Chapter 14
Application of the Ecological Network Analysis (ENA) Approach in Water Resource Management Research: Strengths, Weaknesses, and Future Research Directions

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Abstract Population growth, climate change, and conflicting demand by industry and agriculture are increasingly straining our planet's water resources. In this light, there is a need to advance holistic approaches and objective tools which allow policymakers to better evaluate system-level properties and trade-offs of water resources. This chapter contributes to the expanding literature in this area by highlighting water resource management strategies based on the ecological network analysis (ENA) approach. This chapter overviews the theoretical underpinnings of the ENA approach and its application, limitations, and weaknesses for water resource management research. Furthermore, through the case study of the Heihe River Basin, this chapter demonstrates how to examine system-level properties and their trade-offs relevant to the resilience of water services. The ENA approach considers holistic trade-offs that may be used to evaluate alternative water recycling and saving scenarios. This approach can complement multiple criteria decision-making framework and scenario planning approaches and can be beneficial in developing new applicable water resource management strategies.

Keywords Resilience · River basin · Water network · Ecological network analysis · Water policy

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14.1 Introduction

With the expansion of anthropocentric activities and climate change, management of scarce water resources has increasingly become one of the most critical challenges for sustainable development. Water scarcity not only exacerbates the vulnerability of food security but also increases the risk of geopolitical conflicts over water access and control. Given the transdisciplinary nature of the challenges associated with water supply and demand, the control and modification of individual sections may lead to unpredictable effects on other sections of the water system. Sustainable water resource management, therefore, requires an integrative evaluation of economic, social, and environmental dimensions. A holistic approach to a water system allows for a better understanding of the system-level dynamics of the water resource system and results in more effective and relevant sustainable decisions (Xue et al. 2015).

Traditionally, water resource management has focused on economic dimensions, while recently there has been a growing consensus on the necessity for more holistic concepts such as integrated water resource management (IWRM). Discussions surrounding IWRM began in the late 1980s and have evolved toward an overarching conceptual umbrella incorporating integrated sustainable social, environmental, and economic principles relevant to better water resources (Gallego-Ayala 2013). Despite its conceptual advantages, the IWRM is weak in practicality and application in the real world. Specifically, researchers have raised concern over the lack of successful evidence of this approach in the literature and the inability of the concept to offer analytical tools for highlighting cost-benefit trade-offs relevant to different water resource management approaches (Chikozho 2008; Garcia 2008). The inability to evaluate trade-offs is most critical with regard to groundwater resources where there is less physical visibility of its flow and recharge dynamics.

The ecosystem services concept has also been proposed by researchers seeking solutions relevant to economic and environmental dimensions (Garcia et al. 2016). In this avenue, a trade-off analysis is conducted with multiple ecosystem services and multiple stakeholders of a water system. This approach is beneficial toward integrating divergent managerial perspectives arising from different environmental and economic expenses and benefits. However, this approach may be overly complicated and would require large amounts of difficult-to-quantify data reflecting costs of each solution, detailed evaluations of the numerous stakeholders, and environmental resources of the water system (Hering et al. 2010; Hering and Ingold 2012).

The criticality of trade-off analysis is most evident with the increasing shift in recent years from consumption of surface water to consumption of less physically visible groundwater sources. While measuring groundwater resources continues to be a challenging endeavor, to a substantial extent conventional hydrological models are theoretically able to predict groundwater dynamics. However, these hydrological models are based on simplifying assumptions and are limited in reflecting network flows such as groundwater recharge, feedback, and water cycles (Goderniaux et al. 2009). Furthermore, these models are limited in their ability to directly examine system-level water network dynamics, most importantly, the resilience of the hydrological cycle. In this avenue, there is a critical need for advancing research on the system-level properties of water resource systems and more importantly develop objective tools to measure and communicate these properties for their application by sustainability practitioners.

In light of the complexities and limitations of previous approaches to water resource management, researchers have been exploring new directions arising from interdisciplinary network approaches. The main strength of holistic network approaches lies in their ability to illustrate system-level properties, trade-offs, and network properties such as the resilience of the system. For example, while the efficient extraction, transport, and consumption of water are commonly ascribed policy decisions, their system-level effects, especially on the resilience of water system, are not well understood (Scott et al. 2014). A resilient water system is defined as a system with the capacity to persist in its ability to deliver water services in the face of various disruptions and shocks, e.g., excessive water consumption, droughts, and climate change impacts. Network approaches are especially beneficial toward evaluating certain dynamics of the water system which are not easily and physically visible – this includes most importantly the dynamics of groundwater flow and recharge.

New insights toward evaluating system-level dynamics of water systems are arising from information-based network approaches such as the ecological network analysis (ENA). The ENA approach defines the dynamics of a resilient water system as arising from a balance between network redundancy and efficiency. In this view, a highly efficient water system maintains lower water flow redundancies and a weaker capacity for resilience. For example, highly efficient irrigation systems of a river basin may restrict the groundwater recharge flows and lower the system's ability to absorb water inflow shocks by relying on groundwater storage. Consequently, while the rate of pumping water may not be increasing, the net amount of what is pumped is increasing, leaving less residual to return to the aquifer. This has been referred elsewhere to the paradox of the "net water use" which is similar to Jevons paradox. Conversely, a highly redundant water system may result in excessive negligence, water loss, and detrimental to the resilience of the water system. The main value of the application of the ENA approach to water resource management research lies in its potential to overcome the limitations of previous approaches and hydrological models in reflecting system-level properties and trade-offs.

