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Validation of the hypothesis on carrying capacity limits using the water environment carrying capacity

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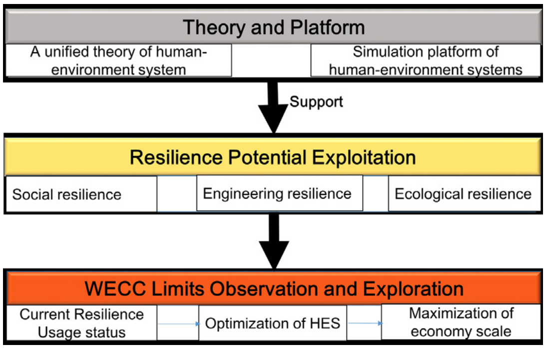
HIGHLIGHTS

- This study distinguished similar concepts related to carrying capacity.
- A framework was established for exploration of WECC limits.
- This study realized the resilience potential exploitation of WECC.
- The results confirmed that WECC limits are dynamic values.
- The results provided some enlightenment for carrying capacity research.

GRAPHICAL ABSTRACT



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ABSTRACT

The concept of "carrying capacity" has been widely used in various disciplines in reference to human-environment sustainability. No unified cognition exists regarding carrying capacity limits for humans. As a typical type of carrying capacity, the water environment carrying capacity (WECC) has been researched for human-water environment sustainability. However, most recent research has focused on the assessment of the water environment carrying capacity of a certain region or river basin. The detailed resilience potential of human-water environment systems that could improve the local water environment carrying capacity has not been systematically exploited. The key concerns of the existence of water environment carrying capacity limits and the exact value have not been addressed. This study first distinguished the characteristics of related concepts, such as carrying capacity, planetary boundaries, resilience, limitations, thresholds and tipping points. An analytical framework was then established to exploit the resilience potential from the four dimensions of "scale, structure, pattern and network". The economy scale with full use of the resilience potential is 11,511,880 M yuan under the current technology and development status, which is nearly 37 times that of the current scale of the economy. The analytical framework confirms that the limit on the water environment carrying capacity is a dynamic value, which could be changed from the four dimensions. The socioeconomic scale that the local water environment can support would be nearly unlimited in some extreme ideal situation. The results would provide some enlightenment on the carrying capacity and other similar marked concepts of theoretical research and provide support for human-environment sustainability.

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1. Introduction

Along with biodiversity loss, environmental pollution, and resource exhaustion induced by rapid economic development and population growth, sustainable development concerns have spawned the concept of "carrying capacity" (Daily and Ehrlich, 1992; Arrow et al., 1995). The concept of carrying capacity has been employed in a variety of disciplines and fields (Sayre, 2008). Many kinds of carrying capacity have been researched according to different objects or fields, such as the ecological carrying capacity (Monte-Luna et al., 2004), environmental carrying capacity (Liu and Borthwick, 2011), land carrying capacity (Cheng et al., 2016), agricultural carrying capacity (Peters et al., 2007), tourism carrying capacity (Bera et al., 2015), and mineral carrying capacity (R. Wang et al., 2016). The water environment carrying capacity (WECC) is a type of carrying capacity that focuses on the environmental properties of water and is concerned with the mechanisms of interaction in human-water environment systems (HWES). There are some concepts related to HWES, such as social-hydrology systems (Sivapalan et al., 2014) and (complex) human-water systems (Baldassarre et al., 2013; Essenfelder et al., 2018). The heterogeneity, feedback and resilience mechanism between human and water systems are the key interests (Liu et al., 2007). Sivapalan et al. (2014) believed that there are three main coevolutionary mechanisms of social-hydrological systems: multiscale structures and dynamics characteristics, physical and governance scales of water-related human-induced outcomes, and the adaptation of individuals and whole societies with respect to water sustainability. Human-water systems are used to reveal the interaction between terrestrial water fluxes and human activities (Wada et al., 2017; Xu et al., 2018). Accordingly, HWES mainly describes the interaction and feedbacks between human activities (industrial production, agriculture, domestic living, etc.) and water (quality and quantity).

The WECC can be defined as "the largest population and economic scale that the water environment can support in a specific region during a period of time without an adverse impact on the local water environment" (Zeng et al., 2011). It consists of various elements, such as population, economy, river basins, landscape and pollutants. The WECC is a powerful theoretical tool for examining the sustainable development of the human-water environment. WECC theory tries to realize the maximum development of the economy and population under the precondition of water quality attainment and development.

To achieve the sustainable development of HWES, an urgent need exists to search developmental routes and exploit the WECC potential to satisfy the maximum development of the population and economy. However, a WECC assessment is central to most current WECC research (Wang and Xu, 2015). Whether the WECC of a study area has been overloaded historically or will be in the future is a concern. Hierarchical multicriteria methods (Giupponi and Rosato, 2002), fuzzy comprehensive evaluation methods (Gong and Jin, 2009) and the water footprint method (Rees, 1992) were used to assess the current and historical WECC status. Zhang et al. (2014) used a system dynamics method to predict the future status. S. Wang et al. (2017) established an integrated method to identify the control factors of WECC in a coastal zone. Wang et al. (2018) used a system dynamics model and an evaluation index system for the WECC assessment of a lake system. Wu et al. (2018) predicted the WECC status through an integrated framework in a continental river basin.

Key concerns of WECC include searching the route to maximize the socioeconomic scale that the local water environment can support to realize WECC improvement and human-environment sustainability, rather than WECC status assessment. This concern is still a blind spot in the current WECC research. The detailed potential hidden in the HWES to improve WECC is unclear. Whether the limits of WECC exist and the exact scale that the local water environment could support have not been discussed or calculated.

Although some research on the limitation of carrying capacity in other fields exists, in that research, the carrying capacity is mainly calculated through relationship indicators or the quota method (Cohen, 1995). The dynamic characteristic of carrying capacity limits is still unclear. This direct question is described in the definition of WECC. Among the existing WECC research, no direct answers or related discussion exists related to the two questions. The deficiencies mentioned above can be summarized in two points: (1) The detailed potential hidden in the HWES to improve the WECC has not been systematically and comprehensively revealed. The improvement measure based on previous WECC assessment methods is not feasible and could not make full use of the potential of HWES for WECC improvement due to the lack of correct recognition of the space-time resilience of HWES. (2) Whether limits to WECC exist is uncertain, and if they do, the exact socioeconomic scale remains unclear.

