Water Science and Engineering 2015, 8(2): 102–113

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Water Science and Engineering

journal homepage: http://www.waterjournal.cn

# Measurement and assessment of water resources carrying capacity in Henan Province, China

Ming Dou*, Jun-xia Ma, Gui-qiu Li, Qi-ting Zuo

*College of Water Conservancy and Environment, Zhengzhou University, Zhengzhou 450001, PR China*

Received 29 September 2013; accepted 25 December 2014
Available online 7 May 2015

**Abstract**

As demands on limited water resources intensify, concerns are being raised about water resources carrying capacity (WRCC), which is defined as the maximum sustainable socioeconomic scale that can be supported by available water resources and while maintaining defined environmental conditions. This paper proposes a distributed quantitative model for WRCC, based on the principles of optimization, and considering hydro-economic interaction, water supply, water quality, and socioeconomic development constraints. With the model, the WRCCs of 60 subregions in Henan Province were determined for different development periods. The results showed that the water resources carrying level of Henan Province was suitably loaded in 2010, but that the province would be mildly overloaded in 2030 with respect to the socioeconomic development planning goals. The restricting factors for WRCC included the available water resources, the increasing rate of GDP, the urbanization ratio, the irrigation water utilization coefficient, the industrial water recycling rate, and the wastewater reuse rate, of which the available water resources was the most crucial factor. Because these factors varied temporally and spatially, the trends in predicted WRCC were inconsistent across different subregions and periods.
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*Keywords:* Water resources carrying capacity; Hydro-economic interaction; Sustainable socioeconomic scale; Water resources carrying level; Henan Province

## 1. Introduction

The concept of carrying capacity is rooted in demography, biology, and applied ecology (Clarke, 2002). In ecology, carrying capacity is defined as the maximum population of a species that a habitat can support without permanent impairment of the habitat's productivity (Rees, 1997). Water resources carrying capacity (WRCC) is a new concept that has not yet been clearly defined and described. Some researchers consider WRCC to be the capacity of water resources to sustain a society at a defined good standard of living, while others consider it the threshold level of water resources at which an environment is capable of supporting the activities of human beings (Seidl and Tisdell, 1999; Li et al., 2000). Internationally, not many breakthroughs have been achieved in the WRCC research; the topic has only been considered briefly in theories of sustainable development (Ofoezie, 2002). Some scholars have used terms such as sustainable water utilization, the ecological limits of water resources, or the natural system limits of water resources to express the meaning of WRCC (Hunter, 1998; Falkenmark and Lundqvist, 1998). Studies focusing exclusively on WRCC have primarily been conducted in China. The concept of WRCC was first applied to the Urumqi River Basin in China in 1989 (Shi and Qu, 1992; Feng et al., 2006). It has been a topic of significant debate since 2001, and represents a new academic frontier (Long et al., 2004).

One definition of WRCC, and the definition used in this study, is the maximum sustainable socioeconomic scale based on available water resources and maintenance of good, defined environmental conditions (Dou et al., 2010). In this concept,

* Corresponding author.
*E-mail address:* dou_ming@163.com (Ming Dou).
Peer review under responsibility of Hohai University.

http://dx.doi.org/10.1016/j.wse.2015.04.007
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the socioeconomic scale is the overall size of a regional socioeconomic system in a certain period, and can be represented by a series of socioeconomic indices (such as total population, urbanization ratio, industrial structure, and grain yield). Good environmental conditions mean a suitable living environment for human beings and the ecological system, in particular good water quality and a healthy aquatic environment. WRCC is an indicator of regional sustainability, and achieving regional sustainability is important because social institutions and ecological functioning are closely linked at this scale (Graymore et al., 2009). Therefore, research on WRCC should be based on two premises: First, it must be possible to sustain the normal operation of a regional socioeconomic system, and as a result researchers must calculate the quantity of water resources required to sustain these social service functions. Second, it is necessary to evaluate the maximum socioeconomic scale that water resources can sustain after meeting the needs of the ecosystem.

