

**Curtin University Sustainability Policy Institute**

**SUSTAINABILITY SCIENCE FOR WATER: BIBLIOMETRIC  
ANALYSIS AND SOCIAL-ECOLOGICAL RESILIENCE  
THINKING**

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**This thesis is presented for the Degree of  
Doctor of Philosophy of  
Curtin University**

**November 2015**

## **DECLARATION**

To the best of my knowledge and belief this thesis contains no material previously published by any other person except where due acknowledgment has been made. This thesis contains no material which has been accepted for the award of any other degree or diploma in any university.



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Date: 24/10/2015

## ABSTRACT

The natural environment is changing with resources becoming more uncertain. Water is one of the sensitive systems facing the growing changes in human demand coupled with various environmental shocks, such as extreme floods, droughts, and storms. Many of the unanticipated and unforeseen surprises result from human activities and anthropogenic climate change. This shifts the thinking about and use of water resources into a new domain where sustainability management has the mission to discover effective ways to better adapt to the changes and cope with uncertainties in both understanding and technological responses. Such a mission requires sustainability science and practices in order to transform research towards interdisciplinary and transdisciplinary fields. Sustainability then becomes a goal which can only be achieved with the triumph of other objectives.

Although a consensus has been reached about integrating social and economic dimensions within a sustainability context, the complexity of coupled social and ecological systems overweighs our current knowledge and ability to understand them. In order to respond to this need, the overarching question addressed by this PhD thesis is: “*How should sustainability management of water resources adapt to the growing changes and uncertainties?*”. This thesis by publication answers the question through seven refereed articles on four subtopics which achieve two objectives: (1) outline the theoretical frontiers in sustainability science and cutting-edge technological research in water sustainability; and (2) integrate creative knowledge into the practices of water resource sustainability based on the example of Dongting Lake in China. Two of the articles use bibliometric analysis to describe the latest achievements in sustainability science and another paper outlines the links between sustainability and resilience positioning the understanding of the sustainability of social-ecological systems within a resilience framework. The remaining four articles focus specifically on water management by first positioning resilience theory into sustainability management of water resources and then exploring its application in the case of Dongting Lake. The four subtopics covered by the thesis are described below.

*Subtopic one:* A bibliometric analysis of resilience theory for sustainability science and technological frontiers in water sustainability (addressed in two articles) – based on cited publications, *Paper One* analyses the development of resilience theory in environment-related contexts between 1973 and 2011. This study provides the theoretical source for applying resilience thinking in sustainability practices. The results from the analysis show a

dramatic increase in resilience research in the area of environmental sciences with a growing attention to social and sustainability contexts which are expected to become the main research direction in the coming decades in order to address the changing and uncertain environmental issues. *Paper Two* presents the trends in scientific exploration in two cutting-edge technologies, namely nano- and biotechnology, and their application for water sustainability issues. The findings demonstrate that nano-biotechnology will be an important technology to be used to effectively address water problems. However, further internationalisation of scientific efforts led by active countries, such as USA, and broader scopes of the applied nano-biotechnologies in water supply and treatment are needed to provide better solutions for the global water challenges in the future.

*Subtopic two:* Interrelationships between resilience and sustainability (addressed in one article) – *Paper Three* examines the relationships between resilience thinking and sustainability through exploring similarities and differences as well as how resilience contributes to sustainability, in which ways resilience for sustainability can be measured and how to manage resilience for achieving sustainability goals. The paper claims that resilience and sustainability have things in common but remain different. This means that neither of them can be used to replace the other at any time but they share interdependency. Measuring resilience is a challenge because of difficulties in identifying the thresholds of the systems' variables. The tasks relate to how to identify the critical variables of the different systems and generalise the dynamics of the social-ecological systems by making use of different techniques, such as scenario analysis, modelling and simulation approaches.

*Subtopic three:* Framework for incorporating resilience thinking into sustainability management of water resources (addressed in one article) – *Paper Four* develops a framework aimed at incorporating resilience into the sustainability discourse in assessment. The paper proposes three general steps to conduct resilience assessment for water sustainability management purpose, namely systematic description, results analysis and decision-making, and post-assessment.

