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Resilience-Based Sustainability Indicators for Freshwater Lakes with Application for Dongting Lake, China

Li Xu[1], Dora Marinova[1], Pei Xin[2] & Xiumei Guo[1]

[1] Curtin University, Australia

[2] Hohai University, China

Correspondence: Dora Marinova, Curtin University, Australia. E-mail: D.Marinova@curtin.edu.au

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Abstract

This paper develops a framework for incorporating resilience into sustainability indicators for freshwater lakes. The sustainability of freshwater lakes is important from both, an ecological point of view and within a socio-economic context, as these systems are sensitive to external disturbances and susceptible to changes in land coverage, vegetation distribution, hydrological conditions and perturbations from human activities. Existing sustainability indicators do not incorporate resilience and consequently do not reflect the ability of the lake to withstand the impacts of shocks and improve its current state for achieving sustainable over time. The developed resilience framework is applied for the case of China's Dongting Lake, which is exposed to the impacts of the Three-Gorges Dam in addition to experiencing ecological and socio-economic changes. The resilience perspective allows 37 indicators to be developed to describe and monitor the Lake's sustainability based on considering known, possible and unknown future changes. They can inform any future resilience management of its complex ecological system.

Keywords: Dongting Lake, environmental change, resilience, social-ecological systems, sustainability, Three-Gorges Dam,

1. Introduction

Increasing scarcity and deteriorating environmental conditions of freshwater resources due to human activities have become the plight of many regions across the world (Gleick, 2003; Vörösmarty et al., 2010). This is the case also in China. Representing 21% of the world's population, the country possesses only 6% of the global freshwater resources (Liu et al., 2013). Two-thirds of China's cities experience water shortage and 80% of its lakes suffer from eutrophication (Chinese Academy Sciences, 2007; Liu & Yang, 2012). If the deterioration of freshwater resources continues, it would affect human health, socio-economic development and may even cause ecosystems to collapse (Cairns, 1997; Xu, 2005).

China has built 87 873 dams and reservoirs with a capacity of 716 billion m^3 representing about 10% of the world's total freshwater storage (China Water Statistical Yearbook, 2011). This has generated remarkable economic and social benefits through flood control, water scarcity prevention, irrigation increase and clean energy generation (Liu et al., 2013). In recent years, however, the engineered disturbance to social-ecological systems (SESs) in the downstream areas started to generate hot debates. The world's largest Three-Gorges Dam (TGD), built on the upstream of the Yangtze River (YR), is such an example and may be one of the most controversial water projects in the world (Zhang et al., 2012). Concerns are raised about the impacts of TGD on the lakes in the middle and downstream of the river, including Dongting and Poyang. The recent decline in water level is likely to indicate a regime shift for the lakes after the operation of the dam (Liu et al., 2013) challenging the sustainability of the joint freshwater system.

Having appropriate sustainability indicators helps describe and understand the current condition of the surrounding SESs, trends in critical ecosystem services, and whether management practices are effective (Carpenter et al., 2012). They generate insights for scientists, politicians, decision-makers and the broader community about how human and environmental systems operate, what the linkages between the different components are and what effects human actions have (Rametsteiner et al., 2011).

Although examples of sustainability indicators for freshwater abound (Sullivan & Meigh, 2003, Chaves et al., 2007, De Carvalho et al., 2009, Pandey et al., 2011), they do not cover the systems' ability to improve their states to become sustainable in the long run. Sustainability is not a stable state of a system but evolves through reacting with external and internal factors. It implies an enhanced capacity not only to adapt to changes but also to cope with undesirable shocks (Milestad & Darnhofer, 2003). Any meaningful measure of sustainability thus should be able to reflect the current conditions as well as ability to absorb stress and cope with changes over the long run (Carpenter et al., 2001; Milman & Short, 2008). This is a big challenge for sustainability management as the environmental, economic and social issues we are currently confronting "display attributes of high uncertainty, urgency, complexity, and connectivity" (Shields et al., 2002, p.150).

Resilience, as a renewed systemic perspective for coping with external perturbations and uncertainties, is an important option for decision-makers in their response to the changing globe and growing human-induced challenges (Xu et al., 2015). It stands for the ability of the system to absorb or tolerate disturbance and maintain its current condition over time without collapsing into a qualitatively different state controlled by another set of processes (Walker et al., 2006; Milman & Short, 2008). Resilience thinking is becoming an increasingly popular topic in ecological, economic and social analysis in relation to disturbances from climate change and natural disasters. Nonetheless, resilience analysis is still in its exploring stage with further research required (Xu & Marinova, 2013). Furthermore, environmental shocks and natural disasters attract more attention than slower environmental changes. Slow disturbances however need to be addressed as the longer the system stays in an affected state the more difficult its recovery becomes, if at all (Carpenter et al., 2012). This is often the case with freshwater resources.

This study aims to incorporate resilience thinking into sustainability indicators for freshwater lakes exposed to increasing perturbations from human-induced slow variables. The following section explains the method of identifying the core subsystems and perturbations affecting freshwater lakes together with techniques used to identify sustainability indicators. This is then followed by the case study of Dongting Lake during which 37 indicators were identified based on considering known, possible and unknown future changes.

2. Method

To better understand sustainability when considering perturbations, research must firstly dissect the complexity of SESs (Ostrom, 2009). Studies have previously shown the dynamics and intricacy of interactions between people and lakes (e.g. Carpenter & Cottingham, 1997, Xu et al., 2013), making the exploration of these relationships (see Figure 1) challenging.

The framework provided by Ostrom (2009) offers an insightful way to analyze SESs by categorizing them into subsystems, including the four core subsystems: resource systems (*RS*) such as forests, water and wildlife; resource units (*RU*) such as trees, wildlife, amount and flow of water; governance systems (*GS*) such as government and organizations managing and establishing rules for those resources; and resources users (*U*), namely people who use the resources for living, recreation or commercial purposes. Each system comprises multiple second- and third-level variables which need to be specified according to studied questions and the type of SES as well as its spatial and temporal scale. In a SES, interactions (*I*) occur among these subsystems and give rise to outcomes (*O*), which can be influenced by external drivers, including climate, markets, catastrophes, social, economic and political settings (*S*).

2.1 SESs of Freshwater Lakes

For lakes (see Figure 1 and 2), *RS* can be defined as those systems that provide services for individuals, communities and endemic species (fish, birds and vegetation) and are involved in natural processes such as nutrient assimilation and other ecosystem services (Jansson et al., 1999). Riparian vegetation, forests, fish, wetlands, macrophytes and water bodies (both lakes and its joint rivers) are considered as key variables for RS participating in the natural process of inland lakes providing ecosystem services (Carpenter & Cottingham, 1997; Jansson et al., 1999; Ostrom, 2009). The *RU* are components of these core RS; their further variables include economic value and mobility of resources, number of units, spatial and temporal distribution, nutrient turnover rate (partuicularly Nitrogen and Phosphorus) and growth or replacement rate (DeAngelis, 1992, Carpenter & Cottingham, 1997, Ostrom, 2009, Ernst et al., 2013). Any lake's *GS* can be divided into formal and informal (similar to Ernst et al., 2013). The formal patterns comprise government authorities, monitoring institutions, regional acts and regulations for the use and protection of the lake (e.g. property rights or maximum annual amount of fishing allowed) and collective-choice rules, namely community established preferences, ways and regimes (Sen, 1970). Informal patterns usually represent nongovernment organizations and social network structures such as social connection, collaboration, knowledge and learning. Variables of *U* for lake regions include number of users, local leadership, location, social norms, technology used and resource importance.