To conquer the first deficiencies in the WECC research, the concept of resilience is first introduced for inclusion with WECC theory for human-environment sustainability. Resilience, which is defined as the capability to retain similar structures and functioning after disturbances for continuous development, is a key characteristic of human-environment systems (Christopherson et al., 2010). The resilience consists of ecological resilience (Zhu and Anderson, 2017), engineering resilience (Juan-García et al., 2017) and social resilience (Folke, 2006). These three types are all present in WECC. For example, the ecological resilience of a river basin could enhance its ability for pollutant degradation. The engineering resilience of sewages plants could reduce the amount of pollutant discharge. The social resilience of industrial structure and cleaner production levels could reduce the amount of pollutant production. In HWES, the WECC and resilience theory both focus on the stability of the water environment and threshold values. The difference between WECC and resilience theory is that WECC cares about the maximum social scale that the water environment can support, whereas resilience cares about the ability to maintain the quality of the water environment and HWES sustainability. The resilience potential in HWES is always the adjustment margin for improving local WECC. Correct recognition and full usage of the space-time resilience potential in human-environment systems is a prerequisite to improving local WECC and realizing the maximum sustainable development.

To conquer the second deficiencies in the WECC research, a unified theory of human-environment systems (AUTHES) from the four dimensions of scale, structure, pattern and network has been adopted to exploit the resilience potential of HWES to improve WECC. A simulation platform of human-environment systems (HESP) based on multiagent systems has been established to observe the socioeconomic scale change that the local water environment can support under the precondition of water quality attainment. This platform has tried to verify the hypothesis of WECC limits and calculate the maximum socioeconomic scale that the local water environment can support based on the framework.

The main novelty of the research can be summarized in two points: (1) resilience theory is introduced into the WECC analysis for the first time, pointing out the key function of the resilience recognition process for WECC improvement and identifying the space-time resilience of WECC to exploit potentialities to maximize the local WECC, and (2) the research establishes a water quality standard as a threshold and the upper limit of WECC to ensure water quality attainment, which is a core precondition of WECC theory. It verifies that the limits of WECC are a dynamic value, which could be changed by the four dimensions of "scale, structure, pattern and network". The scale of population and economy that a local water environment could support would be unlimited in some extreme ideal situation.

This article is organized as follows: Section 2 emphasizes the methodology, including exploitation of the resilience potential from the four dimensions and WECC limitation calculation. Section 3 illustrates the results of the resilience potential identification and WECC calculation to reveal the routes of WECC improvement, discuss limits to the existence of WECC and its exact value, and present some enlightenment for carrying capacity research. The last section concludes the study and evaluates the significance.

2. Methods

2.1. Comparison of similar concepts

To realize human-environment sustainable development, various concepts, such as carrying capacity, resilience, planetary boundaries, thresholds, and tipping points have been introduced to support policymaking. To better show the research significance, the characteristics of these concepts are distinguished here. Carrying capacity is defined as the maximum number of individuals or units of organisms that can be maintained in a given area on a long-term basis (Convertino et al., 2015; Konar et al., 2013). The linkages between the biological side and the economic side of the human-environment system can be connected through the concept of carrying capacity. The concept of limitation is always used, along with carrying capacity, to describe the value of the limiting factors and the corresponding limitations of the socioeconomic scale (White, 2007). Rockström et al. (2009) introduced the concept of planetary boundaries to estimate a safe operating space for humanity with respect to the functioning of Earth's system. Resilience is defined as the capability to retain similar structures and functioning after disturbances for sustainable development (Folke, 2006). Thresholds are an intrinsic feature of the human-environment system and are often defined by a position along one or more control variables. Boundaries are human-determined values of the control variable set at a "safe" distance from its global threshold. Thresholds are defined as transition points between alternate states (Repetto, 2006). These thresholds include spatial and temporal thresholds (Liu et al., 2007). A tipping point or threshold is described as a nonlinear relationship between the anthropogenic drivers and the biosphere response (Hughes et al., 2013). Transgressing a tipping point always indicates the occurrence of regime shifts.

Fig. 1 distinguishes the characteristic of these similar concepts. The concept of limitation, threshold and tipping points share a very similar definition; they refer to a specific system status that, once eroded, could threaten the environment, and thereby, could threaten human viability. The concepts of threshold and tipping points mainly describe the influence level from human systems that could cause a status change in environmental systems. The concept of limitation could not only describe the maximum allowable value of the factors that limit the influence of human systems but could also describe the maximum allowable value of environmental criteria and maximum socioeconomic scale. The concept of tipping points strengthened the point significance for the regime shifts. The concept of carrying capacity mainly concerned the maximum scale of socioeconomic systems that certain limited factors could support. The value of resilience is the space within the carrying capacity limitation, whereas the value of planetary boundaries is set at a "safe" distance from its global threshold. The concept of resilience mainly strengthened the recovery function of the human-environment systems after disturbances.

These concepts define the safe space and edges of human systems to achieve the positive interaction between human and environmental systems and sustainable development. Compared with other concepts that focus on the influence from human systems, such as resource usage and pollutant emission, the carrying capacity concept concerns