This article aims to introduce the ENA approach and discuss its strengths, limitations, and future research directions to a wide audience of researchers and practitioners in the area of water resource management. This chapter is organized as follows: Section 14.2 discusses the theoretical underpinning of the ENA approach and particularly focuses on network properties relevant to system resilience. Section 14.3 presents a review of the literature applying the ENA approach to water resource management research. Section 14.4 provides a case study example of the application of the ENA approach toward evaluating the trends of river basin network and applying relevant alternative scenario options. Finally, a discussion, conclusion, and future research directions follow in Sect. 14.5.

14.2 Ecological Network Analysis (ENA) Approach

The ecological network analysis (ENA) approach examines the emerging network structure from the flow of materials, e.g., information, money, electricity, nutrients, and water, among the node components of a system. This approach can be applied to systems that can be pictorially depicted as a web structure, i.e., a collection of compartment boxes connected by directed and weighted arrows that describe exchanges of materials that allow the functioning of a system. Rather than emphasizing the particular characteristics of nodes within a system, the ENA approach emphasizes the flow transfers between the nodes (Ulanowicz 1986). The ENA approach allows for a detailed examination of the system-level properties of the network and reveals network properties influencing the resilience of the system (Fath and Patten 1999). The underlying assumptions of this approach are, first, that growth and development are fundamentally two distinct system properties (Huang and Ulanowicz 2014). While growth reflects an extensive property of a system, e.g., the size of a system as quantified through the total system throughput (TST), development reflects an intensive property of organization within the system. More specifically, the development of the system is based on two dialectically related system-level network properties of efficiency and redundancy. In this avenue, the second underlying assumption of the ENA approach is the notion that the resilience of a networked system depends on the balance between network efficiency and redundancy arising from the topology and magnitudes of the pathways through which materials are circulated.

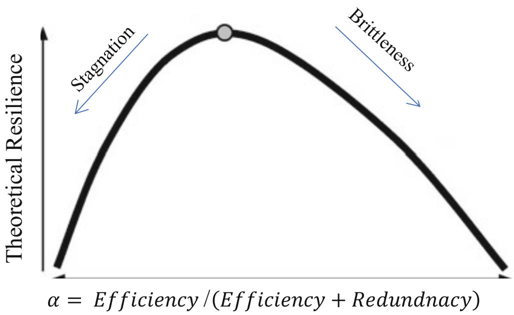
While in the long term, natural systems have been observed to increase their efficiency at the expense of their redundancy (Ulanowicz 1997), current levels of a trade-off between these two system variables depend on agency behavior, environmental constraints, and shocks or disruptions directed at the system. The efficiency of a system can be defined as the degree of articulation or constraints of flows in a network. In a water system, the efficiency of a system can be increased, for example, through the development of irrigation and drainage canals and aqueducts. In more objective and quantifiable terms, the average mutual information (Ulanowicz 2009; Ulanowicz and Norden 1990) is used to define the network efficiency of a system as:

$$\text{Efficiency} = \sum_{i,j} \frac{T_{ij}}{T_{..}} \log \frac{T_{ij} T_{..}}{T_{i.} T_{.j}} \tag{14.1}$$

Here, T_{ij} is a flow from agent i to agent j, $T_{i.} = \sum_j T_{ij}$ is the total flow leaving agent i, $T_{.j} = \sum_i T_{ij}$ is the total flow entering agent j, and the sum of all flows in the system, $T_{..} = \sum_{ij} T_{ij}$, is known as the total system throughput (TST).

The redundancy of a system, the countering variable to efficiency, can be defined as the degree of freedom or overhead of flows in a network. Network redundancy reflects the diversity of pathways in a system and is critical for a system's flexibility and capacity to adapt to changing environmental conditions arising from shocks and disruptions. In a water system, the redundancy of a system can be increased, for

Fig. 14.1 The conceptual model of the ecological information-based approach



example, through the application of water reuse and recycling technologies or through the expansion of wetlands and aquifer recharge. In more objective and quantifiable terms, the conditional entropy is used to define the network redundancy (Ulanowicz 2009) of a system as follows:

$$\text{Redundancy} \quad = -\sum_{i,j} \frac{T_{ij}}{T_{..}} \log \frac{T_{ij}^2}{T_{i.}T_{.j}} \tag{14.2}$$

Both values of efficiency and redundancy are intensive, dimensionless, and based on units of information depending on the base logarithm used in their calculation, e.g., bits if the base 2 logarithm is used or nats if the natural logarithm is used. In the ENA literature, the natural logarithm is predominantly used in calculations.

Intuitively, following a disruption, networks with more diverse connections are more flexible in rerouting their flows and maintaining critical functions. Conversely, a more efficient network with a minimal number of well-organized connections can concentrate its capacity for growth and development. As illustrated in Fig. 14.1, overly redundant networks may be incoherent and lacking the efficiency to grow, while overly efficient networks may be brittle and prone to collapse when subjected to stress. To help determine a balance between constraint imposed by efficiency and the flexibility provided by redundancy, the relative order in the system is introduced as:

$$\alpha = \text{Efficiency}/(\text{Efficiency} + \text{Redundancy}), \quad \text{where } 0 \le \alpha \le 1 \tag{14.3}$$

The ratio α is a convenient way to express the degree of which property dominates the system at a given time. Departing from the relative order and invoking the Boltzmann measure (Boltzmann 1872) of its disorder, the level of a system's theoretical resilience can be expressed as (Ulanowicz et al. 2009):

$$\text{Theoretical Resilience} = -\alpha \ \log(\alpha) \tag{14.4}$$

From Eq. 14.4, a maximum value for theoretical resilience is derived as $1/e \approx 0.3704$ (independent of the logarithm's base). Empirical investigations have determined that natural networks, e.g., ecosystems and food webs, lie in close proximity to this maximum (Ulanowicz 2009), while economic systems indicate higher levels of redundancy (Kharrazi et al. 2013). The maximum resilience value, however, should be seen as a theoretical benchmark; optimal (minimal) vulnerability of real heterogeneous systems under various environmental conditions may be different from this value.