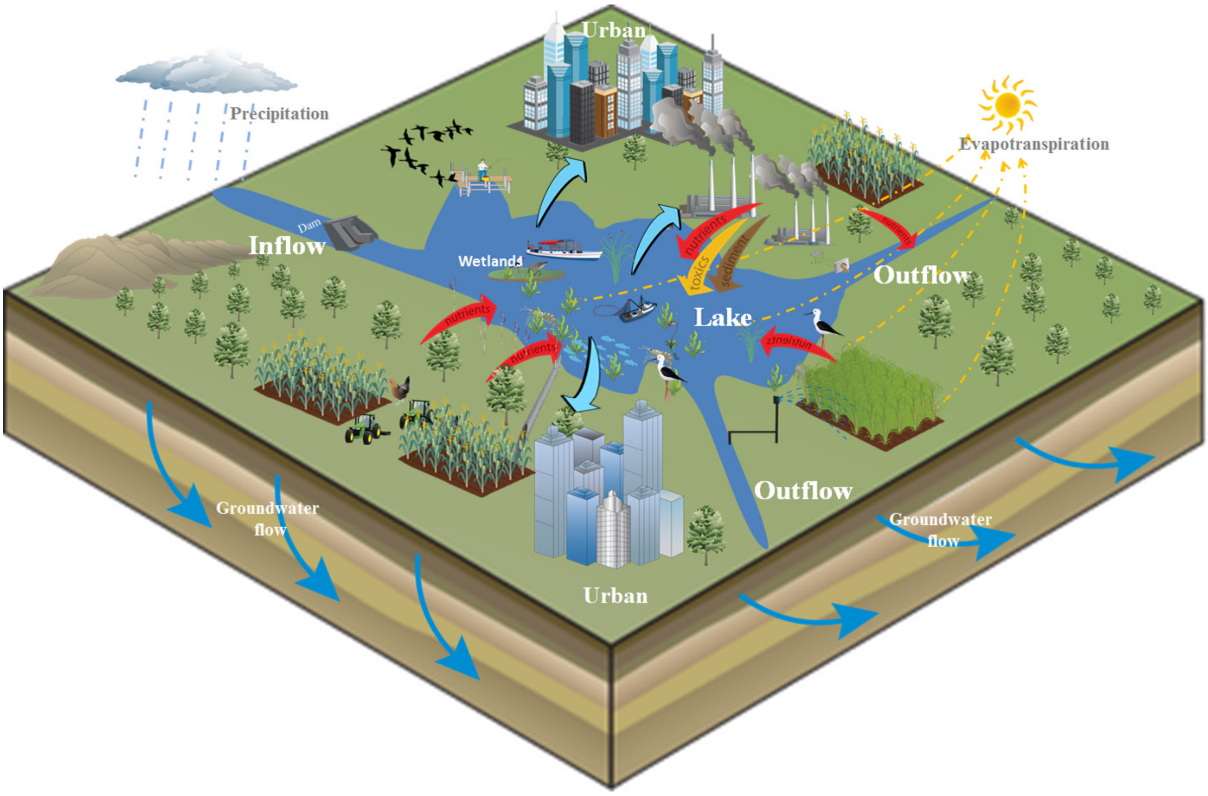

Figure 1. Dynamics of SESs of Freshwater Lakes

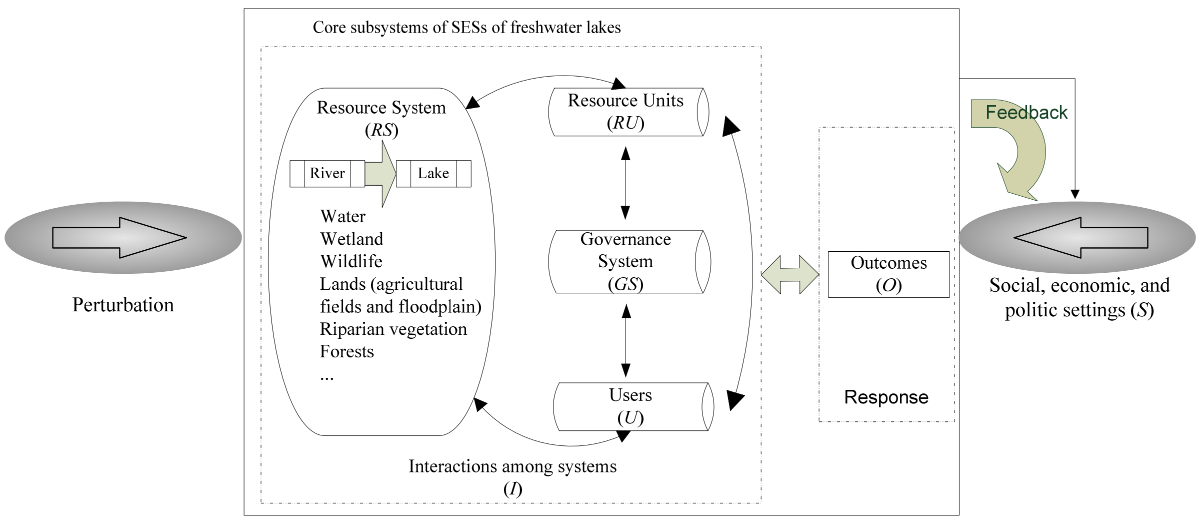

Figure 2. Core Subsystems of SESs of Freshwater Lakes

The interactions among the different systems and variables give rise to outcomes – different performances and complexity of SESs. Lakes provide water to humans for drinking, household use, irrigation, industry, transportation, recreation, fishing and aesthetic landscape (Postel & Carpenter, 1997). Their conditions are affected not only by pollutants from human activities but also indirectly by changes in the landscape, atmosphere and alteration in the water's natural flow (National Research Council, 1996). Human activities, for example hydropower stations, dams, agriculture, land use and urban development, lead to lake degradation through waste discharge and changes in the hydrological cycle (National Research Council, 1996). The degradation of inland lakes is commonly caused by pollutants from sources related to these large-scale human systems, including domestic sewage sludge, sewage treatment plants, food processing, household waste, land use, agriculture, constructions and operations of dams in the upstream (National Research Council, 1992 & 1996; Carpenter & Cottingham, 1997; Jansson et al., 1999).

Through the hydraulic exchange, conjunct rivers have significant impacts on the water level and volume of the lakes, their multiple functions and state. Changes can be triggered by human disturbances or climate change. Global warming is increasing evapotranspiration, which may cause lower soil moisture, ground water and stream flows thereby affecting the water cycle of the region. Wetlands and riparian vegetation similarly play an important role for inland water systems not only in providing habitat for species but also as nutrient sinks in assimilating nitrogen (Jansson et al., 1994 & 1999). Climatic warming may lead to a decline of the wetlands' water table which may cause increase in greenhouse gas emissions (National Research Council, 1996).

2.2 Framework for resilience-based sustainability indicators

The sequence of steps to develop resilience-based sustainability indicators based on Ostrom's (2009) framework is presented on Figure 3. It includes the following four steps.

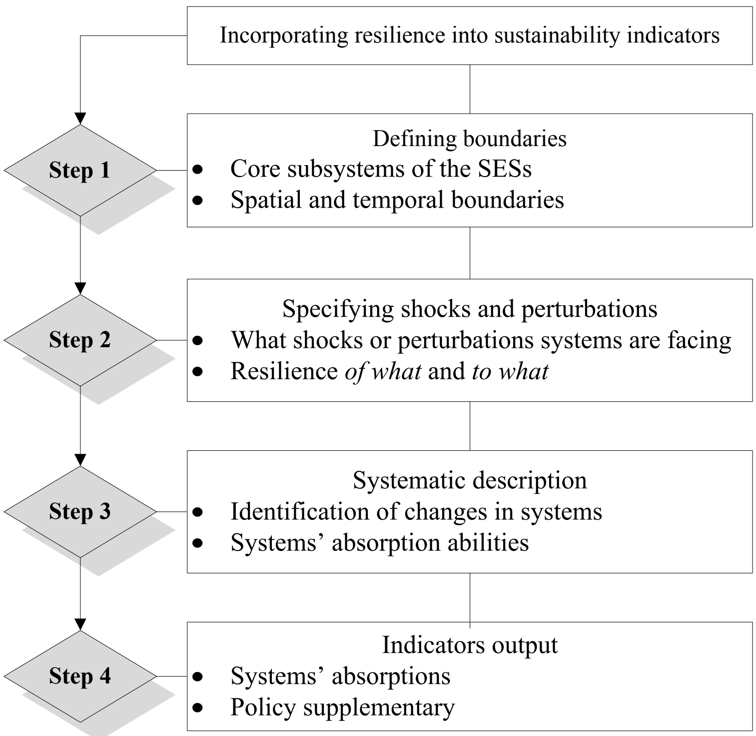

Figure 3. Flowchart for Developing the Indicators Set

• Step 1: Defining boundaries – boundaries and scale of coverage is the first step in defining the system and its subsystems. The next question relates to the space and time over which sustainability is to be achieved (Bell & Morse, 2008). Not including spatial and temporal boundaries is the main criticism for existing sustainability indicators (Briassoulis, 2001; Milman & Short, 2008). Core subsystems and their boundaries are essential for understanding the sustainability of a lake in response to disturbances.