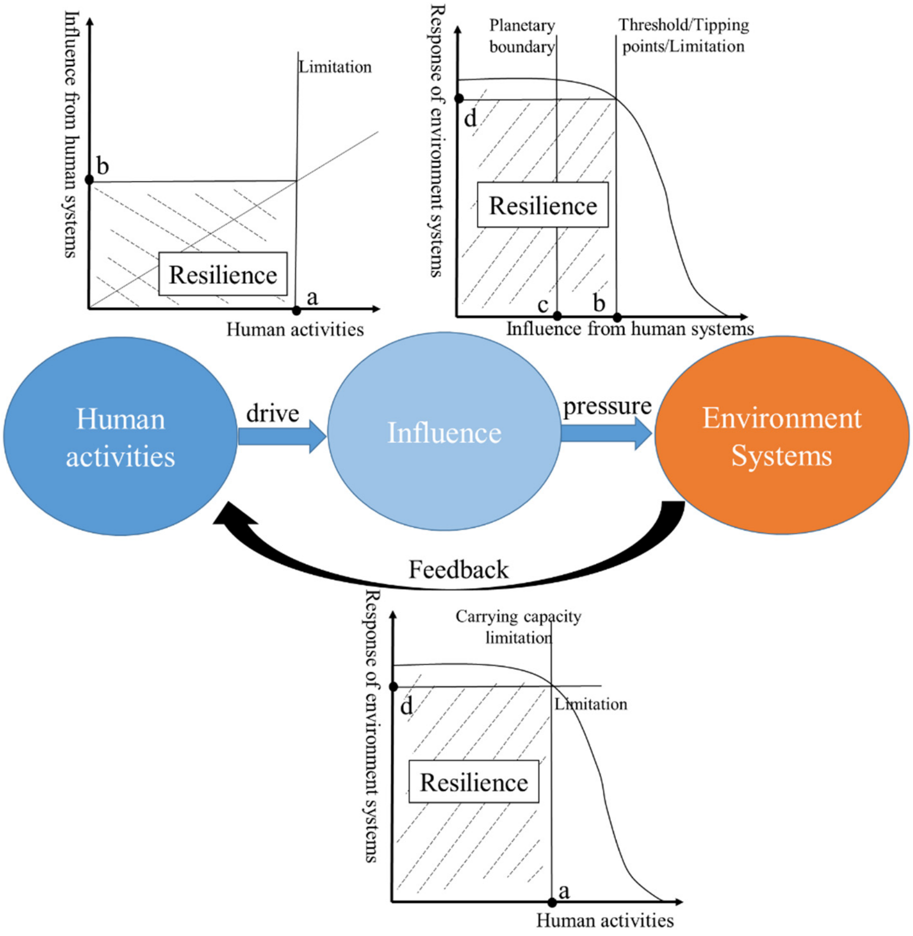

Fig. 1. Distinguishing among similar concepts in human-environment systems.

the human system itself under limitation for limited factors. The concept of resilience provides the space for the enhancement of carrying capacity.

2.2. Analytical framework

An analytical framework of the exploitation of resilience potential and the calculation of scale limits of WECC is shown in Fig. 2. Based on the theory and platform support, the three types of resilience potential are first exploited from the four dimensions of scale, structure, pattern and network. The final WECC limits are then discussed and calculated through three steps.

2.3. Theory and platform

2.3.1. AUTHES theory

A unified theory of human-environment systems (AUTHES) has been established as a unified language to achieve integrated human-environment research (Fig. 3). Through AUTHES, any type of human-environment system, including WECC, could be panoramically and systematically portrayed from the four dimensions of "scale, structure, pattern and network". Scale indicates the extent of the element. Describing a system from the scale dimension is a common method. For a landscape system, the scale represents the area (Van der Plas et al., 2016). For an economic system, the scale could be indicated by production quantity or production value (Moore and Donaldson, 2016). For a river system, the scale could be indicated by the amount of water resources or capacity of the water environment (Feng et al., 2016). Structure indicates the internal ratio of different subclasses. For a landscape system, the structure indicates the proportion of each land use type (Hamstead et al., 2016). For a population system, the structure could indicate the ratio of urban and rural population (Y. Wang et al., 2016). For an economic system, the structure could indicate the ratio of different industrial types, such as agriculture, industry and service industry (Serrenho et al., 2016). Pattern indicates the spatial layout of the element. For a landscape system, it indicates the land use pattern (Zhang et al., 2017). For an economic system, it indicates the economic pattern (Rios and Gianmoena, 2018). A famous phenomenon named industrial agglomeration is a typical pattern of an economic system (Fan and Scott, 2003). Network indicates the spatial linkage of different objects or the temporal linkage of the same object. For an economic system, it could indicate the linkages of upstream and downstream industry chain (Omta et al., 2001). For a river system, it could indicate the linkages between the upper and lower reaches of rivers (Seher and Löschner, 2018). The linkage between the economic system and river system could be established from pollutant production to pollutant loading into the river (Castiglioni et al., 2018).

2.3.2. Simulation platform

A simulation platform of human-environment systems (HESP) has been established based on multiagent systems (MAS). MAS is a major bottom-up tool that has been extensively employed to represent and explain complex systems, such as land use systems, urban transport systems and water resources management (Schröder and Liedtke, 2017; Shen et al., 2018; Zhang et al., 2016). MAS has a powerful ability to reveal the spatial heterogeneity and dynamic interaction of human-environment systems (Groeneveld et al., 2017). The main modules and variables of HESP are shown in Table 1. The concept of HESP in this study is that all the real-world elements of the human-environment systems are represented one-to-one by computational agents. The elements include population, economy, landscape, river basins and pollutants. HESP is mainly used to simulate the process of human activities, pollutant production, pollutant treatment, pollutant discharge, pollutant flow and pollutant monitoring (Fig. 4), and it could represent the characteristics of each element and the interaction mechanisms among them. The characteristics of HESP are presented from four dimensions that include scale, structure, pattern and network. The characteristics and interaction process are described as properties and rules in MAS. It is a powerful tool to support the exploitation of resilience potential and calculation of scale limit from the four dimensions in combination with AUTHES. All exploitation of resilience potential hindered by the dimensions of "scale, structure, pattern and network" could be exploited through HESP. The existing WECC limits could be discussed through the scenario adjustment based on HESP, and the results of the limits could also be calculated if these limits exist.

2.4. Resilience potential exploitation

For WECC research, the resilience potential indicates the unused space to enhance the social-economic scale under the precondition of

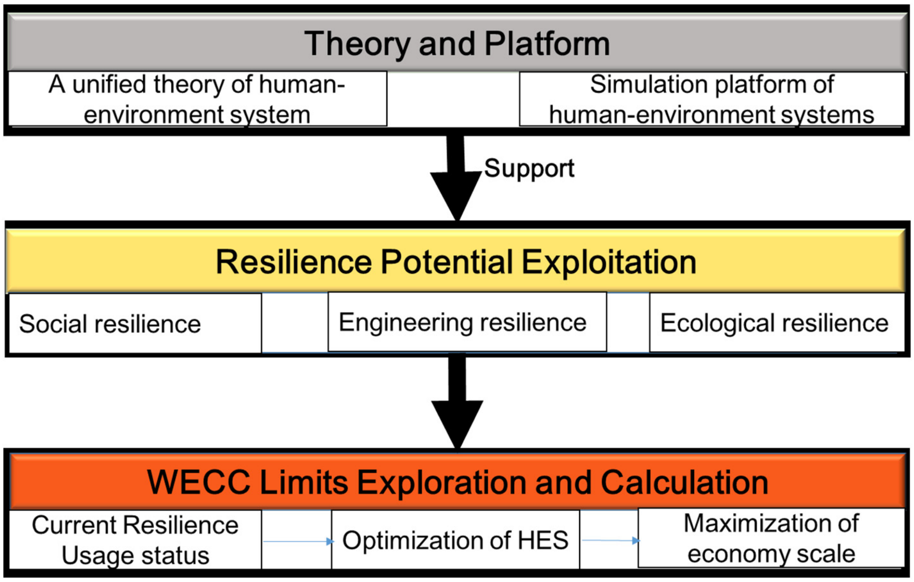

Fig. 2. Analytical framework of resilience potential exploitation and scale limits exploration of WECC.