Theoretical resilience (Eq. 14.4) signifies the balance between efficiency and redundancy as a single metric and therefore is useful in exploring and comparing the configurations of heterogeneous networks. However, the analytical implications of the variable are limited and should be approached with caution. Firstly, the variable does not differentiate among shocks against which the network system might be judged to be resilient. Secondly, despite arguments of biomimicry, derived from evolutionary observations (Kharrazi et al. 2016a, b), it may be difficult to prescribe an optimal level of theoretical resilience to socioeconomic networks. Without a normative value, changes to the network configurations may be difficult to translate into actions, strategies, and practices.

14.3 Applying the ENA Approach in Water Resource Management Research

While the roots of the ENA approach lie within the ecological modeling and food web literature (Mukherjee et al. 2015), the approach has been gradually expanded to other economic (Goerner et al. 2009; Huang and Ulanowicz 2014) and environmental research areas (Chen et al. 2011, 2015). The ENA is a well-matched research approach for water system research as water systems encompass different inputs, outputs, and transformations between their compartments. Within the water resource management research domain, researchers have applied the ENA approach at different scales including, for example, at the level of urban, river basin, and virtual water systems.

At the level of urban water networks, the ENA approach has been applied in Albareto, Ravenna, and Sarmato in Italy (Bodini 2012; Bodini and Bondavalli 2002; Bodini et al. 2012). Within these studies, the ENA approach was used to illustrate water exchanges between the different sectors of the cities, and comparisons were made between present network configurations and network configurations arising from new water usage scenarios. In the same research vein, Pizzol et al. (2013) apply the ENA approach in examining the urban water management system of Hillerød, Denmark, using data from 2004 to 2008 and two future scenarios for 2015 and 2020. In this study, the authors compare the network properties found in the urban water system to natural ecosystems and discuss network-based strategies for increasing the resilience of the system to flooding and heavy rain events.

The ENA approach has been most frequently applied to the level of river basins, and most studies are based on case studies based in China. In one of the earliest studies in this avenue, Li et al. (2009) apply the ENA approach to six subsystems of the Yellow River Basin in China based on data from 1998 to 2006. This study develops new metrics based on the ENA approach and attempts to incorporate socio-environmental properties underlying the supply and demand of water. In a similar study, Li and Yang (2011) examine four subsystems of the Haihe River Basin in China based on data from 1999 to 2002 and 2005 to 2007. Within this study, the authors examine the optimal balance of network properties relevant to the resilience of the water system, i.e., efficiency against redundancy, in seven distinct scenarios. More recently, Hai et al. (2015) develop three new composite indicators based on the concept of optimality within ENA approach and in combination with conventional multidimensional social, economic, and environmental indicators. Using these composite indicators, the authors examine four subsystems of Huaihe River Basin in China from 2005 to 2011. The ENA approach has also been employed to examine the network configurations of the Baiyangdian River Basin in China from 2008 to 2013. Within this study, the authors attempt to advance the use of subsystem-level ENA indicators in examining different scenarios of the water system. Finally, Kharrazi et al. (2016a, b) examine the changes to system-level network configurations of the middle reaches of the Heihe River Basin in China from 2000 to 2009. In this study, the authors focus their discussion on the long-term resilience of the water system and more specifically the effects of changes in the groundwater body levels. The authors advance two hypothetical alternative scenarios, based on water recycling and saving strategies, to improve the long-term resilience of the water system.

The ENA approach has also been applied at the scale of virtual or embodied water flows. In this avenue, Fang and Chen (2015) construct virtual water network consisting of six economic sectors for Ganzhou District in the Heihe River Basin in China using data from 2002 to 2010. In addition to the system-level network properties reflecting the efficiency and redundancy of the water system, this study examines the dominant controlling sectors for water circulation and the utility relationships between pairwise sectors within the system.

14.4 Applying the ENA Approach in the Middle Reaches of the Heihe River Basin

Case studies are essential in advancing the application, practicality, and understanding of the strengths and limitations of the ecological network analysis (ENA) approach for water resource management research. Toward this end, we introduce a recent case study research by Kharrazi et al. (2016a, b) in examining the trends of the network properties of middle reaches of Heihe River Basin. The Heihe River Basin, China's second largest inland river basin, begins from the heights of the Qilian Mountains and ends in the perimeter of China's Gobi Desert (see Fig. 14.2). Given its bountiful water resources, this river basin has increased the region's capacity for agricultural development, especially in its middle reaches. The increasing anthropogenic activities

