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# Evaluating the evolution of the Heihe River basin using the ecological network analysis: Efficiency, resilience, and implications for water resource management policy

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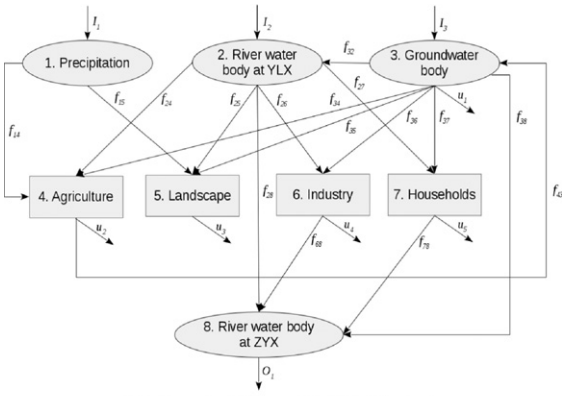
## HIGHLIGHTS

- We examine the network evolution of the Heihe River Basin from 2000 to 2009.
- Results indicate improvement in network efficiency while decreasing resiliency.
- We demonstrate alternative scenarios for decreasing efficiency and improving resiliency.

## GRAPHICAL ABSTRACT




Water flow network diagram of the Heihe River basin.

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## ABSTRACT

One of the most critical challenges in the anthropocentric age is the sustainable management of the planet's increasingly strained water resources. In this avenue, there is a need to advance holistic approaches and objective tools which allow policy makers to better evaluate system-level properties and trade-offs of water resources. This research contributes to the expanding literature in this area by examining the changes to system-level network configurations of the middle reaches of the Heihe River basin from 2000 to 2009. Specifically, through the ecological network analysis (ENA) approach, this research examines changes to the system-level properties of efficiency, redundancy, and evaluates the trade-offs to the resiliency of ecosystem water services of the middle reaches of the Heihe River basin. Our results indicate that while the efficiency of the middle reaches has increased from 2000 to 2009 by 6% and 78% more water is released to the lower reaches, the redundancy of the system has also decreased by 6%. The lower level of redundancy, particularly due to the changes in the groundwater body levels, has critical long-term consequences for the resilience of the water ecosystem services of the middle reaches. In consideration of these holistic trade-offs, two hypothetical alternative scenarios, based on water recycling and saving strategies, are developed to improve the long-term health and resilience of the water system.

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## 1. Introduction

Rapid urbanization, population growth, and the increasing demand for socio-economic development places critical strains on the world's scarce water resources. Given the significance of water for human livelihood, sustainable water resource management is one the most important Sustainable Development Goals (UN, 2014) among policy makers, practitioners, and researchers. Previous approaches towards sustainable water resource management have focused on developing various indicators which attempt to include multi-dimensional economic and environmental aspects (Singh et al., 2009). However, the sustainable management of water resources are particularly complex as water is imported, distributed, consumed, and discharged as a result of different activities through multiple interlinked components, e.g., upstream and downstream areas, surface and underground aquatic components, and socio-economic components such as agriculture and industry. Given this inherent complexity researchers have increasingly questioned the utility of aggregating separate indicators and instead have called for the development of holistic approaches for the sustainable management of resources (Chen et al., 2014; Lopez-Ridaura et al., 2002).

Sustainable water resource management is inherently interdisciplinary and requires the integration of various economic, social, and environmental dimensions. Given the interconnectedness of the various dimensions of a water system, the management of each individual component may influence other components in unpredictable or adverse ways. A holistic approach to the supply and demand of the individual dimensions of water resource systems and their emerging systems-level dynamics will therefore lead to more effective and preferable social and environmental decisions (Xue et al., 2015). Research on holistic water resource management is an expanding area. Notably, researchers have argued for the need to seek optimal and holistic solutions from socio-economic and environmental aspects through the ecosystem services concept (Garcia et al., 2016). In this research avenue, holistic solutions are evaluated through a trade-off analysis with multiple ecosystems services and multiple stakeholders, e.g. private sector, public sector, and ecological assets.