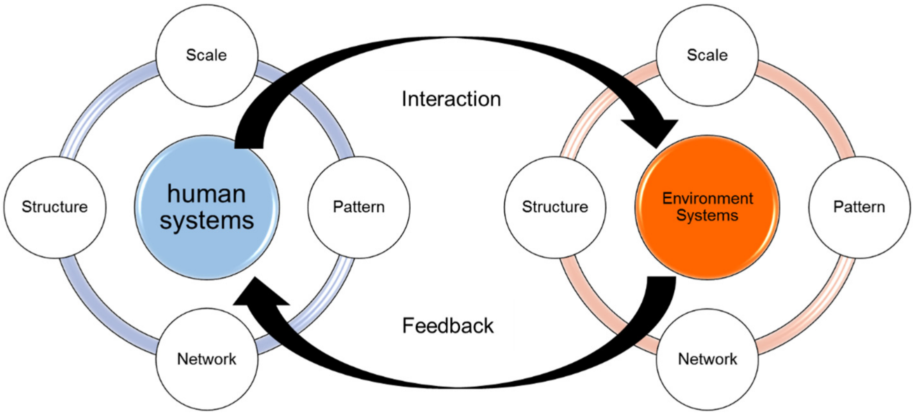

Fig. 3. Illustration of conceptual framework.

water quality attainment. Resilience exists in the three types of systems: social systems, engineering systems and water environment systems. Resilience potential could be systematically described from the four dimensions of "scale, structure, pattern and network" based on AUTHES theory. Therefore, the four dimensions of "scale, structure, pattern and network" could be recognized as indicators to express the resilience usage status. The resilience potential could be exploited through scale adjustment, industrial upgrading, pattern match, and network optimization according to the real social-natural condition and current technology level. The resilience potential is exploited according to the real social-natural conditions and current technology level. A water quality standard is set as the threshold of WECC and the upper limit of resilience potential, thereby serving as the upper limit of the WECC scale.

2.5. WECC limits observation and exploration

To prove whether WECC limits exist or not and to further calculate the scale limit if it exists, three steps should be implemented. First, the current resilience usage status should be assessed. Second, the minimum resilience usage situation and realization approach should be clarified. Finally, the scale limits can be observed or calculated once the resilience potential has been exploited.

Table 1
The main modules and variables of HESP.

Submodules		Formula	Variables
Planting	Pollutant production	$\mathrm{SMC} = \frac{\sum_{i=1}^{n}(W_i \times EMC_i)}{\sum_{i=1}^{n} W_i}$	EMC (the event mean concentration) SMC (site mean concentration), Wi (the runoff volume in one-time rainfall)
	Pollutant discharge coefficient	$\mathrm{EC(kg/ha)} = 0.01 \times \mathrm{P} \times \alpha \times \mathrm{SMC}$	EC (pollutants-discharge coefficients), P (precipitation), α (runoff coefficient)
Domestic living	Pollutant production	$\mathrm{DP} = \varepsilon \times \mathrm{P}$	DP (pollutant production amount), P (population amount),ε (pollutant production coefficient)
	Pollutant discharge coefficient of rural population	$R_{rr} = \alpha(1-\gamma_1)\gamma_2 + \alpha(1-\gamma_1)\gamma_3(1-\gamma_4) + \beta(1-\gamma_5)$ $RP = R_{rr}P$	R_{rr} (pollutants-discharge coefficient) α (the ratio of water flushing toilet and dry toilet), γ_1 (the pollutant removal efficiency of a septic tank), γ_2 (the ratio of pollutant flow from septic tank to river directly), γ_3 (the ratio of pollutant flow into sewage plants), γ_4 (the pollutant removal efficiency of domestic sewage treatment facilities). γ_5 (the ratio of returning dry toilet manure as a fertilizer), *RP* (production discharge amount)
	Pollutant discharge coefficient of urban population	$\gamma_{ur} = (1-\vartheta)$	ϑ (pollutant treatment ratio from urban domestic living), γ_{ur} (pollutant discharge coefficient)
Industry	Pollutant production	According to local environmental statistical data	
	Pollutant discharge coefficient	$\gamma_{ir} = (1-\vartheta)$	ϑ (pollutant treatment ratio from industrial production), γ_{ur} (pollutant discharge coefficient)
Livestock and poultry breeding farms	Pollutant production	$\mathrm{YPF} = \mathrm{PDPF} \times \mathrm{D} \times \mathrm{P}$ $\mathrm{YPN} = \mathrm{PDPN} \times \mathrm{D} \times \mathrm{P}$ $\mathrm{YPP} = (\mathrm{YPF} + \mathrm{YPN}) \times \mathrm{R}$	YPF (manure quantity production per time), PDPF (manure quantity production per time per head), YPN (urine quantity production per time), PDPN (urine quantity production per time per head), D (feeding period), P (number of livestock and poultry), R (pollutant concentration), and YPP (pollutant production amount)
	Pollutant discharge	$R_{ar} = \beta\gamma_1\gamma_2(1-\gamma_3) + \beta(1-\gamma_1)(1-\gamma_3) + (1-\beta)\gamma_4$ $\mathrm{AP} = R_{ar}\mathrm{YPP}$	R_{ar} (pollutant discharge coefficient), AP (pollutant discharge amount), β (the ratio of large-scaled poultry and livestock breeding farms), γ_1 (the ratio of large-scaled poultry and livestock breeding farms that fecal and urine are treated with dry and wet separation), γ_2 (the ratio of pollutant in the fecal and urine of large-scaled poultry and livestock breeding farms which are treated with dry and wet separation), γ_3 (pollutant treatment ratio of large-scaled poultry and livestock breeding farms), γ_4 (the ratio of pollutant which is directly discharged in the scattered poultry and livestock breeding farms)
River	Pollutant degradation	$C_x = C_0\ exp(-K\frac{x}{u})$	C_0 (the background pollutant concentration in the river), Cx (the pollutant concentration through degradation) x (river length), K (pollutant degradation ratio), u (the average river velocity).