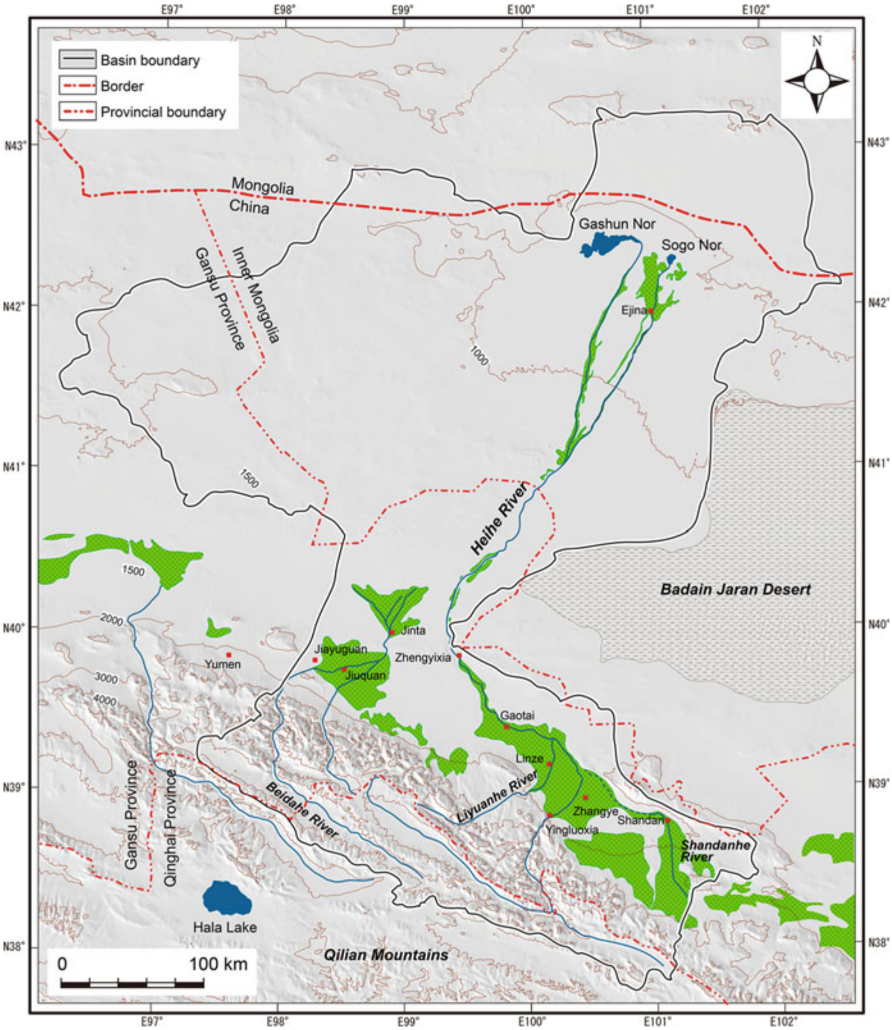


Fig. 14.2 A map of Heihe River Basin

require further exploitation of the surface and groundwater resources and in turn harming the ecology of the lower reaches. Realizing such critical trends, since the 2000s, the Chinese government has implemented regional water resource management plans, e.g., agricultural water quotas, more efficient water canals, and water conservation strategies (Cheng et al. 2006).

To examine the steady-state network (Jørgensen et al. 2007) of the Heihe River Basin, an eight-compartment model was constructed to represent the various hydrological and consumption flows between the compartments. This eight-compartment model represents hydrological inputs, outputs, and socioeconomic consumption

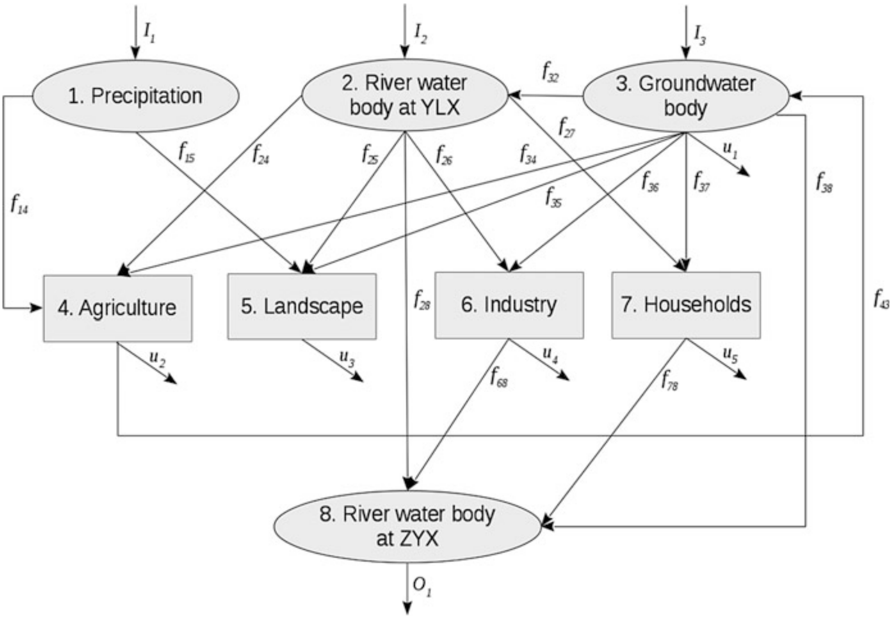


Fig. 14.3 The eight-compartment water network flows of Heihe River Basin

components of the river basin. The first compartment reflects rainwater, the second compartment represents river water from the upper reaches, and the third compartment reflects groundwater. The first three environmental compartments of the model circulate water to the social-economic compartments (4–7), i.e., agriculture, natural landscape, industry, and households. The output of the model to the lower reaches of the river basin is represented in the eighth compartment. Particular to the case study region, certain assumptions were made for this model. The groundwater recharge from the natural landscape f_{53} was not considered because annual rainfall below 200 mm usually results in negligible groundwater body recharge (Scanlon et al. 2006). All flows are static annual flows of water (10^8 m^3). Figure 14.3 illustrates the network model, and Table 14.1 illustrates the construction of the matrix of the network model, and a description of flows is given in Table 14.2. The data collected for this model is from the year 2000 to the year 2009.