Regional carrying capacity depends on water resources. There have been many theoretical studies of carrying capacity based on regional water resources because this concept is most often considered within a larger theoretical context of sustainable development. In particular, severe water shortage problems have forced the Chinese government to initiate a series of studies to determine the carrying capacity based on regional water resources in arid and semi-arid areas, such as western China and the North China Plain (Xia and Zhu, 2002; Dou et al., 2010; Zai et al., 2011). In recent years, with increasingly serious water pollution, there have even been some studies conducted in eastern China, where water resources are abundant (Liu and Borthwick, 2011; Liu, 2012). Furthermore, Falkenmark and Lundqvist (1998) have used estimates of the maximum global use of water resources to study how carrying capacity is determined by regional water resources. The National Research Council (NRC) (2002) studied the Florida Keys Basin's carrying capacity in the United States under different land-use scenarios. Lane et al. (2014) offered a Carrying Capacity Dashboard (QUT, 2012) to highlight one way in which some basic resource-based parameters have been utilized. In practice, carrying capacity is often estimated by comparing stress on the environment (e.g., demand of natural resources) against environmental thresholds (e.g., available natural resources) (Clarke, 2002; Oh et al., 2005).

On the whole, the current studies on WRCC emphasize harmonization of the demands of socioeconomic development with the supply of water resources. Regional socioeconomic systems and water resources systems are often represented using areas such as river basins, which allow researchers to analyze the systems' structures, functions, and processes and determine the WRCC. In China, the regional socioeconomic scale may be determined by the urban population growth rate and economic development goals. Constraints imposed by the availability of water and other natural resources are rarely considered in planning, which may explain why most Chinese cities are facing severe water shortages and experiencing environmental problems (Zhang et al., 2010). Therefore, it is necessary to develop a suitable methodology to effectively describe hydro-economic interaction in highly populated regions and to choose the best strategies to alleviate the conflict between socioeconomic development and water resources exploitation.

Henan Province, China's most populous province and the province with the fifth highest gross domestic product (GDP), has long suffered from an intense conflict between the limited water resources and the rapid growth of water demand. In this study, we developed a method for calculating Henan's WRCC based on available water resources and relevant water environment protection goals, and analyzed spatial and temporal variations of the WRCC. First, considering the spatial differences of the economic development level and water resources conditions, a distributed hydro-economic model was developed to describe the interaction between the socioeconomic and water resources systems. Second, a WRCC quantification model was developed to identify the maximum sustainable socioeconomic scale based on the hydro-economic interaction relationship and a series of constraint conditions. Finally, on the basis of the models, Henan Province's WRCC was calculated for different development periods, and the change tendency of the water resources carrying level was analyzed.

## 2. Framework and methodology

### 2.1. Overview

Research on WRCC involves many disciplines, including hydrology, ecology, environmental sciences, economics, sociology, and management science (Zhang et al., 2010). Many methods can be used, of which the most common are trend analysis (Liu, 2012), the fuzzy comprehensive evaluation method (Prato, 2009), system dynamics (Feng et al., 2008; Dang and Guo, 2012), multi-objective decision-making and analysis (Xu and Cheng, 2000), the large-scale system theory, the optimization method, and the projection pursuit approach (Zhang and Guo, 2006; Liu and Borthwick, 2011). Trend analysis is based on empirical analysis of some socioeconomic indices under water resources constraints. The fuzzy comprehensive evaluation method is a common assessment method based on a set of index systems. System dynamics can reflect the interaction and feedback mechanism between human activities and the water resources system. Multi-objective decision-making and analysis can obtain the maximum sustainable socioeconomic scale under a series of water environmental and resources constraints. The large-scale system theory can use the idea of decomposition and coordination to solve a large-scale system problem. The optimization method finds the global optimal solution for complex problems based on given criteria. Finally, the projection pursuit approach is a new statistical method solving multi-dimensional socioeconomic and water resources system problems. From a management perspective, the large-scale system theory and the optimization method are most appropriate because the former shows the interaction between the

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