesel and electricity by their emission factors. The emission factor used for the burning of diesel fuel was 3.06 t CO_2/t, and the emission factor used for electricity was 0.766 kg CO_2/kWh. The results are shown in Table 3.

Table 3 Emissions for construction

Item	Total amount	Diesel (Mt)	Electricity (MkWh)	Total emissions (Mt CO_2)
Soil-rock excavation	660 Mm3	1.5	---	4.590
Soil-rock filling	230 Mm3	0.25	---	0.765

Channel Lining	1383 km	3.7	2.7	11.324
Concreting	15 Mm3	---	24	0.018
Tunnel excavation	8.5 km	---	15	0.011
Total	---	---	---	16.708

Once the project is running for 30 years, and assuming that the annual transfers of water are 9500 Mm3, according to the equation (4) the carbon footprint for the water resource diversion project during the construction period will be 0.170 kg CO_2.

4.1.4 Operation and maintenance

China's south-to-north water diversion project was put into use in 2014, and the total amount of transferred water has not yet reached the scale of the design. As there is no complete annual dataset for the energy consumption of the operation and maintenance stages, this paper used forecast estimates and engineering analogies to compute the necessary data. China's south-to-north water diversion project basically involves the use of artesian water, and the transfer process does not require pumping. Hence, energy consumption of the operational stage is mainly due to the management, operation, and monitoring of sluices.

(1) Operation

Buildings involved in the control of the main canal include 61 check gates, 53 exit sluices, 88 turn-out gates, and 60 siphon export control gates, which collectively form a coalition control system [48]. The opening and closing of the sluices are controlled by hoists, and every sluice is equipped with 10 hoists. The power used by a hoist is 12 kW, and the hoists work 10 hours per day. Consequently, the hoists in China's south-to-north water diversion project consume 114.756 MkWh of electricity every year, which results in carbon emissions of 0.088 Mt CO_2. Thus, the carbon emissions associated with transporting one cubic meter of water are 0.009 kg CO_2.

(2) Maintenance

Maintenance activities mainly include inspections, equipment and infrastructure maintenance, emergency responses, management assessments, safety assessments, and decision-making as well as engineering information management [49]. Considering that engineering inspections and complex maintenance tasks have a relatively low frequency, the energy consumption of these activities is relatively small; when the energy consumption was apportioned to each cubic meter of water, the results were negligible.

4.1.5 Carbon footprint of water resources

When the operation period reaches 30 years, the carbon footprint for each cubic meter of water, which was calculated by equation (6), was estimated to be 0.179 kg CO_2.

4.2 The UAE desalination plant

The impacts of desalination plant energy consumption on the environment are highest (e.g., they can reach 90% of the total energy consumption) during the operational stage compared to the construction and other stages [44]. The UAE desalination plants use three different techniques for water desalination: the multi-stage flash (MSF) method, the multiple effect distillation (MED) method, and the reverse osmosis (RO) method. These different techniques have different energy consumption rates [42, 44].

Table 4 Emissions for the UAE desalination operation stage

Technique	Processing	Energy consumption	Total	Carbon

used at the desalination planta	capacity (m3/d)	Thermal energy (kWh/m3)	Electricity (kWh/m3)	emissions (t CO_2/d)	footprint (kg CO_2)
MSF plant	5,032,133	12	3.5	13667.27	2.716
MED plant	621,674	6	1.5	723.63	1.164
RO plant	625,035	---	3	1455.08	2.238

aMSF (multi-stage flash), MED (multiple effect distillation), and RO (reverse osmosis)

During the production of one cubic meter of freshwater, the carbon footprints of the UAE desalination plants were estimated to be 2.716 kg CO_2 for the MSF method, 1.164 kg CO_2 for the MED method, and 2.238 kg CO_2 for the RO method.

The carbon footprints of the desalination plant construction stage were mainly the result of energy and raw material consumption during the equipment manufacturing process; these activities include the manufacturing of centrifugal pumps and other special pumps, RO membranes, evaporators, condensing systems, and so on. According to data for a desalination plant in Tianjin, China, the carbon footprint for the construction period was estimated to be about 10% of the carbon footprint of the operation stage.

Table 5 Carbon footprint of the UAE desalination project

Technique used at the desalination planta	Carbon footprint of the operation stage (kg CO_2)	Carbon footprint of construction (kg CO_2)	Total carbon footprint (kg CO_2)
MSF plant	2.716	0.272	2.988
MED plant	1.164	0.116	1.280
RO plant	2.238	0.224	2.562

aMSF (multi-stage flash), MED (multiple effect distillation), and RO (reverse osmosis)

Therefore, the total carbon footprints of UAE desalination plants were estimated to be 2.988 kg $CO_2$for the MSF method, 1.280 kg CO2 for the MED method, and 2.562 kg CO_2 for the RO method (Table 5).