14.4.1 Heihe River Basin Case Study Results

Through the ENA approach, the evolution of the network topology of the middle reaches of the Heihe River Basin from 2000 to 2009 can be revealed. As seen in Table 14.3, the extensive variable of TST, reflecting the total flows of the system, indicates a positive increase in the total size of the system during the 10-year period

Table 14.1 The matrix of the network model and corresponding row and column number, where (f) are internal flows between the compartments, (I) are boundary input flows, (u) are boundary output flows, and (o) is the water output to the lower reaches of the river basin

	1	2	3	...	...	...	...	n	$n+1$
1	–	–	–	f_{14}	f_{14}	–	–	–	–
2	–	–	–	f_{24}	f_{25}	f_{26}	f_{27}	f_{28}	–
3	–	f_{14}	–	f_{34}	f_{35}	f_{36}	f_{37}	f_{38}	u_1
...	–	–	f_{43}	–	–	–	–	–	u_2
...	–	–	–	–	–	–	–	–	u_3
...	–	–	–	–	–	–	–	f_{68}	u_4
...	–	–	–	–	–	–	–	f_{78}	u_5
n	–	–	–	–	–	–	–	–	o_1
$n+1$	I_1	I_2	I_3	–	–	–	–	–	–

Table 14.2 The flows and their description of the Heihe River Basin networks

Flows	Description
I_1	Precipitation
I_2	Annual river discharge at YLX
I_3	Groundwater discharge from mountainous areas
O_1	Annual river discharge at ZYX
u_1	Groundwater storage change
u_2	Evapotranspiration from the farmland
u_3	Evapotranspiration from the landscape
u_4	Consumptive water use of industrial sector
u_5	Consumptive water use of domestic sector
f_{14}	Precipitation to the farmland
f_{15}	Precipitation to the landscape
f_{32}	Groundwater discharge to surface water
f_{24}	Agricultural water use from surface water source
f_{25}	Landscape water use from surface water source
f_{26}	Industrial water use from surface water source
f_{27}	Domestic water use from surface water source
f_{28}	Surface water flowing from YLX directly to ZYX
f_{34}	Agricultural water use from groundwater source
f_{35}	Landscape water use from groundwater source
f_{36}	Industrial water use from groundwater source
f_{37}	Domestic water use from groundwater source
f_{38}	Annual groundwater discharge to ZYX
f_{43}	Groundwater recharge from agriculture
f_{78}	Domestic waste water

by 11%. While the overall scale of the network has increased in size, the inner development of the system as reflected in the intensive network properties reveals important changes in the configuration of the network. Specifically, the efficiency (E) variable has increased by 6%, while the redundancy (R) variable has decreased by 6% from 2000 to 2009. These trends warrant a more in-depth examination of the inner dynamics of the water network.

Table 14.3 Trends of ENA variables of the Heihe River Basin network from 2000 to 2009

Year	TST	(*E*)	(*R*)
2000	85.45	1.00	1.53
2001	78.93	0.98	1.60
2002	85.19	1.04	1.50
2003	94.50	1.05	1.45
2004	79.98	1.03	1.51
2005	88.80	1.04	1.52
2006	90.50	1.06	1.46
2007	95.62	1.06	1.43
2008	93.51	1.04	1.49
2009	94.69	1.06	1.43
Average	88.72	1.04	1.49
Lowest	78.93	0.98	1.43
Highest	95.62	1.06	1.60
% change	11%	6%	−6%

The health of the groundwater body is fundamental to the health of the river basin network through time. Excessive extraction or insufficient recharge of the groundwater component damages the health of the network through time. Given the static nature of the annual data snapshots of the Heihe River Basin and the limited understanding of the storage capacities, it is difficult to dynamically examine the dynamics of the groundwater body component and its responses to flow changes in the system. However, some insight can be attained by examining the input and output trends of the groundwater body component. As seen in Table 14.4, it is evident that the output consumption of the groundwater is increasing, while most critically, the groundwater recharge is decreasing. Furthermore, it is evident that the hydrological outputs of the groundwater have also been reduced. These trends indicate a critical negative balance of the groundwater component of the Heihe River Basin.

The results of the trend in the network configuration of the Heihe River Basin reveal two important points relevant to the long-term sustainability of the system. The decreasing trend of firstly the network redundancy and secondly the groundwater recharge flows harms the long-term resilience of the water availability in the middle reaches of the Heihe River Basin. The discussed trends indicate the decreasing capacity of the system to withstand potential shocks and disruptions, for example, hydro-environmental changes or excessive water consumption, and lower the system's flexibility in rerouting water flows in response to such stresses. The weakening of the resilience of the system to potential stresses is perhaps best illustrated in the flow changes directly affecting the groundwater body component. Results indicate excessive extraction and more importantly a significant decrease in recharge, i.e., a reduction of 31%, to this critical component. Considering the input-output flow balance to the groundwater body component, the long-term health of the system has been weakened. This may indicate a strong connection between improvements in the irrigation canals and, consequently, decreasing water seepage and lower groundwater recharge flows.

Table 14.4 Trends of groundwater body input and output flows from 2000 to 2009

			Output							
	Input		Consumption				Hydrological			Balance
Year	I_3	F_{43}	F_{34}	F_{35}	F_{36}	F_{37}	F_{38}	F_{32}	u_1	Inputs – outputs
2000	2.64	12.3	1.92	1.36	0.06	0.04	0.87	7.65	2.9	0.14
2001	2.64	11.64	2.79	1.58	0.1	0.07	0.85	6.01	2.8	0.08
2002	2.64	9.06	2.49	1.17	0.09	0.07	0.94	6.7	0.65	−0.41
2003	2.64	9.76	2.83	0.91	0.12	0.09	1.14	6.81	0.62	−0.12
2004	2.64	9.89	3.25	1.48	0.15	0.11	0.67	5.63	0.37	0.87
2005	2.64	7.67	3.16	1.06	0.15	0.11	1.61	4.98	0.49	−1.25
2006	2.64	9.34	3.25	1.32	0.15	0.11	0.68	5.8	0.43	0.24
2007	2.64	6.46	2.86	0.88	0.09	0.08	0.73	5.5	0.39	−1.43
2008	2.64	8.57	3.46	1.56	0.1	0.08	1.29	4.95	0.85	−1.08
2009	2.64	8.46	3.33	1.76	0.1	0.09	0.49	4.23	1.2	−0.10
Average	2.64	9.32	2.93	1.31	0.11	0.09	0.93	5.83	1.07	−0.30
Lowest	2.64	6.46	1.92	0.88	0.06	0.04	0.49	4.23	0.37	−1.43
Highest	2.64	12.30	3.46	1.76	0.15	0.11	1.61	7.65	2.90	0.87
% Change	**0%**	**−31%**	**73%**	**29%**	**67%**	**125%**	**−44%**	**−45%**	**−59%**	**−167%**
Std. Dev.	0.00	1.73	0.47	0.30	0.03	0.02	0.33	1.01	0.97	0.74