Holistic solutions are beneficial in reconciling different water resource management perspectives and reflect the different financial and environmental costs and benefits (Hering and Ingold, 2012) relevant to the system-level dynamics of the water system. Equally important, holistic solutions reflect the different pieces of legislation regulating the separate dimensions of the water system (Corominas et al., 2013). However, the usage of the ecosystem services concept for seeking optimal water resource management solutions is made difficult by the large amount of data, costs, and detailed assessment of various stakeholders and environmental assets (Hering et al., 2010). In light of the complexities of trade-off and stakeholder analysis, researchers have been exploring new directions for accounting the consumption and supply of water systems and their system-level dynamics through interdisciplinary network approaches.

Holistic network approaches are especially relevant in illustrating system-level trade-offs. For example, while water conservation and efficient water extraction and irrigation have become common policy options, the effects of their implementation at the system-level especially to resilience are poorly understood (Scott et al., 2014). Resilient water systems can be defined as the degree to which these systems can withstand shocks, e.g. droughts and excessive demands, and continue the delivery of water services for both human and environmental needs. Highly efficient water systems, result in decreasing flow redundancies, and weaken the system's resilience, e.g., by restricting groundwater body recharge from inefficient irrigations, and consequently decrease the system's capacity to absorb shocks.

The ecological network analysis (ENA) is a holistic approach that can be used to examine the system-level configurations and trade-offs relevant to resilient management of water resources. Through this approach, the components of a water system are represented as nodes and the corresponding water flows among the components as interlinkages among the nodes. The ecological information-based approach focuses on the transfer of flows between nodes rather than the individual properties of the nodes (Fath and Patten, 1999; Ulanowicz, 1986). By doing so it permits the researcher to study complex ecosystems at the system-level. This approach has been applied to urban water networks (Bodini et al., 2012; Li and Yang, 2011), virtual water (Fang and Chen, 2015), urban metabolism (Chen and Chen, 2012), but also in other areas such as economic resource trade networks (Huang and Ulanowicz, 2014), and food webs (Wulff et al., 1989).

In this paper, the ecological network analysis (ENA) is introduced as a method for investigating the complex relationship among various socio-economic and hydrological components of the Heihe River basin in China. This case study was chosen not only for the regional significance of Heihe River basin in China but also because recent advances in water resource management increasingly place river basins as an appropriate unit for study (Dasgupta, 2008). While the history of the anthropocentric development of the Heihe River basin can be traced to the Qin Empire of 210 BCE, significant changes to the river basin resulting from agricultural development only occurred during the latter part of the 20th century (Wang and Cheng, 1999; Xuequan and Qianzhao, 2002). Given the rapid economic development of China in the past decade, the middle reaches of the Heihe River basin has experienced an increase in population density and in anthropogenic activities. This has increased the exploitation of surface and ground water in the middle reaches while decreasing the level of water flows and consequently damaging the ecological environment of the lower reaches of the Heihe River basin. With the aim of providing a more even flow of water between the middle and lower reaches of the basin, in the year 2000 the Chinese government began to implement water distribution plans (Zhang et al., 2004). These plans focused on implementing water quota targets for the agricultural sector, improvement of the efficiency of irrigation canals, and water conservation so that more water could flow from the middle reaches to the lower reaches of the river basin (Cheng et al., 2006).

System-level properties, their trade-offs, and implications for the resilience of the system, are poorly understood in holistic water resource management approaches. Therefore there is a critical need for research in advancing our understanding of such system-level properties and developing objective tools to measure these properties and make them more relevant to policy makers and practitioners. This research contributes to the expanding literature in this area by examining the changes to system-level configurations of the middle reaches of the Heihe River basin from 2000 to 2009. More specifically through the ENA approach this research reveals changes to the system-level properties of efficiency, redundancy, and discusses trade-offs to the resilience of the middle reaches of the Heihe River basin resulting from the recent water efficiency and conservation plans. The paper is organized as follows: Section 2 introduces the Ecological Network Analysis approach. Section 3 discusses the data on the Heihe River basin. The results from the ENA approach in addition to two scenarios are presented in Section 4. Section 5 presents a discussion of the results together with an outline for future research avenues. We hope that this paper contributes towards the creation of a new generation of objective monitoring