• Step 2: Specifying shocks and perturbations – resilience can be specific (in relation to certain shocks and perturbations) and general (in relation to all kinds of shocks and perturbations) (Walker et al., 2009). It needs to be defined in terms "*of* what *to* what" – what system state is being considered and what perturbations are of interest (Carpenter et al., 2001). Shocks and perturbations need to be classified as known and unknown (Walker et al., 2009; Carpenter et al., 2012). Questions to be addressed include (Grigg & Walker, 2012): the resilience of which attributes is of most concern, to what kind of shocks the systems need to be resilient, what is the greatest threat from the shocks, what knowledge do we have about what shocks?

• Step 3: Systematic description – it is conducted in two parts: first, changes are categorized according to their possibility of occurrence; and second, the systems' responses are analyzed in terms of self-organizing abilities and policies. Some changes may be clear while others may be hard to identify. The description should show what abilities the systems have to absorb changes and what policies or strategies are needed to ensure the systems withstand such changes in the long run.

• Step 4: Indicators output – this is the process of selecting suitable indicators. They should be measurable (to describe the status and trends of the systems in the face of perturbations) and guide decision-making (what needs to be done to approach the systems' desirable states). Hence some indicators reflect the systems' abilities to absorb changes and others are related to policies supporting this. Often suitable indicators are hard to find, difficult to be measured or even observed. A possible approach is to employ surrogate indicators which are similar or inversely related to the system's resilience and are easier to measure (Carpenter et al., 2001, 2005; Walker & Salt, 2006; Darnhofer et al., 2010; Xu et al., 2015). For example, the desirable social-ecological resilience of lake systems can be measured by indicators, such as: the ability of farmers to reduce nonpoint pollution from their lands, public support for pollution control, externalities captured by market means such as phosphorus quotas, phosphorus pollution costs, and social networks or groups facilitating collaborative actions.

2.3 Techniques for Indicator Development

In the case of high uncertainty, participatory approach (local stakeholder engagement) is suggested as an efficient way to develop a suite of indicators and has been widely used (Reed & Dougill, 2002; Pokorny et al., 2004; Santana-Medina et al., 2013). It is also an effective way to build up social-ecological resilience and overcome challenges triggered by external shocks (Walker & Salt, 2012) with local people obtaining ecological knowledge about changes in the surrounding environment through learning-by-doing experience (Olsson & Folke, 2001). However, participatory methods are usually time and resource consuming and stakeholder engagement can generate a large number of potential indicators (Reed et al., 2006). In this study we use a combined top-down (expert-led) and bottom-up (local stakeholder engagement) approach (Turcu, 2013) based on Ostrom's (2009) SESs framework as the main lead for participants using techniques such as participatory meetings, surveys, key informant interviews, workshops and focus groups (Reed et al., 2006, Santana-Medina et al., 2013). This integrated approach is recommended for sustainability management (Reed et al., 2006, Ingram 2008; Santana-Medina et al., 2013), and has been proved effective for developing sustainability indicators (Adrianto et al., 2005; Turcu, 2013). We specifically search for sustainability indicators that reflect the social-ecological resilience of SESs in response to the defined perturbation.

• Expert participation – it includes an online survey followed by semi-structured interviews. As the experts are based in different cities, the online survey through prompting emails is an effective way to obtain their opinions (Zakaria et al., 2013). Their task at this stage is to identify the core subsystems and the corresponding main multiple variables based on their knowledge of the studied area and the provided previous research by Ostrom (2009), Basurto et al. (2013) and Ernst et al. (2013). During the semi-structured face-to-face interviews, feedback from the online survey is provided to each expert individually with a request for comments on differences, confirmation or validation of answers. The aim is to obtain an agreement about the core subsystems and main variables.

• Local stakeholders – they represent the communities who rely on the ecological health and services of the lakes. Together with experts they are engaged through individual interviews to gather their opinion and knowledge of local environmental changes, what they have witnessed, current abilities to adapt and what the governments should do.

3. Results for Dongting Lake, China

This section presents the case study, summarizes the collected data and the analysis performed to identify the resilience-based sustainability indicators for Dongtong Lake.

Located in the northern part of Hunan Province, Dongting Lake (see Figure 4) is one of the two (the other being Poyang Lake) freshwater lakes connected with the YR in its middle stream and is the second largest freshwater lake in China. It plays a pivotal role in water storage and provides habitat for numerous species. Global warming and the TGD have serious cross-effects on Dongting Lake. Specifically, climate change has generated negative impacts on the wetland ecosystems of the basin and changed the evapotranspiration of the lake, which exacerbated the desertification of land, distribution of vegetation and changed the migratory routes as well as breeding time of water birds, reducing biodiversity and increasing the frequency in extreme weather events in the lake's region (Li et al., 2013, Deng et al., 2014).

Recent studies identified significant impacts of the TGD on the lakes in downstream YR, including on Dongting Lake's flow regime (hydrological and hydraulic conditions), wetland patterns, sediment loading and altered interactions between the Lake and YR (Yuan et al., 2012; Sun et al., 2012; Gao et al., 2013; Lai et al., 2013; Feng et al., 2013). The Lake has been drying up since the TGD's impoundment (Feng et al., 2013). In particular, the extremes of wet and dry conditions intensified by the TGD are making the Lake drier and causing changes in its water flow regulation. The hydraulic dynamics between Dongting and Poyang Lakes and the YR are being impacted, including the volume of water exchange during the different seasons (Zhang et al., 2012). In October when the dam starts to store water, the flow of the YR is reduced causing influx from the lakes into the river. It is also reported (Chinanet, 2011) that the TGD causes the lakes' dry season to arrive earlier and span longer compared to the years prior to the operation of the dam.

3.1 Experts and Stakeholders Identification

• Expert panel – considering the focal impacts of the TGD on Dongting Lake, hydrologists, environmental engineers, limnologists, ecologists, economists, sociologists and governmental officers (planners) familiar with relevant issues participated as experts in the study. The snowball-sampling technique (Goodman, 1961) was used to identify the right experts. We started with the leading researcher of Group 5 of the National Basic Research Program of China (covering 973 projects related to the YR and joint lakes) who had being researching the health of the Dongting Lake's wetland for more than 10 years. During the interview, he introduced his colleagues and other researchers from his networks. In total, 18 experts were interviewed – from hydrology (3), environmental engineering (2), limnology (2), ecology (3), economics (2), sociology (2) and local governance (4).

• Stakeholder participation – people whose livelihood or well-being depends on Dongting Lake are identified as the local stakeholders because of their dependence on the freshwater lake's resources and the close relevance of their knowledge and aspirations for the management of these resources (Santana-Medina et al., 2013). Twenty stakeholders were interviewed from critical areas, namely fishers (5), farmers (5), indigenous people (5), members of local non-government organizations (2) and economic developers (3).

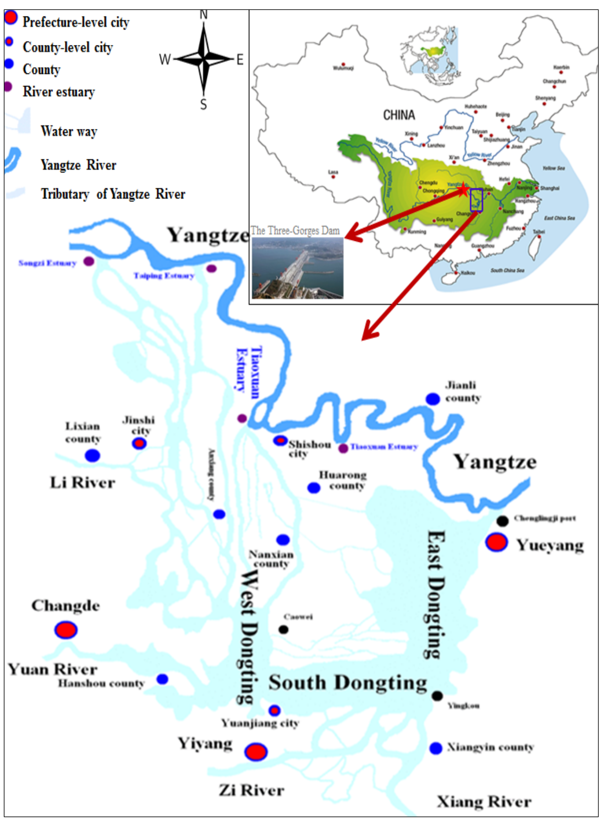

Figure 4. Location of Dongting Lake

3.2 Defining Boundaries

• Core subsystems – the core RS of freshwater lakes include wetlands, water, wildlife, land (including agricultural fields), riparian vegetation (plants and surrounding grass for people's recreation) and forests which provide services not only to the ecosystems of the lake but also to the local socio-economic systems (see Figures 1 & 2). These systems were also identified with a high level of agreement (83%, i.e. 15 out of 18) by the participating experts. When the focus was put specifically on Dongting Lake, the core RS were identified and ranked according to relative importance as: water, wetland, water birds and fish. With reference to the three previous studies on SESs (Ostrom, 2009; Ernst et al., 2013; Basurto et al., 2013), the experts also identified the core subsystems and corresponding variables most important for the sustainability of Dongting Lake in response to the perturbations of the TGD (see Table 1).