14.4.2 Scenario Analysis

In response to the critical challenges discussed in the previous section, based on the 2009 network, two alternative scenarios are proposed. The first scenario focuses on water recycling, while in the second scenario, in addition to water recycling, water conservation and a groundwater recharge strategy are envisioned. In the first scenario, water recycling is proposed between the agriculture, industry, and household compartments of the system, i.e., between agriculture and industry as f_{46} and f_{64} both for 0.5 10^8 m^3, households and industry as f_{67} and f_{76} both for 0.25 10^8 m^3, and households and agriculture as f_{74} and f_{47} both for 0.25 10^8 m^3. The amount of recycled water reflects annual rates and therefore does not pressure the input and output flows of the system. Furthermore, these small volumes demonstrate how basic changes to the flow structure can affect network indices. In the second scenario, water saving in the agriculture compartment by 0.5 10^8 m^3 and its diversion to the groundwater recharge (f_{43}) is proposed.

The results of the network configuration of these two scenarios can be seen in Table 14.5. The results from the first scenario reveal a significant increase in the redundancy (R) and a small decrease in the efficiency (E) of the system. In the second scenario, these changes were more pronounced. Due to additional water flow from recycled flows, results from both scenarios revealed an increase in the TST value. Results from the second scenario revealed that the increase of groundwater recharge flows (f_{43}) did not significantly change the network configurations of the water system. However, the increasing recharge flows changed the input-output balance of the groundwater body to positive levels and therefore consequently improves the long-term health of the groundwater body compartment.

14.4.3 Policy Considerations for Sustainable Water Resource Management

The results of the trends of the network configurations of the middle reaches of the Heihe River Basin reveal two important water resource management considerations. First, the efficiency of the water network in the middle reaches needs to be maintained at a level which also allows for ample water flow to the lower reaches. The efficiency of the water network can be configured through water resource management strategies promoting conservation, for example, through enhanced

Table 14.5 The system-level and subsystem-level indicators of the two alternative scenarios and their changes relative to the 2009 network configurations

Index	Original (2009)	Scenario 1	Change (%)	Scenario 2	Change (%)
TST	94.6928 10^8 m^3	96.6928	2.11	96.6928 10^8 m^3	2.11
E	1.0575 nats	1.0526	−0.46	1.0454 nats	−1.14
R	1.4339 nats	1.5237	6.27	1.5211 nats	6.08

water canals, less intensive agriculture, and water tariffs and quotas. Second, the redundancy of the water network in the middle reaches needs to be maintained so as not to harm the long-term health and resilience of the water system. As reflected in the results of the case study, these two water resource management considerations may pose trade-offs. In this avenue, the alternative scenarios may provide preferable modifications to the network configurations which better reflect both of the above considerations. However, these scenarios are realistic to a certain extent and do not completely reflect economic or environmental costs.

14.5 Discussion and Conclusion

The ecological network analysis (ENA) approach enables important insights toward the sustainable management of water resource systems. As a holistic approach, the strength of the ENA approach lies in its ability to evaluate system-level trade-offs and better policies in consideration of the resilience of the water system. As illustrated in the case study of the Heihe River Basin, the ENA approach is specifically insightful toward evaluating the health of physically less visible components of water systems such as the groundwater flows and its recharge dynamics. Through the ENA approach, the resilience of a water system is evaluated as a balance between the network efficiency and redundancy of water flows. In the case of the Heihe River Basin, higher network efficiency was achieved through governmental efforts toward the improvement of irrigation canals and water usage quotas. The success of these efforts was confirmed through increases in the value of efficiency (*E*) of the system and evident through the increase of boundary outflows to the lower reaches of the river basin. This outcome, however, resulted in lower water flow redundancies. A highly efficient water system negates the capacity of the system for resilience and its ability to absorb, for example, climatic and/or socio-economic shocks. The detrimental effect of higher network efficiency resulting from the implementation of the government's water policy was best illustrated through the changes to the input-output flow balance of the groundwater component of the system.

While the ENA approach can raise awareness among policy- and decision-makers of system-level trade-offs critical to resilient water resource management, the limitations and weaknesses of the application of the approach should also be considered. In this avenue, researchers should take caution in utilizing the ENA approach in deriving optimal values for the network configurations and should instead consider optimum values that meet local conditions – see Eq. 16 in Ulanowicz et al. (2009). The discussions surrounding optimal network configurations can be traced to research on natural ecological networks, where these systems were found to maintain configurations within a window of vitality (Ulanowicz 2009). Based on this, some researchers have advanced the idea of biomimicry and the need to change network configurations toward this optimal point for maintaining system resilience. However, this line of reasoning is questionable and its application to systems involving human activities uncertain. Firstly, the literature examining the relationship of natural systems to this optimal point is not systematic, and only 17 ecosystem flow networks have been found to be in close proximity to this optimal point (Ulanowicz 2009). Therefore, to ascertain the existence of such optimality, more natural networks need to be examined. Secondly, while biomimicry in itself is not necessarily without merit, the brutal evolutionary dynamics underlying such optimality may not be possible or desirable in systems involving socioeconomic agents. Therefore, it is questionable whether the evaluation of systems against an optimal point is indeed fruitful – systems may, in fact, maintain heterogeneous optimal points based on their environmental surroundings and the potential shocks and disruptions they may face. Toward this end, it may be insightful to examine whether if networks from different classes of systems, e.g., water, energy, food, and trade, cluster around certain ranges.