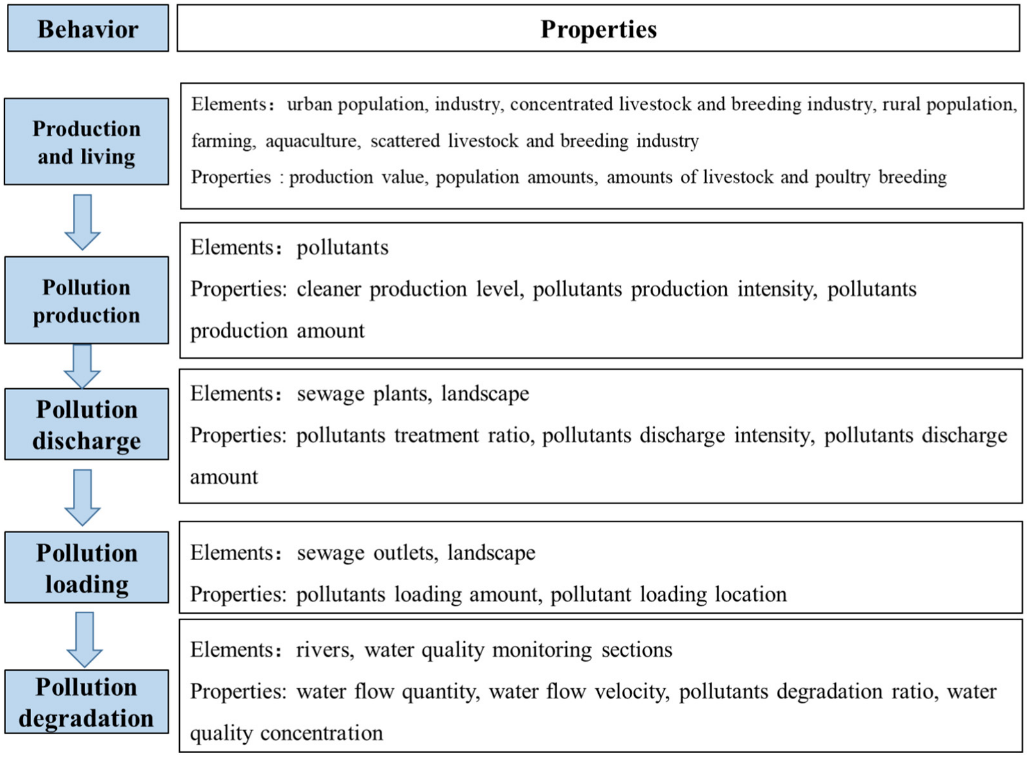

Fig. 4. The whole process of pollutants from production to monitoring.

2.6. Data sources and study area

Changzhou City, located on Taihu Lake in China, is a prefecture-level city in southern Jiangsu Province and is used as the study area. It is a typical city with pollution-induced water shortages and is proper for WECC limits research. The data sources and study area were shown in our previous paper (Zhou et al., 2017). An amount of data from various sources is collected to support the research, including social-economic and environmental statistical data, and the domestic and industrial pollution are obtained through local investigation. The non-point pollution status is calculated based on field experiments. The pollution degradation ratio data are also from data measured by the research group. Water quality and quantity data are obtained from the local hydrological and water quality monitoring stations (Table 2). The typical pollutant type, chemical oxygen demand (COD), is adopted to reveal the interaction between human-water environment systems.

3. Results and discussion

3.1. Minimum resilience usage status

The resilience potential among the social system, engineering system and water environment system is exploited from the four dimensions of "scale, structure, pattern and network". For social and engineering systems, the resilience potential could be exploited through human initiative activities, such as economy adjustment and infrastructure investment. For water environment systems, the resilience potential could be exploited through an active adaptation to natural characteristics and variation. The resilience potential could be exploited through initiative activities and active adaptation. Initiative activities means that we could reduce environmental impact through industrial structure upgrading, spatial pattern optimization, advance technology adoption and infrastructure investment. Active adaptation means that we should realize fully the usage of the water environment capacity to actively support economic development based on the spatial-temporal variation characteristics of natural environment systems. Thus, we could realize benefit maximization between economic development and environmental protection. The exact space-time resilience potential identification would provide a detailed route for WECC improvement. To calculate the maximum scale of the economy and population that the local water environment can support and to explore the detailed route to reach the sustainable goal, this study employed the four dimensions of scale, structure, pattern, network (including technology) to deconstruct and analyze WECC theory. To reveal the WECC limits, the resilience potentials of these four dimensions were determined under the condition of water quality attainment for the entire river basin. The resilience potential existed in every process of human activities-pollutant production-pollutant discharge-pollutant flow into the river. The resilience potential of each dimension is recognized according to the locally most advanced level of cleaner production and sewage treatment.

Table 2
Data and sources.

Data	Sources
Social-economical data	The statistical yearbook of study area and local survey
River pollution degradation index	Local measurement by the research group
Pollution sources and discharge data	Environmental statistical data, monitoring data, field experiments and local survey
Water environment data	Local water quality monitoring stations
Water resource data	Local hydrological monitoring stations
Drainage map	Local government planning

The minimum resilience usage situation with the most pollutant reduction was calculated based on the current development situation of the study region (Table 3).

3.1.1. Structure upgrading

Structure upgrading is an approach to reduce, as much as possible, the amount of pollutants discharged into the river. Structure upgrading consists of population structure upgrading, industry structure

Table 3
The status of four dimensions under different resilience usage status.

Dimensions			Current resilience usage status	Minimum resilience usage status	Resilience potential exploitation status
Resilience	Structure		The main emission source of agriculture is the livestock and poultry breeding industry, accounting for 73.72% of the total agriculture emissions. The local pillar industries, the chemical industry and textile industry contribute to 76.56% of the total secondary emissions.	Remove chemical industry and textile industry, scattered livestock and poultry breeding farms changed into large-scaled poultry and livestock breeding farms	Manufacturing industry
	Pattern		The COD emissions hot spots are population- and industry-intensive regions. Although agricultural COD emissions accounted for 40.44% of the total emissions, their emissions intensity is far less than domestic, secondary and service industry emissions. Domestic COD emissions make up 31.84% of the total emissions, secondary COD emissions accounted for 20% of the total emissions, followed by the tertiary industry, at 7.96%.	All the scattered livestock and poultry breeding farms changed into large-scaled poultry and livestock breeding farms and were moved to the suburban of the three subregions. All pollutants from rural living flow into sewage plants.	Seven manufacturing industrial park in the suburbs outside the ecological red line
	Network	Spatial morphology	Point: sewage plants, enterprises, sewage outlets Line: rivers Polygon: rural living, scattered livestock, fishery, farmland.	Non-point sources of scattered livestock and poultry breeding farms and rural living were changed into point sources through unified disposal.	Industrial park (Polygon) with independent sewage outlets (point)
		Spatial linkages	See Fig. 4	The pollutants from rural living flowed into sewage plants rather than flowing into river directly	Enterprises-sewage outlets-river
		Technology level	The pollutants-production intensity of industry: 0.00015–1614 kg/10 thou yuan The pollutants-treatment ratio of industry: 0–100% The pollutant-treatment ratio of comprehensive sewage plants: 74–95% The pollutant-treatment ratio of industrial sewage plants: ~99% The pollutant-treatment ratio of large scale: ~52–97%	All large-scaled poultry and livestock breeding farms and the sewage plants adopted the most advanced pollutant-treatment levels. All industry types adopted the most advanced technology of cleaner production and pollutant treatment.	COD-treatment ratio: 80%
Limits	Scale		Economy scale: 304489 M yuan	Economy scale: 273524 M yuan	Economy scale: 11511880 M yuan