• Spatial and temporal boundaries – taking into considerations data availability, economic development, sensitivity to the TGD and relative importance of the location, the spatial boundary of the system was identified as three geographically divided areas, i.e. East, South, West Dongting Lake (ED, SD and WD) with the surrounding cities *Yueyang City* (ED), *Yiyang City* (SD), and *Changde city* (WD). The experts, especially the hydrologists and ecologists, advised that the focus of the study should be East Dongting Lake (ED) – the eastern section of the lake, because of the following reasons. First, data are available for ED as most existing studies and observations about Dongting Lake were conducted in this area. Second, the water level and wetlands coverage in ED dramatically change due to the fluctuating water exchange between the Lake and YR. Hence, ED with its surrounding city Yueyang City was the identified critical area.

Table 1. Core Subsystems and Multiple Variables of SESs of the Dongting Lake Region[1]

Core subsystems and second-level variables	Critical variables/ third-level variables	Explanations	Regional descriptions
Resource Systems (RS)			
RS1 Sectors	*RS1.1* Water; *RS1.2* Wetlands; *RS1.3* Fish; *RS1.4* Water birds	Critical sectors of the region identified by experts	Water, wetlands, fish, and water birds are the main resources of Dongting Lake for its biodiversity and ecological health
RS2 Size of resource system	*RS2.1* Moderately sized geographical zones for purposes of monitoring, management, and accessibility	The moderately sized zones are more likely to organise	Dongting Lake is geographically divided into three parts: East, South, and West Dongting Lake
RS3 Location and clarity of system boundaries	*RS3.1* Temporal and spatial distribution of resource systems	To let users know where resource systems start and end	According to the seasonally different water level of the lake, the distribution of resources is different
RS4 Productivity of system	*RS4.1* Stock status *RS4.2* Biophysical factors	Rate of generation units of biomass as determined by production by a given year Biophysical factors affecting the generation of units of biomass	Resources are affluent but the stock status is changing because of the growing external disturbances
RS5 Predictability of system dynamics		Degree to which users can estimate or identify patterns in environmentally driven variability on recruitment	Moderately predictable because of the more uncertainties from the cross-effects of climate and human activities
RS6 Storage characteristics	*RS6.1* Storage in natural patterns *RS6.2* Storage in a human-designed manner	Degree to which users can leave resource units in their natural habitat and man-made places until harvest	Normally resources (mainly for fishery) are input into the markets directly
Resource Unit (RU)			
RU1 Resource unit mobility		Slow mobility happens to one resource of the system can cause the moving of other resources when external disturbances take	Slow and seasonal mobility of resources exist in the system caused by water level changes

		place	
RU2 Growth and replacement rate		Descriptions of changes in quantities of resource units over time	Slow
RU3 Economic value		Value of resource units available to users including explicit and implicit values	The economic value of Dongting Lake is high, especially wetlands
RU4 Number of units		Number of resource units that can be extracted by users	Moderate, the resources are decreasing in recent years
RU5 Spatial and temporal distribution	*RU5.1* Non-homogeneous distribution of units *RU5.2* Homogeneous distribution of units	Allocation patterns of resource units across geographic area seasonally	On-shore and off-shore seasonal movement relating to the water level
Government Systems (GS)			
GS1 Policy area	*GS1.1* Ecology	Rules tailored to managing ecological health of the lake	Floodgates proposal, "4350" program, periodical restriction to fishing, pollution control
	GS1.2 Economic-ecology	Rules tailored to governing economic development and ecology relations	Adjustment of the economic structure, establishment of Clean Development Mechanism, eco-agriculture development, technological innovation
	GS1.3 Socio-ecology	Rules tailored to governing relations of human and ecological protection	Incentive instruments for facilitating public to participate in restoration of the ecosystem of the lake, education, extended observation of mass media and public
GS2 Organisations	*GS2.1* Government organizations	Institutions with authority mandated to protect resources and public trust	State authority of protected areas, local fisheries, governmental research institutions, funding support
	GS2.2 NGOs	Institutions without authority mandated to protect resources and public trust	Strong presence and support in the area including WWF and local universities' communities
GS3 Rules in use	*GS3.1*Property rights	Specific rules (formal and informal) determining which users have the right to use resources and which actions are allowed	Reasonable formal (licensed) rules are using for the right of using resources of the lake (almost 60% fishers have licensed)
	*GS3.2*Collective-choice rules	Rules that were constructed to control the use of resources so as to protect their health	Incentive policies exist to control fishing so as to protect the fish resources such as job transformation training programs
GS4 Norms and strategies		Human behaviours shaped by personal belief and environmental situations	Strong belief and dependence exist in older generations of fishers and illegal fishing behaviours still exist
GS5 Network structure	*GS5.1* Horizontal	Connections among users, scientists, and leaders to act collectively	Moderate well connections among users, scientists, and leaders
	GS5.2 Vertical	Connections with other organizations or state across levels	Connection has been established between states
GS6 Monitoring and sanctions	*GS6.1* Local observation	Local users or outsiders legitimized by them observe other users' behaviours in the use of	As GS1.3

	GS6.2 Enforcement of rules	resources and units, and report changes in the SES Users who break operational rules are given a sanction with its serious and the time they offended	Fisheries and authority have been presented in protected areas of the lake and the whole lake
Users (U)			
U1 Number of users		Number of users affecting decision-making process of managing resources	Large
U2 Socioeconomic attributes	*U2.1* Education attainment *U2.2* Level of poverty	Education attainment and the income level of users affect their behaviours of using resources and the system dynamics	Low level in average
U3 History		The duration of using resources	Long time period
U4 Location		The distance and physical place where users are in relation to resources and the market	Most of users are local, very small part of users are from outside for example fisherman from catchments
*U5*Leadership		Users who have skills to lead or organise actions and are followed by their group members	Not well-educated leaders
U6 Social capital	*U6.1* Independence *U6.2* Common interest/shared norms	Strongly intertwined by kinship relations and more shared norms or interests make stronger trust and substantial social capital	Tight community and strong dependence among users in the same group as most of users are native and have long time intertwined relationships between each other
U7 Knowledge of SES		Degree to which stakeholders understand of the characteristics of the dynamics of the SES	High level of knowledge for local users from their experience
U8 Importance of resource	*U8.1* Economic dependence *U8.2* Cultural dependence	Degree to which users rely on the resources economically and degree to which resources constitutes the source of local cultural values, practices, and services. These attributes affect to what extent users are willing to sustain their livelihoods	Strongly dependent on the resources both economically and culturally
U9 Technologies available	*U9.1* Ownership of technologies	Accessibility of users to technologies for their production	Moderate level

Note: [1] The identifications of systems' components in Table 1 are consulted with experts and modified from Ostrom (2009, p. 421), Basurto et al. (2013, p. 1375-1378), and Ernst et al. (2013, p. 1388).

A long-term view is important as a temporal dimension to reflect the external perturbation to the Lake's SESs and its ability of absorption. However, such data are hardly available in the region. Instead, a 30-year period was defined as the temporal boundary for this study because nowadays this seems to be one generation (or the average age at which humans produce offspring) in the industrialized world (Gregory, 2012). Such temporal scale is also the time-series baseline used by many international organizations such as the World Meteorological Organization (WMO), US National Oceanographic and Atmospheric Administration (NOAA), and US National Weather Service (NWS) (see Alessa et al., 2008). The temporal boundary of this study is set as the next 30 years in order to estimate whether the Lake's SESs would be able to absorb the identified changes having in mind its current capabilities and what policies are needed to improve its abilities to absorb perturbations.