The application of the ENA approach to water systems is also weak in considering changes in the quality of the water flows. The issue arises when one considers the various qualities and their suitability for consumption. For example, while water used for agriculture can be reused by industry, water used for the industry may perhaps not pass the quality requirement for household consumption. As the ENA approach assumes the quality of all water flows as equal, researchers need to take caution and also consider the qualitative aspects of water flows in the system under their examination. In the meantime, a number of different models have been developed to investigate material cycles in river basins. They have been developed, respectively, to examine nitrogen cycles (Do-Thu et al. 2014), phosphorus cycles (Strokal et al. 2015), and other chemical compositions. Overcoming existing challenges around these models such as data availability and uncertainty, it becomes possible and worthwhile to integrate ENA with them.

The values of the network configurations resulting from the ENA approach may be affected by how the researcher develops and designs the model reflecting the water system. In this avenue, the discretion of the researcher in considering the scale, boundary, and detail of the components of the water system is important. The inclusion or exclusion of nodes representing environmental, water distribution, and socioeconomic components may, in fact, result in the reduction or increase of pathways within the network and influence the values of the network configuration. Although researchers are limited in their ability to model a system based on data availability and policy relevance, it is necessary to take into account the limitations of taking under consideration all components of a system and the effects that model design may have on network configuration values.

For future research, it is necessary to advance the applicability of the ENA approach for water resource management and make it more communicable to policy- and decision-makers. Toward this end, more scenarios testing the resilience of the water system to various probable and possible socio-environmental shocks are necessary. These scenarios increase the ability to situate the network configurations of a system to relevant policy deliberations. In the same vein, the ENA approach can also be utilized toward the examination of the system-level effects of water policy scenario options. As illustrated by the two alternative scenarios in the case study of the Heihe River Basin, water conservation, recycling, and groundwater recharge policies can alter network configurations and positively affect the resilience of the water system. In the case study of the Heihe River Basin, the alternative scenarios, although not far from reality, were hypothetical in nature and did not consider the social, economic, and environmental feasibilities and costs. Therefore, new research directions are essential in better situating water scenario planning options utilizing the ENA approach. In this avenue, the multi-criteria decision analysis (MCDA) framework is a promising research direction. The MCDA framework allows for the performance ranking of various scenario decisions against multiple criteria which may be even measured through different units (Hajkowicz and Collins 2007). The MCDA framework is also beneficial towards more stakeholder community engagement and decision-making transparency and allows system-level deliberations to be better grounded in social, environmental, and economic realities.

The future application of the ENA approach to water resource management can be strengthened through more abundant and higher-quality data sets. These data sets should include various hydrological and socioeconomic flows reflecting urban, regional, and river basin water systems and enable researchers to better compare findings across different research scales. While the ENA approach has been applied to analyze steady-state system-level properties and trade-offs of water resources, it also has the potential to make more detailed temporal and spatial analytical insights. In this vein, the ENA approach can, for example, be used to integrate material cycle, hydro-ecological, and multi-agent models based on the finite element method. Although the spatial differences among administration, river, and groundwater basin boundaries pose challenges of boundary setting and data collection, it is probable that the integration of these models would be a promising future research area. Furthermore, as water resource management is an issue of optimization of the allocation of water resources and given the increasing amounts of data used for toward their analysis, it is worthy to examine new approaches based in quantum computing as well as quantum annealing to solve relevant combinatorial optimization problems. Finally, new directions leveraging big data, citizen science, low-cost sensors, and hydro-informatics are also promising approaches in this avenue (Chen and Han 2016).

This chapter expanded on the theoretical underpinnings of the ecological network analysis (ENA) and discussed the strengths, weaknesses, and limitation of its application in water resource management research. It is hoped that this article inspires further research in applying the ENA approach toward sustainable water resource management and advancing this holistic approach for practical water policy deliberations.

References

Bodini A (2012) Building a systemic environmental monitoring and indicators for sustainability: what has the ecological network approach to offer? Ecol Indic 15(1):140–148. https://doi.org/10.1016/j.ecolind.2011.09.032

Bodini A, Bondavalli C (2002) Towards a sustainable use of water resources: a whole-ecosystem approach using network analysis. Int J Environ Pollut 18(5):463–485. https://doi.org/10.1504/IJEP.2002.002340

