Science of the Total Environment 619–620 (2018) 721–731

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Sustainability of mega water diversion projects: Experience and lessons from China

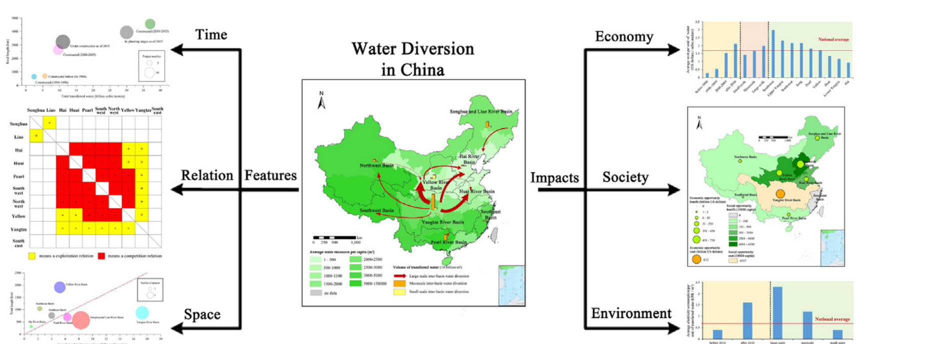
Min Yu [a], Chaoran Wang [a], Yi Liu [a,*], Gustaf Olsson [b], Chunyan Wang [a]

[a] *School of Environment, Tsinghua University, Beijing, China*
[b] *Industrial Electrical Engineering and Automation, Lund University, Sweden*

HIGHLIGHTS

- Temporal and spatial patterns of 59 mega water transfer projects were investigated.
- The total amount of transferred water was almost 100 billion m^3 as of 2015.
- China's water diversion covered more than 17 provinces and 60 cities.
- Water diversion leads to severe energy, environmental and social consequences.
- Four types of innovative measures are urgently needed to ensure the sustainability.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 13 September 2017
Received in revised form 31 October 2017
Accepted 1 November 2017
Available online xxxx

Editor: D. Barcelo

Keywords:
Water scarcity
Water transfer
River basin operation
Multi-objective analysis
Pumping energy
Opportunity cost

ABSTRACT

Water availability and water demand are not evenly distributed in time and space. Many mega water diversion projects have been launched to alleviate water shortages in China. This paper analyzes the temporal and spatial features of 59 mega water diversion projects in China using statistical analysis. The relationship between nine major basins is measured using a network analysis method, and the associated economic, environmental and social impacts are explored using an impact analysis method. The study finds the development of water diversion has experienced four stages in China, from a starting period through to a period of high-speed development. Both the length of water diversion channels and the amount of transferred water have increased significantly in the past 50 years. As of 2015, over 100 billion m^3 of water was transferred in China through 16,000 km in channels. These projects reached over half of China's provinces. The Yangtze River Basin is now the largest source of transferred water. Through inter-basin water diversion, China gains the opportunity to increase Gross Domestic Product by 4%. However, the construction costs exceed 150 billion US dollars, larger than in any other country. The average cost per unit of transferred water has increased with time and scale but decreased from western to eastern China. Furthermore, annual total energy consumption for pumping exceeded 50 billion kilowatt-hours and the related greenhouse gas emissions are estimated to be 48 million tons. It is worth noting that ecological problems caused by water diversion affect the Han River and Yellow River Basins. Over 500 thousand people have been relocated away from their homes due to water diversion. To improve the sustainability of water diversion, four kinds of innovative measures have been provided for decision makers: national diversion guidelines, integrated water basin management, economic incentives and ex-post evaluation.

* Corresponding author.
E-mail addresses: yu-m12@mails.tsinghua.edu.cn (M. Yu), yi.liu@tsinghua.edu.cn (Y. Liu), gustaf.olsson@iea.lth.se (G. Olsson), wangchunyan13@mails.tsinghua.edu.cn (C. Wang).

https://doi.org/10.1016/j.scitotenv.2017.11.006
0048-9697/

1. Introduction

Owing to uneven temporal and spatial distributions of freshwater resources, it is common for some basins in China to have more water than required by local residents, industry and agriculture, while others have less (Zhang et al., 2015). In order to address the spatial and sometimes temporal mismatch between supply and demand of freshwater, inter-basin water diversion projects, in which river connectivity is restructured via man-made canals, are an increasingly popular solution, especially in less developed countries (WWF, 2007). A number of inter-basin water transfer projects have been launched in Australia, Canada and United States. These include the Snowy Mountains Hydro-electric scheme (Bergmann, 1999), the Great Lakes Basin water diversion (Becker and Easter, 1995), and the Central Valley Project (Mariño and Loaiciga, 1985). Inspired by the global experience, China has advocated the re-allocation of water resources from basins perceived as being water-rich to ones where water scarcity is a constraint to the growth of urban populations and industrialized economy (Liu et al., 2013). However, inter-basin water diversion projects can have negative energy, environmental and social consequences. There is an urgent need to investigate the consequences of current inter-basin water transfer projects and use this information to influence the management of water diversion.