3.3 Specifying Perturbation

From a specific resilience perspective (or "of what to what" according to Carpenter et al., 2001), we define as sustainable the state of the SESs of Dongting Lake at which its ecosystems are healthy for all livings species and its water is accessible for human use as well as for the economic development in the region ("of what"). In order to assess the responses of the Lake's SESs, the main external perturbation specified for this study is the TGD; that is, the resilience of SESs of the Dongting Lake region to the TGD ("to what"). Other perturbations, especially climate change, also play important roles in the dynamics of SESs. However, although we generally understand the nature of the climate change perturbations, it is difficult to separate them from the impact of the TGD because there are high uncertainties, insufficient data and evidence to distinguish between them.

3.4 Systematic Description

The complex dynamics of the SESs lead to similarly complex interactions between their subsystems. Changes happening in either the ecological or social system can lead to regime shifts in the other. Also, SESs can have reciprocal influences with a shift happening in only one or both systems (Walker & Meyers, 2004). For example, changes in the Lake's water quality and level can cause substantial economic losses –reduced fish quantities decrease fishing revenue, degraded water quality increases treatment costs for drinking water and loss of riparian vegetation decreases recreational opportunities for local people (National Research Council, 1996). The change in the Lake's water level may further alter the spatial and temporal distribution of wetlands and vegetation, drive the government to change current regulations and affect the harvest of fishers, thus affect the social, economic and environmental performance of the region and its sustainability.

Resilience thinking accepts changes and finds ways to cope with them rather than to attempt to control them (Ahern, 2011). When the performance of the Lake's SESs influenced by the dam are monitored or measured, information feedbacks and corresponding social, economic and political settings could be created to help the systems absorb and withstand such perturbations preventing them from undesirable regime shifts. Putting resilience into practice thus requires identifying the changes in the system and their impacts.

Some changes are already known, some may happen in the foreseeable future and others may be unknown. Using the experts' judgment and local stakeholders' experience, the changes were classified in five groups (see Table 2 and Figure 5) according to their likelihood of occurrence – certain, somewhat possible, unlikely (or not really), unknown and certainly not. The variables identified in the "certainly not" category are not considered for indicator development. "Certain" refers to known changes. The categories "somewhat possible" and "not really" were combined as possible changes. “Unknown” is also a separate category of changes (some participants grouped it together with "not really"). These change categories are discussed in relation to resource systems, resource units, governance systems and users.

3.4.1 Known Changes

For *RS*, the known changes recognized by both experts and local stakeholders are the water situation (hydrological conditions), wetlands, productivities and storage in natural patterns (refer to Figure 5a, Table 1 & 2). Many – 32 out of 38 participants (84%) recognized that the water system of Dongting Lake has been certainly affected by the operation of the TGD including seasonal water level alteration, runoff and sediment loads (Yuan et al., 2012; Gao et al., 2013). It has also been observed that the main mouths (connected to the YR) of Dongting Lake (Songzi, Hudu and Ouchi) are facing the increasingly severe problem of discontinuous flow, especially since 2002. In east of Songzi, the average period of discontinuous flows used to be 150 days but extended to 205 between 2003 and 2007. Similarly, the average periods of discontinuous flow in Hudu and Ouchi increased to 155 and 255 days respectively by 2007. These places reached maxima of up to 280 and 338 days in 2009 (Department of Water Resources of Hunan Province, 2009).

Half of the interviewees (19) are convinced that the Lake's wetlands have been affected since the TGD started to control the water of the YR. The majority of the experts pointed out that the vegetation distribution and duration of the emerged and submerged areas of the wetlands have changed. This was supported by a third of the local people (8 somewhat and 5 certainly) based on their long-term personal observations. More than 40% of the participants believed that the productivity of the systems has been affected by changes in the water level. According to the ecologists, changes in water levels encourage hydrophilous or hydrophobic plants to grow in the Lake's wetlands. A typical example is the replacement of the hydrophilous *Cyperus glomeratus* (a herbaceous sedge producing food for water birds) with hydrophobic *Reed.* Prior to the TGD operation, *Cyperus glomeratus* was the dominant species near and along the lakeshore areas. Because of the decreasing water level after the TGD impoundment, *Reed* has moved closer to the water and is becoming the dominant species in areas previously occupied by *Cyperus glomeratus* resulting in a dramatic decline in the number of migrating water birds (Zhao et al., 2012). Local stakeholders (13 out of 20 participants) described a certain change in relation to the natural storage of fish in the Lake dramatically reduced since the operation of the dam.

Table 2. Changes Identified by Experts and Local Stakeholders

Core subsystems	Certainly	Somewhat	Not really	Unknown	Certainly not
		RS			
RS1.1	32	4	1	1	0
RS1.2	19	11	7	1	0
RS1.3	8	22	2	6	0
RS1.4	3	6	9	15	5
RS2.1	0	1	10	8	19
RS3.1	0	8	12	5	13
RS4.1	22	9	2	5	0
RS4.2	17	11	5	5	0
RS5	3	8	12	14	1
RS6.1	6	9	6	6	11
RS6.2	8	3	9	3	15
		RU			
RU1	26	9	0	3	0
RU2	9	13	14	2	0
RU3	19	10	5	2	2
RU4	26	8	3	1	0
RU5.1	3	11	10	13	1
RU5.2	20	9	5	4	0
		GS			
GS1.1	7	16	8	1	6
GS1.2	5	13	10	9	1
GS1.3	6	10	12	8	2
GS2.1	3	6	10	5	14
GS2.2	9	13	9	5	2
GS3.1	7	9	18	1	3
GS3.2	7	7	13	0	11
GS4	2	8	11	6	11
GS5.1	2	3	10	5	18
GS5.2	2	3	10	5	18
GS6.1	6	10	12	8	2
GS6.2	2	3	10	1	22
		U			
U1	3	14	9	6	6
U2.1	1	5	9	8	15
U2.2	8	8	4	2	16
U3	1	1	1	2	33
U4	3	3	11	9	12
U5	6	9	7	14	2
U6.1	0	1	4	4	29
U6.2	9	11	8	4	6
U7	10	14	8	5	1
U8.1	15	10	2	6	5
U8.2	6	15	9	7	1
U9.1	2	6	10	5	15

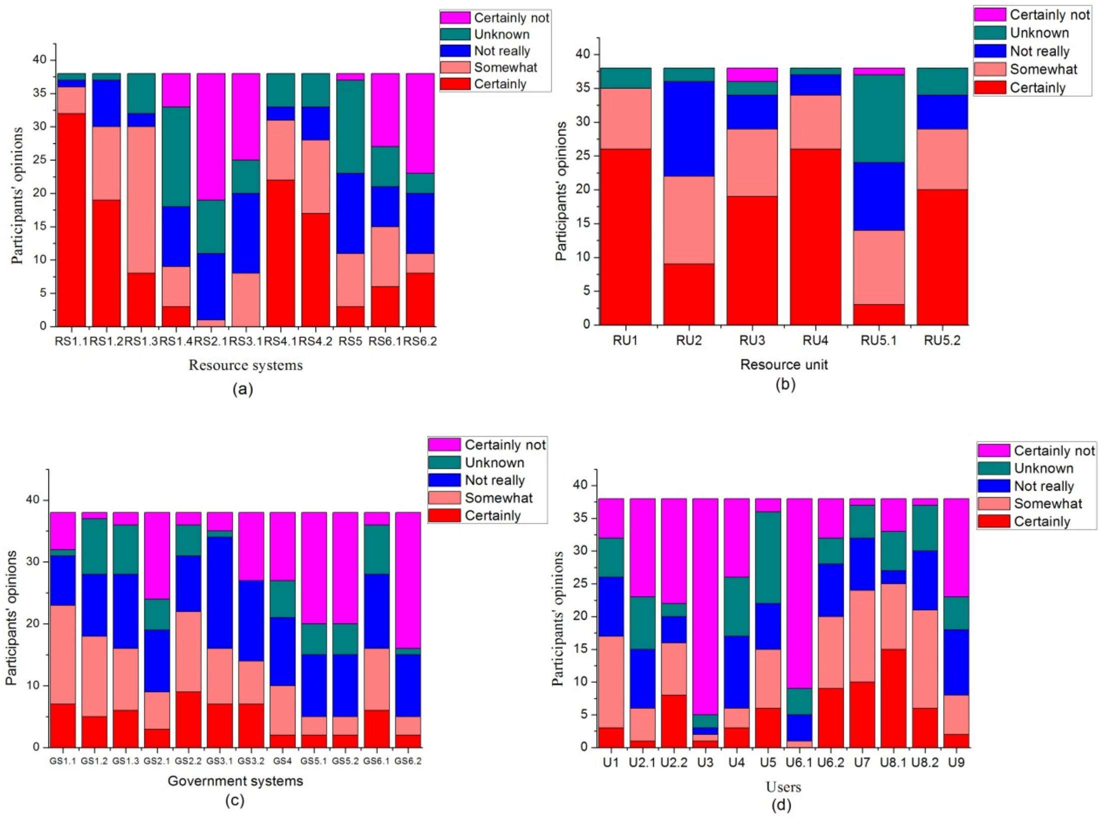

Figure 5. Identification of Changes

Four known changes were identified in *RU*, namely resource unit mobility, economic value, number and homogeneous distribution of units (refer to Figure 5b, Table 1 & 2). Resource mobility is demonstrated with the example of *Carex heterolepis* being replaced altering the habitat for birds (Zhao et al., 2012). Two-thirds of the participants (26 of 38) agree that explicit economic loss was induced to fishery and agricultural irrigation by the reduced water level in the Lake, changing its economic value. Another important change in economic value may occur to the implicit ecosystem services provided by the Lake, such as the capacity of the wetlands to control floods and provide habitat to migratory birds. These services were valued at CNY8 billion with CNY3 billion for flood control (Zhang et al., 2004). The number of units is another certain change in RU as demonstrated by fish reduction.