Bodini A, Bondavalli C, Allesina S (2012) Cities as ecosystems: growth, development and implications for sustainability. Ecol Model 245:185–198 Retrieved from http://www.sciencedirect.com/science/article/pii/S0304380012000981
Boltzmann L (1872) Weitere studien über das wärmegleichgewicht unter gasmolekülen. Sitzungsberichte Akademie Der Wissenschaften 66:275–370
Chen Y, Han D (2016) Big data and hydroinformatics. J Hydroinf 18(4):599–614
Chen SQ, Fath BD, Chen B (2011) Information-based network environment analysis: a system perspective for ecological risk assessment. Ecol Indic 11(6):1664–1672
Chen SQ, Chen B, Fath BD (2015) Assessing the cumulative environmental impact of hydropower construction on river systems based on energy network model. Renew Sustain Energy Rev 42:78–92
Cheng GD, Xiao HL, Xu ZM, Li JX, Lu MF (2006) Water issue and its countermeasure in the inland river basins of Northwest China – a case study in Heihe River Basin. J Glaciol Geocryol 28(3):406–413
Chikozho C (2008) Globalizing integrated water resources management: a complicated option in Southern Africa. Water Resour Manag 22(9):1241–1257
Fang D, Chen B (2015) Ecological network analysis for a virtual water network. Environ Sci Technol 49(11):6722–6730. https://doi.org/10.1021/es505388n
Fath BD, Patten BC (1999) Review of the foundations of network environment analysis. Ecosytems 2(2):167–179
Gallego-Ayala J (2013) Trends in integrated water resources management research: a literature review. Water Policy 15:628–647. https://doi.org/10.2166/wp.2013.149
Garcia LE (2008) Integrated water resources management: a 'small' step for conceptualists, a giant step for practitioners. Int J Water Resour Dev 24(1):23–36
Garcia X, Barceló D, Comas J, Corominas L l, Hadjimichael A, Page TJ, Acuña V (2016) Placing ecosystem services at the heart of urban water systems management. Sci Total Environ 563–564:1078–1085. https://doi.org/10.1016/j.scitotenv.2016.05.010
Goderniaux P, Brouyère S, Fowler HJ, Blenkinsop S, Therrien R, Orban P, Dassargues A (2009) Large scale surface-subsurface hydrological model to assess climate change impacts on groundwater reserves. J Hydrol 373(1–2):122–138. https://doi.org/10.1016/j.jhydrol.2009.04.017
Goerner S, Lietaer B, Ulanowicz RE (2009) Quantifying economic sustainability: implications for free-enterprise theory, policy and practice. Ecol Econ 69(1):76–81 Retrieved from http://linkinghub.elsevier.com/retrieve/pii/S0921800909003085
Hai R, Shi H, Zhang B, Zhai Y, Li Y, Wang W (2015) An ecological information analysis-based approach for assessing the sustainability of water use systems: a case study of the Huaihe River Basin, China. Clean Techn Environ Policy 17:2197–2211
Hajkowicz S, Collins K (2007) A review of multiple criteria analysis for water resource planning and management. Water Resour Manag 21(9):1553–1566
Hering JG, Ingold KM (2012) Water resource management: what should be integrated? Science 336:1234–1235
Hering D, Borja A, Carstensen J, Carvalho L, Elliott M, Feld CK et al (2010) The European water framework directive at the age of 10: a critical review of the achievements with recommendations for the future. Sci Total Environ 408(19):4007–4019. https://doi.org/10.1016/j.scitotenv.2010.05.031
Huang J, Ulanowicz RE (2014) Ecological network analysis for economic systems: growth and development and implications for sustainable development. PLoS One 9(6):1–8
Jørgensen SE, Fath BD, Bastianoni S, Marques JC, Müller F, Nielsen SN et al (2007) A new ecology: systems perspective. Elsevier, Amsterdam
Kharrazi A, Rovenskaya E, Fath BD, Yarime M, Kraines S (2013) Quantifying the sustainability of economic resource networks: an ecological information-based approach. Ecol Econ 90:177–186
Kharrazi A, Akiyama T, Yu Y, Li J (2016a) Evaluating the evolution of the Heihe River Basin using the ecological network analysis: efficiency, resilience, and implications for water resource management policy. Sci Total Environ 572:688–696. https://doi.org/10.1016/j.scitotenv.2016.06.210

Kharrazi A, Fath BD, Katzmair H (2016b) Advancing empirical approaches to the concept of resilience: a critical examination of Panarchy, ecological information, and statistical evidence. Sustainability 8(9):935. https://doi.org/10.3390/su8090935

Li Y, Yang Z (2011) Quantifying the sustainability of water use systems: calculating the balance between network efficiency and resilience. Ecol Model 222:1771–1780 Retrieved from http://linkinghub.elsevier.com/retrieve/pii/S0304380011001086

Li Y, Chen B, Yang ZF (2009) Ecological network analysis for water use systems – a case study of the Yellow River Basin. Ecol Model 220(22):3163–3173. https://doi.org/10.1016/j.ecolmodel.2009.08.007

Mukherjee J, Scharler UM, Fath BD, Ray S (2015) Measuring sensitivity of robustness and network indices for an estuarine food web model under perturbations. Ecol Model 306:160–173

Pizzol M, Scotti M, Thomsen M (2013) Network analysis as a tool for assessing environmental sustainability: applying the ecosystem perspective to a Danish water management system. J Environ Manag 118:21–31

Scanlon BR, Keese KE, Flint AL, Flint LE, Gaye CB, Edmunds WM, Simmers I (2006) Global synthesis of groundwater recharge in semiarid and arid regions. Hydrol Process 20 (15):3335–3370

Scott CA, Vicuña S, Blanco-Gutiérrez I, Meza F, Varela-Ortega C (2014) Irrigation efficiency and water-policy implications for river basin resilience. Hydrol Earth Syst Sci 18:1339–1348

Ulanowicz RE (1986) Growth and development: ecosystems phenomenology. Springer, New York

Ulanowicz RE (1997) Ecology, the ascendent perspective. Columbia University Press, New York

Ulanowicz RE (2009) The dual nature of ecosystem dynamics. Ecol Model 220(16):1886–1892

Ulanowicz RE, Norden JS (1990) Symmetrical overhead in flow networks. Int J Syst Sci 21 (2):429–437 Retrieved from http://www.tandfonline.com/doi/abs/10.1080/00207729008910372

Ulanowicz RE, Goerner S, Lietaer B, Gomez R (2009) Quantifying sustainability: resilience, efficiency and the return of information theory. Ecol Complex 6(1):27–36

Xue X, Schoen ME, Ma XC, Hawkings TR, Ashbolt NJ, Cashdollar J, Garland J (2015) Critical insights for a sustainability framework to address integrated community water services: technical metrics and approaches. Water Res 77:155–169