5. Discussion

Because China's south-to-north water diversion project (the middle line) basically consists of artesian water, the carbon emissions during the operation stage are estimated to be relatively small. The main carbon emissions were associated with the construction period, which includes material production, material transportation, and construction. Hence, the carbon footprint of the water resource project decreased as the number of operating years increased, as shown in Fig. 1.

Fig. 1 shows that when the operation period reaches 30 years, the carbon footprint for the water diversion project will be 0.179 kg CO_2. Different operation periods result in different carbon footprints. Greater amounts of water will be transferred over longer operation periods. When the total carbon emissions during the construction period are allocated to each cubic meter of water, the carbon footprint is smaller. With the increase of the operation period, the rate of reduction in the carbon footprint slows down. When the operation period is 10 years, the carbon footprint of the water resource project is 0.518 kg CO_2; when the operation period is 70 years, the carbon footprint of the water resource project is as low as 0.082 kg CO_2. In the early project planning and construction period, selecting a reasonable operation period is critical to achieve the low carbon development goals of the project.

Additionally, our results suggest that in order to develop low carbon water diversion projects, the most benefits will be gained from improving energy efficiency, which reduces energy consumption, and from

reducing carbon emissions during the construction period of the project. Moreover, because of the long-distances involved in water diversion projects, the carbon emissions in terms of access to water in areas receiving the water are mostly transferred to other areas. Hence, the carbon footprint of water resources may be a powerful tool for spatial analyses.

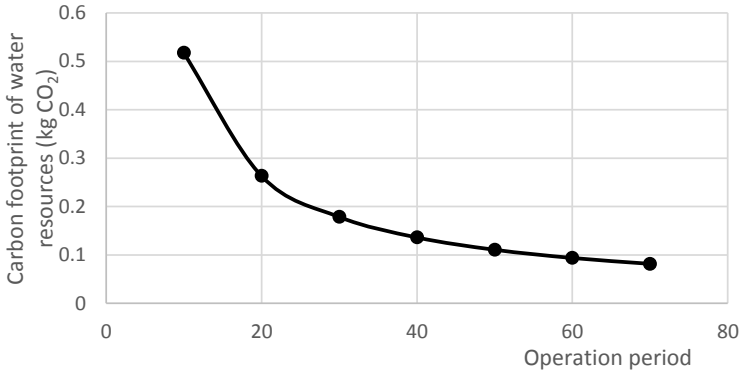

Fig. 1 Carbon footprint of water resources during different operation periods

This paper also calculated the carbon emissions of UAE desalination plants during the operation stage. The carbon footprints of UAE desalination plants during the production of one cubic meter of freshwater were estimated to be 2.716 kg CO_2 for the MSF method, 1.164 kg CO_2 for the MED method, and 2.238 kg $CO_2$for the RO method.

Desalination is a high-energy consumption method compared to the water diversion project. However, with the development of new desalination technology, the efficiency of energy use can be effectively improved. With different fuels and different production arrangements, the carbon footprint has a large fluctuation range. Researchers have studied the fluctuation range of carbon emissions in the three different desalination techniques. For the MSF method the carbon footprint of water production varies from 1.98 kg CO_2 to 34.68 kg CO_2; for the MED method the carbon footprint of water production varies from 1.19 kg CO_2 to 26.94 kg CO_2; and for the RO method the carbon footprint of water production varies from 1.75 kg CO_2 to 2.79 kg CO_2 [44]. Our results were within these ranges. From the aspect of carbon emissions, the RO technique typically has the highest energy utilization rate so the carbon footprint is relatively small and the impacts on the environment are minimal. However, there is a big potential for improvements in the MSC and MED techniques that will reduce carbon emissions, i.e., if reasonable production processes are chosen, their carbon footprints can likely be significantly reduced.

This paper only estimated the carbon footprints of water resources for the water diversion project in China and the UAE desalination projects. The carbon footprints of other water resource projects should be studied for comparative purposes. Meanwhile, the calculation method for carbon footprints needs to be more meticulous and precise. With such tools, the future development and utilization of water resources can focus not only on the economic costs and benefits of water resource use but also on the social and ecological costs and benefits. Thus, the use of carbon footprints in the development and utilization of water resources has the potential to hasten the overall goal of achieving low carbon developments.

6. Conclusion

With social progress and development, the acquisition and transportation of water requires an increasing

amount of energy. These processes will inevitably result in a certain amount of carbon emissions. Thus, it can be expected that increasing energy consumption in water resource engineering projects will result in increasing carbon emissions. Carbon footprints can provide a useful tool to evaluate the carbon emissions associated with different types of projects and production processes. Although carbon footprint methods still need to be standardized, they show great promise for identifying ways to reduce carbon emissions in an objective manner and minimizing the potential environmental impacts of water resource developments.

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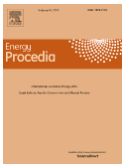

Biography

The biography of the corresponding author.

Professor Liu is the director of urban hydrology and engineering, China Institute of Water resources and Hydropower Research, and he is also the research fellow of State Key Laboratory of Simulation and Regulation of Water Cycle in River Basin.