The participants acknowledged that none of the *GS* subsystems was changed due to the TGD (refer to Figure 5c). With the dam commencing operation only a decade ago and its impacts demonstrating slowly, nogovernance changes have yet occurred. The problems around Dongting Lake attracted attention only recently and to respond to them, policy instruments rely on understanding the SESs and clear identification of impacts and critical variables.

Only one variable in the system of users (*U*) was identified as a known change brought by the TGD (refer to Figure 5d, Table 1 & 2), namely economic dependence on the Lake's resources. Almost 40% (15 of 38 participants) agreed about the high dependence of locals on the resources from the lake including impacts from fish reduction.

3.4.2 Possible Changes

In relation to *RS* and *RU*, fish was identified as a "more likely" change brought by the TGD. Although all fishers in the survey claimed that the fish presence in the lake has certainly decreased since the operation of the dam, most other participants (58%) believed that the dam might have an impact on the fish population in the Lake. The experts explained that it is arbitrary to draw any conclusions prior to obtaining proper evidence. Their research experience indicates some impacts on the fish; however, they are conducting further research, particularly as to whether all fish species have been affected and which is the critically influenced element for the fish's habitat.

The only "less likely" change that might have happened in *RU* is related to growth and replacement rate of resources over time. Experts stated that because of the seasonally changing water level, the habitat for some resources has certainly changed which might affect their growth and replacement rate. *Cyperus glomeratus* is a typical example. However, in the absence of data for the whole system this phenomenon is not seen as a certain change for all natural resources in the area, including fish.

The more likely changes for *GS* are ecological and economic-ecological policies as well as NGOs related to ecological engineering, adjustment of economic structures and research projects. The most likely ecological policy change is the proposal to build floodgates in the three lake mouths (Songzi, Hudu and Ouchi) to compensate for the water loss. Although advocated by many experts, this proposal has not yet been approved by the Chinese Central Government. The majority of participants (61%, including both, more and less likely) thought that the economic-ecological policy is likely to have changed specifically because of the impacts of the TGD. Experts stated that the altered hydrological conditions, especially the reduced water level and sediment loads, affected the water quality of the Lake in its critical areas at different times of the year. For example, the Nitrogen and Hydrogen Nitride content in the water may drop during May and June but goes up in September and October because of the changes in the Lake's water level generated by the TGD water control. As a result, the water quality fluctuates, which forces the government to put economic structures in place to reduce pollutants from economic activities (as listed in Table 1). Similarly, efforts are also made by non-governmental institutions, such as numerous research projects around reducing the impacts of the dam on the Lake's health. An example is "The interactions between the Yangtze River and joint lakes" project supported as a China National Basic Research Program.

The less likely changes include social-ecological policy, regulations for property rights and collective choice as well as local observation for the purpose of monitoring and sanctions. Many policies have been issued for protecting the ecological health of the Lake and social wellbeing (Table 1). Nevertheless, almost a third of the participants thought that these policy changes were not specifically triggered by the impacts of the TGD.

More than half of the participants (53%) viewed common interests as more likely to have changed and they believed that the connections between people (*U*) with common interests have become closer. The reduction in fish affected in particular the interests of fishers and their attitude towards building networks to put pressure on the government to mitigate this impact. For example, according to local protection rules fishers who live in the protected areas of ED have only a limited time to fish during the year. The decreasing water level is shortening further this limited fishing time. This impact is strengthening their willingness to revert fishing rights which were sold to private companies by the government. Most participants thought that local people's knowledge of SESs is likely to have improved due to witnessing the impacts of the dam and noticing the reciprocal effects between changes in the ecology of the Lake and their wellbeing.

Other "more likely" changes are the number of users and cultural dependence of local people. To counteract the impacts of the decreasing fish stock in the Lake, the local fishery and environmental protection authorities issued incentive policies, such as occupational training programs and compensation for spring fishing bans, with the aim of encouraging fishers (especially younger generations) to transform their traditional fish-dependent activities, and paying for loss in production to protect the output of the Lake. This changed the number of fishers, their traditional lifestyles and dependence.

3.4.3 Unknown Changes

Two unknown changes in *RS* were identified – in water birds and predictability of the system dynamics. Although the changed water level of the Lake has altered the distribution of wetlands and their vegetation, most experts and local residents (15 of 38) were not sure whether this affected water birds because of their high adaptability and mobility. According to the experts, long-term observations are needed. Predicting the system dynamics is complicated due to the highly uncertain disturbances caused by climate and other human activities. Many interviewees (14 of 38) could not tell whether the impacts of the dam have impacted the predictability.

Non-homogeneous distribution of units is the only unknown change identified in *RU*. The experts explained that the spatial and temporal distribution of the Lake's resources have changed but it is still unknown whether this was triggered by the dam. This is at the exploration stage as the main topic of their "973 program".

Some of the interviewees (9 of 38) noted that since the operation of the TGD leadership might have somewhat appeared within NGOs with the aim of improving the adaptability of the SES to the impacts. The majority of the participants however did not notice any change among different local stakeholders.

3.5 Indicators Output

The systems' capacities to absorb changes reveal their resilience in relation to their own ability as well as institutional arrangements to absorb or adapt to external disturbances. Social-ecological resilience requires the system to have capacities to absorb external perturbations by its abilities of reorganizing or self-organizing, renewing and learning in order to avoid a shifting into another undesirable configuration (Folke et al., 2006, 2005; Gunderson et al., 2006). For instance, algae blooms and changes in wetland plant communities are regarded as the main signals of a regime shift in the ecological health state of freshwater lakes (Folke et al., 2004). Plants can counteract such a shift and increase water clarity as well as enhance their own growing conditions making the state self-stabilizing (Scheffer et al., 2001). However, when a critical threshold (such as Phosphorus concentration) is passed because of increased nutrient concentrations, reduction in water clarity occurs with increase in turbidity and submerged plants may disappear. Avoiding critical tipping points of SESs being crossed not only requires the systems to keep access to natural capital but also external support, such as appropriate institutions, financial resources, professional skills of individuals, and technology improvements (Table 3). According to the responses listed in Table 3, the developed suite of resilience indicators is presented in Table 4 to understand what is happening for Dongting Lake's sustainability.

4. Discussion

This paper addressed three issues missing in the existing literature on resilience related to incorporating resilience thinking in sustainability science. Firstly, a framework was developed to present how resilience thinking can be employed for establishing sustainability indicators. Secondly, a combined approach of experts and local stakeholders is used to specify systems' changes, which allows difficult to identify changes to be recognized, especially for SESs. Thirdly, by using the TGD as the main external disturbance for Dongting Lake, a resilience-based indicators set was developed for freshwater lakes which can be used to analyse the SESs' current status and future trends in the face of slow perturbation from the dam.

4.1 Framework for Resilience Indicators

According to Grigg and Walker (2012), the task of resilience management is to let us live in a resilient world full of changing circumstances. This requires us to anticipate change and respond wisely, take strategies to prevent undesirable changes, sometimes accept inevitable changes and find ways to absorb or transform their impacts. All this needs to start with analyzing the system dynamics, especially feedbacks. In this study using systemic perspectives (Fiksel, 2006), we developed a framework for incorporating resilience thinking into sustainability indicators that help anticipate and understand the changing world.