upgrading and sewage plant structural upgrading, etc. In this study, due to the limitation of data, only the industry structure was analyzed. The chemical industry and textile industry with high-intensity pollutants were considered to be removed. It is the trend to reduce the industrial proportion of the chemical industry and textile industry in the study area now; however, it might not be removed completely in the actual situation. The main reason to propose the ideal structure upgrading measure of removing the chemical industry and textile industry is to realize better impact from structure upgrading on the characteristic of WECC limits. The scattered livestock and poultry breeding farms were integrated as large-scale poultry and livestock breeding farms. Nonpoint sources of scattered livestock and poultry breeding farms and rural living were changed into point sources through unified disposal. The measures could not influence the pollutant production amounts, but they could obviously influence the pollutant treatment ratio and the pollutant amounts loading into the river. Finally, they could enhance the economic scale that the local environment could support.

3.1.2. Pattern match

From the view of WECC, improvements were based on pattern dimension. The pattern match is an approach to active adaption of a natural system and full exploitation of the water environment endowment of river basins. To realize spatial layout optimization, all the concentrated livestock farms were moved from regions with an overloaded WECC status to other nearby regions with spare water environment capacity, such as to some high-intensity enterprises.

All the scattered livestock and poultry breeding farms changed into large-scale poultry and livestock breeding farms and were moved to suburban areas of the three subregions. The pollutants from rural living flowed into sewage plants rather than flowing directly into the river.

3.1.3. Network optimization

For WECC, the dimension of the network mainly indicates the pollutant flow of the HWES. Structure upgrading would influence the pollutant flow in social systems. A pattern match would influence the pollutant flow between the social system and natural system. Another key factor influencing the network dimension is the technological level, which included a cleaner production level and pollutant treatment ratio. The pollutant production and discharge intensity were mainly determined by a cleaner production level and pollutant treatment ratio. To identify the maximum resilience potential of the WECC, the lowest pollutant production and discharge intensity were used as a common level that certain spatial objects should reach. For the industrial system, the lowest pollutant production and discharge intensity of all the enterprises in a certain industry type was recognized as a common level that every enterprise under the same industry type should reach. During the process of pollutant discharge, the pollutant discharge intensity is mainly determined by pollutant treatment, especially the composting method for livestock manure. The best treatment ratio of sewage plants was also taken as the common level that every plant should reach. All pollutants from the rural population were considered to have been processed by the nearest treatment plant and were discharged uniformly.

3.1.4. Scale calculation

The data from the scenario of minimum resilience usage mentioned above would be served as the input to support HESP simulation (Table 3). In the HESP simulation, the impact of each measure, including structure upgrading, pattern match, and network optimization, and their comprehensive effect on water environment is simulated to determine the economy scale that the local water environment could support. Once the measures were implemented, the economy scale would decrease accordingly. The scale of the economy in the study region was 273,524 M yuan once the minimum resilience usage had been realized.

3.2. Resilience potential exploitation and limit exploration

The resilience potential was exploited to allow the existing limits to be observed and to attempt to calculate the limits of WECC. The maximum scale of the economy and population that the local water environment can support is calculated by adding industry according to the spatial linkages between each spatial object based on AUTHES and HESP (Fig. 5). The newly added types of economy and population were consistent with the previous types. A variety of economic choices to maximize the scale of the economy were based on WECC theory, according to the comprehensive consideration of regular economy development and demand: (1) The function of agriculture and tertiary industry is mainly for human living and entertainment, and to develop such industry blindly is inappropriate. Therefore, the feasible way is to develop a secondary industry, and inclusion of the manufacturing industry was adopted as the main industry type to expand the local economy scale through consideration of a local development plan and the current development status. The coefficients of pollutant production and pollutant treatment ratios were achieved according to the current relatively advanced level of cleaner production and pollutant treatment (Table 3).

To achieve the goal of maximum scale of economy and population, first, the pollutant discharge intensity per production value should be reduced, and second, as much as possible, the full use the water environment carrying capacity should be defined according to the precondition of water quality attainment. In particular, to ensure the sustainability of socioecological systems, the ecological red line is considered in this study, and only the water environment carrying capacity outside the red line is used; the layout of the industrial park should also be outside of the red line. Therefore, seven industrial manufacturing parks were built in the suburban area of the study region outside the ecological red line. The pollutant flow process is from the industrial parks' sewage plants to outlets to rivers. The COD-production coefficient and COD-treatment ratio is set according to the most advanced level of the manufacturing industry. The COD-treatment ratio is 80%. Through the simulation of WECC calculation module, the economy scale based on WECC theory has been reached, at 11,511,880 M yuan, nearly 37 times that of the current economy scale (Table 3). Although these results may never happen in the real world, the results provide a quite useful information, which suggest that the WECC could be nearly unlimited once the resilience has been identified and used fully and properly through the aspects of structure upgrading, pattern match, and network