Research on inter-basin water transfer has gained momentum since 1972, and accelerated in the past 20 years. A majority of the research focuses on the trigger mechanisms that tell project operators when to start and stop diverting water. These mechanisms often consider available water resources in both the source and receiving basins. On this basis, water diversion is initiated only if water resources are abundant in the donor reservoir and scarce in the recipient reservoir. This type of research is often conducted in a specific water diversion project at micro level (Cheng et al., 2014; Peng et al., 2015). For example, Zeng et al. (2014) proposed a new water transfer triggering mechanism which consists of a set of water transfer rule curves to divert water from areas of abundance to areas of scarcity in a specific inter-basin water diversion project. Rey et al. (2015) promoted a method called ELECTRE-III-H to evaluate different sectorial water allocation policies to mitigate water scarcity in the Mediterranean area of north-eastern Spain. Other research discusses the impacts of inter-basin water transfer projects on water quality and biodiversity (Quan et al., 2016; Zeng et al., 2015). For example, a water diversion project in Brazil was examined for its suitability to supply water to the metropolitan area of Sao Paulo using a dynamic systems simulation model (Cabo et al., 2014). Using a game theory framework, Becker and Easter (1995) found that a Tragedy of the Commons situation may happen when states and provinces along the North American Great Lakes divert water even when it is not necessary. Some studies have focused on the political conflicts caused by water diversion projects and social equity between the water source and receiving districts (Berkoff, 2003; Cheng et al., 2014; Moore, 2014).

Numerous studies have investigated the impact of water diversion projects in China (Barnett et al., 2015; He et al., 2014; Liu and Yang, 2012). Most of them have focused on specific projects, e.g. environmental and ecological effects of the South-to-North Water Diversion Project (SNWDP), the construction management of the SNWDP, the environmental geology of its Middle Route Project, the protection of cultural relics, water conservation and water purification, regional water security, the impact of the project on groundwater resources, pricing and water resource allocation and policy in China (Cheng et al., 2014; Feng et al., 2007; Liu and Zheng, 2002; Yang et al., 2015; Zhang, 2009). However, a comprehensive review of the path of China's water conservancy development and investigation of achievements, problems and challenges, to the best of our knowledge, is not available in the literature or official reports.

Understanding the achievements and problems of China's inter-basin water transfer development is the key to directing future construction of new water diversion projects. Meanwhile, China's experience can provide valuable lessons for other developing countries where huge water diversion investments are planned. This article provides an overview of China's inter-basin water transfer projects and explores their economic, environmental and ecological impact. It discusses the future challenges that confront China's water transfer projects. In particular, the far-reaching implications of China's integrated management of water transfer projects are elaborated in the Section 4.

2. Methods and data sources

2.1. Research description and framework

The research framework is shown in Fig. 1. Data for 59 major inter-basin water diversion projects in China, including diversion routes, completion year, location, construction cost, were collected based on a literature review. Descriptive statistics, ecological network analysis and impact analysis were adopted. Patterns of change in water diversion were analyzed from the temporal dimension and spatial dimension. Transferred water flows among nine river basins and economic, environmental and social impacts were investigated. Details of analytical methods will be described in the following sections.

2.2. Descriptive analysis

The variation of water diversion projects was summarized from both temporal and spatial perspectives based on inter-basin water diversion data. To better illustrate patterns of change, three indices were proposed: number of projects, transferred water volume and the distance between water source and receiving districts. In the temporal dimension, the development of water diversion projects over the last 50 years in China was discussed in detail. Four typical stages of water diversion development were proposed on this basis.

Spatial distributions of these projects among major water basins were presented separately and the features of water diversion projects in each basin were summarized. In this study, China was divided into nine major water basins (called level-1 water basins) according to National Water Resource Integrated Planning (2010–2030) (MWR, 2011). This is shown in Fig. 2 and Table 1. Each major water basin was divided into several sub-basins (called level-2 water basins) and each level-2 water basin was further divided into several sub-catchments (called level-3 water basins). If the source and receiving region of water diversion are located in two different level-1 water basin, this project was identified as a large-scale water diversion project; if the water source and receiving region are located in the same level-1 water basin but in two different level-2 basins, this project was identified as a mesoscale water diversion project; if the water source and receiving region are located in the same level-2 water basin but in two different level-3 basins, this project was identified as a small-scale water diversion project. The transferred water volume in each major basin was the sum of transferred water volume of all mesoscale and small-scale water diversion projects in this basin.

2.3. Ecological network analysis

To analyze the diversion interrelations among major water basins, an ecological network method was applied. Ecological network analysis (ENA) is currently one of the most common methods for analyzing the interactions between structure and function of any ecosystem. It has been widely applied not only to natural ecosystems but also to social systems (Bailey et al., 2004; Bodini and Bondavalli, 2002; Lu et al., 2012). Network utility analysis (NUA) is an ecological network approach used to express the benefit to cost relationship in networks (Chen and Chen, 2016). Detailed descriptions of ENA and NUA can be found in numerous studies (Fath et al., 2007; Ulanowicz, 2004; Zhang