Similar to previous research (e.g. Bennett et al., 2005), our framework described the process of resilience analysis and indicator identification by defining systems and external perturbations, depicting the systems' status and identifying indicators. In addition, it builds on Ostrom's (2009) thinking about SESs, which provides a way to dissect the core systems to better detect system dynamics. This framework highlighted the importance of putting resilience thinking into sustainability policies and practices through identifying systems' boundaries, perturbations, systems' changes and feedbacks.

4.2 Expert-Local Stakeholder Participation Technique

Analyzing and synthesizing ecosystems with social interactions is a different task from dealing with them separately. There are always challenges because changes in social systems are harder to capture and sometimes even to observe. The benefits of participatory approach are apparent in analyzing complex problems of SESs (Walker et al., 2002; Brigg & Walker, 2012) as various stakeholders bring different knowledge and experiences to help link ecological and local social systems (Olsson & Folke, 2001). We used experts and local stakeholder interviews to identify environmental changes triggered by external perturbations. This expert knowledge helped narrow the research scope before involving broader stakeholders, which is useful for cutting down time and resources. Such a combined top-down and bottom-up approach is also a suitable way to prevent redundant and identify complementary indicators (Reed et al., 2006).

Table 3. Systems' Resilience to Changes in Core Subsystems

System	System change	Capacity to absorb change (Resilience)	
		System's ability	**Policy response**
RS	• Water (RS1.1) a. seasonal alteration to water level b. drying up water volume • Wetlands (RS1.2) c. vegetation distribution (coverage) d. areas of emerged wetlands • Productivity of system (RS4) e. Stock status (RS4.1) f. Biophysical factors (RS4.2)	a. Water compensation from Xiang River, Zi River, Yuan River, and Li River b. Supply/demand ratio in various months c&d. Permanent wetland within key vegetation (emergent macrophytes) coverage e&f. The regeneration rate of resources with the changed hydrological conditions	a & b. Water quantity adjustment proposals for the next 30 year c&d. Availability of restoration plans for the wetlands of the lake for the next 30 years with the aim of adapting to the TGD e&f. Availability of plans for protecting and increasing the stock of resources in the next 30 years
	• Fish (RS1.3) g. Living space h. Food chain	g. NA h. NA	g. Fish protection and reproduce plans for the next 30 years h. Food chain protection plans for the next 30 years
	Nil	Nil	Nil
	i. Water birds (RS1.4) j. Predictability of system dynamics (RS5)	i. Habitat transformation j. Key variables in different systems	i. Long term regular observation on distribution and quantity of water birds especially during the period when water level has been changed j. Monitoring for key variables in the long run
RU	• Resource unit mobility (RU1) a. Spatial mobility b. Temporal mobility • Economic value (RU3) c. Explicit economic value loss d. Implicit economic value loss • Number of units (RU4) e. Fish output and food availability for water birds • Spatial and temporal distribution (RU5) f. Homogeneous distribution of units (RU5.2)	a. Liveable space of species (key plants, fish, and water birds) b. Food availability c. Community's ability to generate wealth d. Accessibility of technology e. RS e&f f. a	a & b. RS a, b, c, d, e and f c. Financial support plans from government in the long run d. Technological support plans in the long run e. RS c&d, e & f f. RS a, b, c, d, e and f
	Nil	Nil	Nil
	g. Growth and replacement rate (RU2)	g. NA	g. Long term monitor plans and experimental programs for key species of the lake
	h. Non-homogeneous distribution of units (RU5.1)	h. Spatial patterns of different systems	h. Availability of monitors for resources
GS	Nil	Nil	Nil
	• Policy area (GS1)	a & b. Flexibility of existing policies (ecology, industry and	a & b. The diversity and redundancy of policy responses for long term purpose

	a. Ecology policy (GS1.1) b. Economic-ecology (GS1.2) • Organisation (GS2) c. NGOs (GS2.2)	agriculture irrigation) c. Degree of multilevel network linkages	c. Policy support for NGOs in the long term (research funding support and funding for other local NGOs)
	• Policy area d. Socio-ecology policy (GS1.3) • Rules in use (GS3) e. Property rights (GS3.1) f. Collective-choice rules (GS3.2) • Monitoring and sanctions (GS6) g. Local observation (GS6.1)	d. a & b e. NA f & g. The reasonability of the rules (equality)	d. a & b e. Availability of compensations for those who would lose rights to access the resources of the lake if change happened f & g. Complementary rules for the long run purpose
	Nil	Nil	Nil
U	• Importance of resource (U8) a. Economic dependence (U8.1)	a. Users' education attainment and skill ability	a. Availability of skill training programs for local people and pathways for people to get other economic income sources
	• (b.) Number of users (U1) • Social capital (U6) c. Common interest/shared norms (U6.2) • (d.) Knowledge about SES (U7) • Importance of resource e. Cultural dependence (U8.2)	b. a c. The degree of trust in social groups d. People's ability to learn knowledge e. NA	b. a c. Availability of policy that can lead those common interest groups to the right way to enhance social belief in building up resilience d. Strategy to help users in deeply understanding the dynamics of SES e. Availability strategy to keep traditional culture in other ways
	Nil	Nil	Nil
	f. Leadership (U5)	f. Social impacts of local groups and the education attainments of their key members	f. Sustainability education or training programs for local people

Note: ---certain changes; ---more likely changes; ---less likely changes; ---unknown changes

Table 4. Resilience-based Sustainability Indicators for Dongting Lake, China

Type of Changes	Core system	Indicator		Explanation
		System ability	Policy response	
Known changes	RS1.1	I_1: Water storage I_2: The water supply-demand ratio	P_1: Availability of water quantity adjustment plans for the next 30 years	Dongting Lake receives water from YR and also runoff from the catchment (Feng et al. 2013), covering the connected Xiang, Zi, Yuan and Li River. The comparison of total runoff between the lake mouths in the YR and the four rivers in different months can show the compensation ability of the Lake. If the ratio is ≥1, the system is resilient and able to tolerate such disturbance. If water compensation from these four rivers is comparable to discharge and inflow from YR during dam impoundment period and a policy response is available for the coming decades, then the Lake can be viewed as having the ability to

				absorb such change.
	RS1.2	I_3: Coverage of emergent macrophytes	P_2: Availability of wetlands restoration plans for the next 30 years	When this coverage is lower than what water birds need, a regime shift will happen in the biodiversity of the Lake induced by the loss of habitat (WRC 2000).
	RS4 RU4	I_4: The regeneration rate of key (highly dependent on water level) resources	P_2&P_3: Availability of protection plans for the resources in the lake for the next 30 years	This is in response to changes in stock and biophysical factors as well as the number of units. If the regeneration rate is lower than the rate of loss, the system is not resilient in relation to this component.
	RU1 RU5.2	I_5: Livable space for key species in the wetlands	P_1, P_2, P_3	If minimum required space is not available for these resources because of changes in spatial and temporal distribution and the water they need, the system will not be able to withstand spatial mobility. E.g. change in spatial and temporal distribution of emergent macrophytes affects the productivity of food sources for water birds. If food from emergent macrophytes is less than the minimum demand, the water birds' habitat would collapse (WRC 2000).
	RU3	I_6: The financial situation of the region I_7: The number of production modes in agriculture and aquaculture	P_4: Availability of government financial support for the next 30 years P_5: Availability of technological support plans for the next 30 years	Studies have shown that a wealthier community can buy themselves out of future problems and is more resilient (Rose and Liao 2005; Alessa et al. 2008). Also, the easier to access technical support is, the more likely the region is to absorb changes in water supply by increasing water use efficiency (i.e. the more resilient the region is).
	RU8.1	I_8: Education attainment and skill ability of people	P_6: Availability of programs (trainings and pathways) to help local people with economic income for the next 30 years	People with higher education levels or specific skills are more likely to find alternative income sources when resources on which they depend are reduced; thus more prone to adapt to changes (Deressa et al. 2009). Skill-training programs, improved education and facilitating ways to access other income sources can alleviate disturbance to local communities.
Possible changes	RS1.3	I_5	P_7: Availability of specific reproduction and protection plans to protect the fish's living space for the next 30 years P_8: Availability of food chain protections for the next 30 years	Fish self-adaptby moving where they can find suitable habitat. Locals observe more fish swimming to the YR for deeper waters, particularly in the dry seasons. However, these fish are at the lower end of the food chain in the big river and their fate as prey is unclear. Hence indicator I_5 is also applicable here.
	RU2	NA	P_9: Availability of long-term monitoring plans and programs for key species of the Lake for the next 30 years	If change in growth and replacement rate (RU2) of resources happens, it is important to understand whether it is faster or slower, whether this new rate is able to produce enough resources to keep their functions and what the main variables causing the change are. Thus the resilience of the systems may rely highly on policy arrangements.
	GS1.1 GS1.2 GS1.3	I_9: The degree of public participation in policy-making	P_{10}: The diversity of policy responses for the long-term	Adjustment to policy areas (GS1) depends on two aspects. The first is the degree to which the existing policies can be adjusted. Stakeholder participation in the process of policy-making can ensure policies are flexible enough to include new information about environmental conditions and changing preferences about management and local