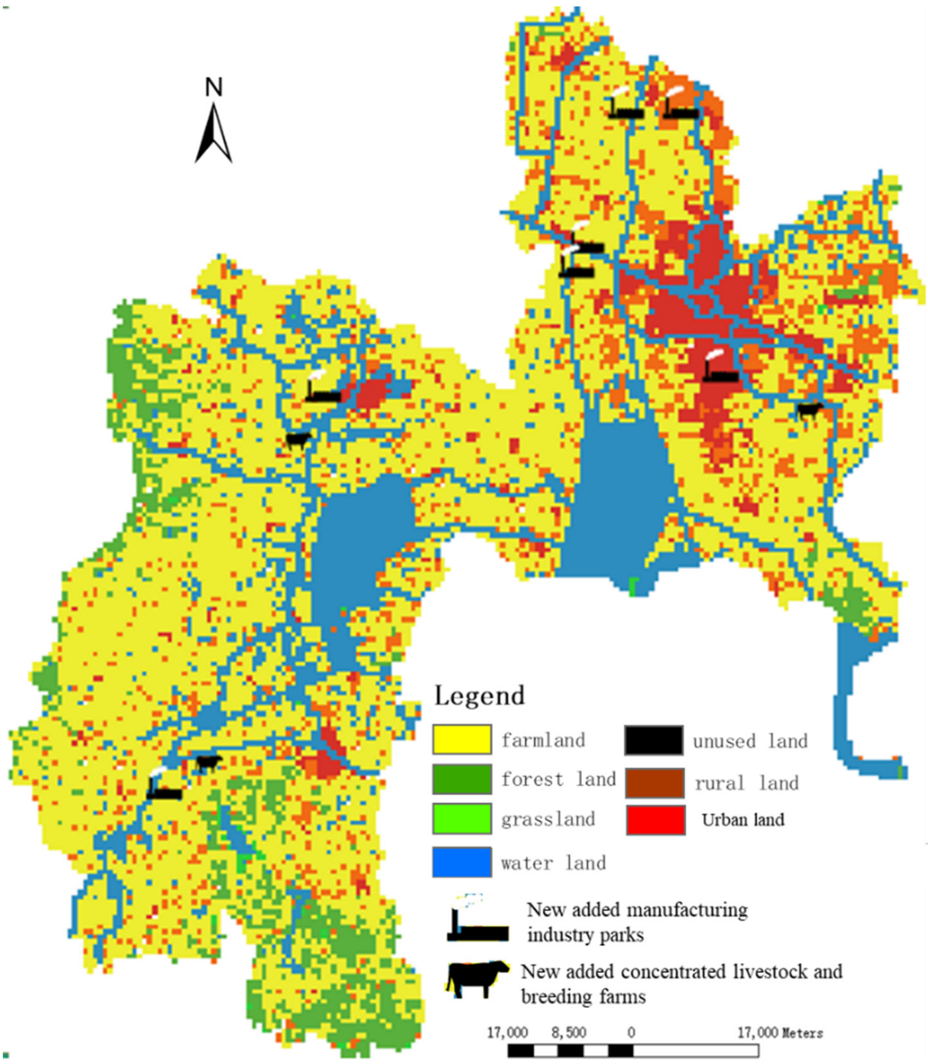

Fig. 5. The spatial pattern of newly added concentrated livestock and breeding farms and industrial manufacturing parks.

optimization (reasonable spatial linkages and advanced level of cleaner production and pollutant treatment). Technological development could be recognized as a key factor. In an extreme ideal situation, all pollutant sources realize the goal of zero emissions, and WECC could be thought to be unlimited regardless of the local water environment carrying capacity. However, in the current situation, due to the limitation of cost-benefits, the dimensions of structure and pattern would still be of key importance to local WECC improvement.

3.3. Water quality comparison under different resilience usage statuses

The water quality standard is set as the threshold and upper limit of WECC in this study. The population and economy scales are larger, and the water quality is worse. The water quality standard directly determines the resilience potential and the WECC limits. From the water quality statuses of the main river basins (Table 4), in the current status, four of the monitored areas exceed the water quality standard. Once all the feasible measures of minimum resilience usage are adopted, the water quality shows a significant decrease. The water quality of all the major monitored sections have reduced to less than 10 mg/L compared with the results of the current status. The water quality of monitored section 159 decreased obviously by 21.78 mg/L. A vast space occurred in the improvement for resilience for the WECC. Once all the resilience potential was exploited to keep the margin of safety, the maximum population scale and economy scale that the local environment expects to be supported is acquired. The water quality of all the monitored sections increases and does not excess the water quality standard.

Index assessment methods and System Dynamics methods are common choices in the existing WECC research (Wang and Xu, 2015; C. Wang et al., 2017). Always, only the scale dimension of the integrated study region as a homogeneous unit is concerned in the WECC assessment results of the traditional methods. The other three dimensions of structure, pattern and network, which play equal key functions in the WECC status, are unable to be revealed. In this research, through the adjustment and simulation from the four dimensions, the resilience potential and WECC status could be more specifically portrayed. Taking Changzhou City as an example, based on the traditional methods, the WECC could be identified as an overloaded status. However, it does not indicate the total study area is in the overloaded status. There is still some area in which the water quality is in good status, such as monitored sections 141 and 154. The main pollution sources are difficult to identify. In the HESP simulation, the WECC characteristic could be represented from the four dimensions. The spatial units that are in the overload WECC status, the main pollution sources and the function of artificial infrastructure for WECC could be revealed through HESP simulation.

Obviously, water quantity is the key factor to determine the threshold of WECC and the upper limit of resilience potential (Yang et al., 2019). The water environment status is the combined result of pollutant loadings and water quantity. Under the same pollutant loading, more water resources could always indicate the better water quality. Precipitation could also influence the amount of pollutant loading from non-point sources. Therefore, the spatial units with good water environment quality either have relative low pollutant loadings or vast amounts of water.

Table 4
Water quality comparison under different resilience usage status (COD: mg/L).

River basins	Monitored section	Current status	Minimum resilience usage	Resilience potential exploitation	Water quality standard
Jinghang	159	31.80	10.02	27.00	30
Danjin	108	26.29	8.14	27.00	30
Zhong	109	29.89	9.57	18.00	20
Desheng	141	14.60	2.08	18.00	20
Zaogang	154	15.80	7.73	27.00	30
Biandan	136	22.60	6.66	18.00	20
Wujingang	173	20.40	8.10	18.00	20

3.4. Enlightenment for carrying capacity research

In fact, the concept of "carrying capacity" is controversial in the various related disciplines. The key concern is whether the limits of carrying capacity even exist. Although many scholars, especially ecological scholars, speak of the limits of carrying capacity (Bartlett, 1996; Meadows et al., 2004), other scholars are suspicious of the concept of carrying capacity. Price (1999) doubts that the environment sets constant limits to growth, and reasons exist to prove that limits are constant. Arrow et al. (1995) denies the existence of particular critical limits of carrying capacity and thinks carrying capacity is a normative and variable concept. Carrying capacity can be recognized as having an overloaded status while ecosystems resilience is being lost (Perrings et al., 1994). Seidl and Tisdell (1999) consider that unequivocal indicators and a standard for transgressing carrying capacity are unclear. Abernethy (2001) believes that technological development will enable humans to overcome putative natural limits. In contrast, possibly, limits to carrying capacities may not exist.