				responses (Tompkins and Adger 2004). Second is the diversity of policies which is key for enhancing ecological resilience and source of socio-economic systems' ability to absorb disturbances and replacement capacity when disturbance occurs (Walker and Salt 2006, Walker et al. 2006).
	GS2.2	I_{10}: The diversity of stakeholder networks in the region	P_{11}: The diversity of policy support from government to local NGOs	I_{10} is an indicator for measuring connections among social networks. Links between NGOs, governments, institutes and other groups are important in sharing power and responsibility (co-management) enhancing social-ecological resilience (Folke et al. 2005). The more social network links, the easier access to information and the more resilient communities are.
	GS3.1	NA	P_{12}: Availability of compensations for lost access to the resources of the Lake	Governance support should be provided in the long-run in aspects of finance, information and rights as policy responses. P_{12} is needed to maintain social stability.
	GS3.2 GS6.1	I_{11}: Percentage of stakeholders affected	P_{13}: Availability of policies for enhancing collective actions among stakeholders	If changes in collective actions rules occur (GS3.2), the altered rules should be equitable for different stakeholders and complementary regulations are needed for the long run.
	U1	I_8	P_6	Users' number is more likely to become smaller due tooccupation transformationin response to reduced income, especially for fishers. Success is similar to that of economic dependence.
	U6.2	I_{12}: The size of local common interests groups	P_{14}: Availability of strategies to encourage social groups	Larger size groups with common interests have stronger trust and the community is more resilient (Pacala et al. 1996). The stronger the trust in social groups with common interests, the more prepared they are to build the resilience of SESs.
	U7	I_{13}: Population's literacy rate	P_{15}: Availability of long-term strategies for education about the dynamics of SESs	Improving people's understanding in SESs (U7) helps boost social-ecological resilience. How much this can be improved relies on people's ability to learn new knowledge and strategies. I_{13}reflects the ability to learn new knowledge and adapt to external disturbances.
	U8.2	NA	P_{16}: Availability of strategies that maintain traditional culture	It can determine whether such changes could result in regime shifts in local cultural systems such as social values and beliefs.
Unknown changes	RS1.4	I_{14}: Transformations (temporal and spatial) of water birds habitat	P_{17}: Availability of long-term observation of distribution and quantity of water birds	It can show whether the dam impacts on water birds. This may include changes in traditional foraging behaviors and living areas.
	RS5	I_{15}: Share of locals concerned about the environment	P_{18}: Availability of long-term monitoring of key variables	The more people do this, the more likely they are able to notice the system dynamics; If people are able to recognize the critical variables of the system they could predict what may happen in the system.
	RU5.1	I_{16}: Spatial pattern change in key systems (location, coverage, quantity)	P_9	Spatial patterns can be early warning signals before tipping points happening (Scheffer et al. 2009).
	U5	I_{17}: Media coverage of local groups I_{18}: Social power	P_{19}: Availability of regulations to give social groups rights for their behaviors	Social impacts of local environmental protection groups can be used as signals of changes, particularly with changes in leadership. I_{17} and I_{18} can be used to identify whether leadership change occurred or whether there is potential for this.

4.3 Resilience-Based Sustainability Indicators for the Dongting Lake Case Study

Using Dongting Lake as a case study, 37 resilience-based indicators were developed to identify the resilience of the freshwater lake's SESs in response to environmental changes. The indicators include two groups: systems' absorption abilities and policy responses. They are able to reflect the current status (systems' absorption abilities) and trends (through policy response) in the face of particular perturbation and environmental changes.

The established resilience indicators show that some core subsystems may need more than one ability to absorb changes occurring to them (see Figure 6). For example, changes in the water system require the ability of water compensation from other joint rivers and capacity of balancing water supply and demand but also ability of sustaining plants. More policy responses are needed to make the system able to absorb these changes. In other words, systems which need more abilities to absorb change are more vulnerable to external perturbations and should be of higher concern; they would have more difficulty recovering if regime shifts happen. On the other hand, some indicators (from both groups) are important to more than one subsystem, which means that those corresponding capacities are key variables that must be measured and monitored carefully for the systems' status. For example, living space for key species (*I5*) can well indicate both the status of wetlands and spatial mobility of resources units while availability of resources protection (*R3*) is significant for projecting whether the SESs can be resilient and sustainable to future changes in productivity and spatial and temporal distributions. Therefore, such indicators should be important signals that must be taken into considerations by decision-makers for sustainability management practices.

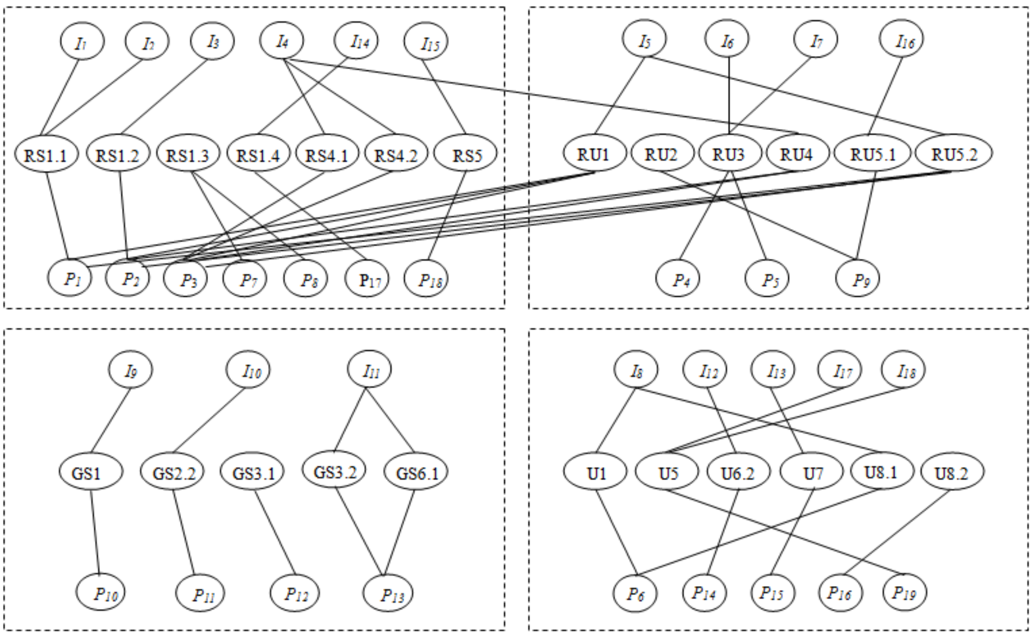

Figure 6. Relationships among Indicators and Core Subsystems of SESs

5. Conclusion

Appropriate indicators are important for integrated natural resources management in assessing the socioeconomic and environmental sustainability of ecosystems and are also useful for decision-makers. Traditionally sustainability indicators do not consider the impacts of certain and uncertain external shocks despite them playing an increasingly important role in affecting the safety of SESs. This paper established an indicators set on the basis of resilience thinking for the sustainability of systems challenged by growing external perturbations. Specifically, a framework from a systemic perspective was developed and combined with expert and local stakeholder participatory approach. This framework, based on Ostrom's (2009) thinking about dissecting SESs, provides a different way to incorporate resilience thinking into sustainability indicators. We used Dongting Lake which is exposed to the disturbance of the engineered perturbation from the Three Gorges Dam as the case study to establish resilience-based indicators and present insight for policy-makers for its sustainability management.

The developed indicators set in this study is a first step in the assessment of the sustainability of disturbed freshwater lakes from a resilience point of view. Future steps are indicator calculation, threshold identification and design of policies. The developed framework incorporates social-ecological resilience into sustainability assessment. These indicators can be further improved by also capturing broader influencing factors, such as climate change. Although the use of long time series is preferred, local knowledge should be treated as an important alternative way to fill the gap between what is available and what are potentially impossible to measure, slow or unobservable variables of social-ecological systems.

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