Based on the results of this study, the limits of carrying capacity are dynamic, and these can be changed by differences in values of the four dimensions. It is a variable concept. The results of this study verify the view of Price and Arrow, who state that at the socioeconomic scale, the local water environment can be unlimited if the resilience potential is exploited (Arrow et al., 1995; Price, 1999). Technological development would finally overcome the limits of natural systems, which is consistent with the view of Abernethy (Abernethy, 2001). However, this is only an ideal circumstance. Due to the cost-benefit considerations, this model is unrealistic in the current world. The "zero-emission" accomplishment of technological application would directly destroy the normal economic development, although the water environment could be improved. Therefore, the discussion of WECC limits should be processed with consideration for both socioeconomic development and water environment development. It is inadequate to discuss limits of WECC from the dimension of technology. Cleaner production levels could only reduce pollutant production. The pollutant treatment ratio could only reduce the pollutant discharge. The implementation of cleaner technology may cost lots of money, although it could reduce the pressure on the water environment.

The concept of "carrying capacity" is proposed for support of human-environment sustainability. Carrying capacity research contains concepts, such as the ecological carrying capacity, resource carrying capacity and environmental carrying capacity. The results of the water environment carrying capacity in this study could provide some enlightenment for other types of carrying capacity. In our opinion, the absolute limit of WECC is not the central concern of the current research; instead, the most urgent and significant issue is to determine the WECC limit that the current human-environment condition could reach and provide detailed routes to realize the maximum social-economy scale that the local water environment could support. Therefore, exploitation of the resilience potential is a key process in the calculation of WECC limits.

The systematic understanding of WECC limits should be from the four dimensions of "scale, structure, pattern and network". The resilience potential also should be exploited. From the dimension of structure and pattern, the results of the water environment carrying capacity could also provide some enlightenment for other types of carrying capacity. Enhancing the carrying capacity can be achieved with structural upgrades, pattern match and network optimization between natural systems and socioeconomic systems. Structure upgrades are a way of reducing pollutant discharge. Pattern match is an approach of full usage of the local water environment endowment and the development of industry clusters. Severe imbalances exist between resource patterns and socioeconomic patterns. Taking China as an example, with the rapid economic growth and urban expansion, the large population and high industrial production have caused water scarcity in many parts of China; meanwhile, the regional imbalances in economic development and the uneven distribution of precipitation have accelerated the tendency of water supply-demand imbalances. Moreover, economic imbalances have restrained the extent of regional urbanization and the socioeconomic scale. The interregional difference of the economic scale and precipitation distribution have induced the contradiction of water supply and demand, whereas some regions have a water surplus, and other regions exhibit the opposite. Generally, the regions with low economic development levels have less pressure on water resources and environment. However, the regions with advanced economic development levels have larger pressure on water resources and environment, which are more vulnerable to water shortages and pollution (Li and Han, 2018). Thus, realizing the pattern match between a socioeconomic system and a water system is becoming an urgent demand for HWES sustainability through transfer of industry or water.

Network optimization is an integrated approach of sustainable development. According to the dimensions of the network, which is different from the resource carrying capacity, the environmental carrying capacity concerns the impact of production waste on the environment. The resource carrying capacity concerns the resource supply ability for socioeconomic development. The technological level plays a key role in the various types of carrying capacity. The increase in the resource usage ratio could enhance the resource carrying capacity, whereas the reduction of pollutant discharge intensity could enhance the environmental carrying capacity. Technological development is just one aspect of network optimization. Network optimization could be regarded as pollutant flow optimization, and pattern matching could indicate the optimization of pollutant flows in a natural system. A more important aspect is the realization of optimized pollutant flows in an economic system. The traditional understanding of pollutants may be advanced. The pollutants of one industry may become primary materials for another industry. Therefore, the previous concept of “pollutants” should be changed into the concept of “materials” if the proper process is implemented. The current ideal form is Circular Economy Parks, which is an attempt to implement “zero-usage”. This approach is an innovative way to improve the water environment carrying capacity and water resource carrying capacity. All the materials are fully used. No pollutants are discharged into rivers. The pressure from human activities on the water environment is eliminated. The “zero-emissions” approach could enhance the WECC into an unlimited scale. A “zero-usage” resource carrying capacity is also possible. The concept of ecological carrying capacity is a further revelation of carrying capacity from the view of ecosystems. Realization of a win-win situation of economic development and environmental protection is therefore relatively feasible.

3.5. Limitations and future research

There are some deficiencies that need to be improved in future research. Because the research object is a quite complex system, data with high spatiotemporal accuracy is required for better simulation performance. A more suitable algorithm should be introduced and developed in HESP, such as machine learning technology, to realize more precise WECC assessment and limitation calculation (Zhang et al., 2018). Research of WECC and human-environment sustainability requires the cooperation and contribution of interdisciplinary knowledge, including economics, the environment, hydrology, geography, computer science, etc. (Sakao and Brambila-Macias, 2018). The linkages between economic activities and domestic living and their combined effects on WECC limits could be researched further in the future.

4. Conclusions

In this study, similar concepts that are used to define the appropriate space and boundaries for human activities and environmental processes have been distinguished. The resilience potential is exploited, and the limits of WECC are discussed for the study area. The resilience concept was first introduced to provide a detailed route for WECC improvement. The four dimensions, including scale, structure, pattern and network, are used to deconstruct the resilience potential and WECC theory creatively. The space-time resilience potential of the HWES systems was also identified clearly. Resilience potential identification provided a feasible and controllable route of WECC improvement for human-water sustainability. This study confirms that the limit of the carrying capacity is a dynamic value, which could be changed by differences in the values of the four dimensions of “scale, structure, pattern and network”. The socioeconomic scale that the local water environment can support would be nearly unlimited once the resilience potential was identified and used fully through the aspects of structure upgrading, pattern match and network optimization (including an advanced level of cleaner production and pollutant treatment).

The research results reveal the characteristic of carrying capacity limitation for the four dimensions of scale, structure, pattern and network. This research also provides support for related research, such as planetary boundaries, tipping points, and resilience. Through the exploitation of resilience potential from the four basic dimensions, humans could realize maximum socioeconomic development, while the requirements of environmental sustainability are satisfied.

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