*Subtopic four:* Application of resilience theory to sustainability practice for water systems (addressed in three articles) – *Papers Five* and *Six* use the second largest freshwater lake of China, namely Dongting Lake, as a case study. The Lake is facing substantial disturbances from the Three Gorges Dam – the world's largest hydrological infrastructure spanning the Yangtze River. These two papers aim at assessing the resilience of the social-ecological

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systems of the Lake regions in response to the perturbations from the big dam. *Paper Five* develops a set of resilience-based sustainability indicators which are then applied to the case area in *Paper Six*. The assessment illustrates that the east part of the studied areas has a relatively higher resilience while the south and west parts are relatively low-resilient to the disturbance from the dam. Further strategies are needed to enhance the systems' absorption abilities as well as to diversify policy responses and enhance the role of social networks in the adaptation process. *Paper Seven* puts a specific focus on how to enhance social networks for community resilience in adapting to environmental changes. The discussion is carried out from the perspective of social bonding relationships ranging from local to national levels.

In conclusion, the PhD thesis proposes future research directions, related to: (1) the interrelationships between different domains of resilience research; (2) overview of recent technological development for water resources sustainability; (3) early warning signals for possible transitions of social-ecological systems; (4) general frameworks for social-ecological resilience assessment of water systems; and (5) exploration of ways to better use social networks in water sustainability governance.

## **ACKNOWLEDGEMENTS**

This PhD would have been a tough journey for me without the support and assistance of many people. I would like to express my greatest appreciation to my supervisor Professor Dora Marinova. Without Dora's guidance and support, this thesis would have not been completed. Her suggestions and encouragement helped me out on many issues not only in academic but also in my life. I am grateful for her invaluable support.

I also would like to thank my co-supervisor Dr Xiumei Guo for her assistance and help in my research and life in Australia. My gratitude is also given to Professor Ling Li from the University of Queensland for his appreciable permission for me to attend their annual meetings of the China's National project ("973" program). The fieldworks in this thesis would not have been possible without his kind introduction to the group.

My great appreciation is also expressed to all the experts and local stakeholders who participated in my interviews and surveys. These includes experts from Group 5 of the National Basic Research Program of China ("973" program), officers from the Department of Dongting Lake Fisheries, local environmental protection, and Authority of Nature Reserve Areas of Dongting Lake, and experts from the Dongting Lake Station for Wetland Ecosystem Research in the Chinese Academy of Sciences, Hohai University, and Nanjing Institute of Geography & Limnology in the Chinese Academy of Sciences, and Nanjing University of Technology.

I would also like to acknowledge that the second fieldwork of this study was financially supported by the Curtin University Postgraduate Student Association (CUPSA). My great thanks also go to all anonymous reviewers of the seven papers for their helpful comments which helped improved the published articles which form the body of this thesis.

My utmost gratefulness must be expressed to my parents and other family members, including my grandparents, uncles, and aunts. This thesis is especially dedicated to my grandma who passed away in the third year of my PhD studies. The understanding and support from all of you inspired me to complete this study.

Thank you!

**STATEMENT OF CONTRIBUTION OF OTHERS**

All of the written materials submitted as part of this PhD by Publication were conceived and coordinated by Li Xu. The majority of the calculation and writing for each publication was undertaken by Li Xu.

Signed detailed statements from each co-author relating to each publication are provided as cover page of each publication.

Signed:



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Li Xu, PhD Candidate



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Professor Dora Marinova, Supervisor

Date: 24/10/2015



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Dr Xiumei Guo, Supervisor

Date: 24/10/2015

**PUBLICATIONS INCLUDED AS PART OF THIS THESIS**

**Paper 1 (Peer reviewed journal article):**

**Xu, L.** and D. Marinova, (2013) Resilience thinking: a bibliometric analysis of socio-ecological research. *Scientometrics*. 96(3): 911-927.

**Paper 2 (Peer reviewed book chapter):**

**Xu, L.** and D. Marinova, (2015) Nano-biotechnology for water sustainability: bibliometric analysis. In Zacher, L. (ed.) *Technology–Society–Sustainability: Selected Contemporary Issues, Concepts and Cases*, Springer (forthcoming, acceptance date 27/07/2015).

**Paper 3 (Peer reviewed journal article):**

**Xu, L.,** D. Marinova and X. Guo, (2015) Resilience thinking: a renewed system approach for sustainability science. *Sustainability Science*. 10(1): 123-138.

**Paper 4 (Peer reviewed book chapter):**

**Xu, L.** and T. Raphaely, (2015) What can we do better for sustainability in the uncertain future?. In Zacher, L. (ed.) *Technology–Society–Sustainability: Selected Contemporary Issues, Concepts and Cases*, Springer (forthcoming, acceptance date 27/07/2015).

**Paper 5 (Peer reviewed journal article):**

**Xu, L.,** D. Marinova, P. Xin and X. Guo, (2015) Resilience-based sustainability indicators for freshwater lakes with application for Dongting Lake, China. *Environment and Natural Resources Research*. 5(2): 165-188.

**Paper 6 (Peer reviewed journal article):**

**Xu, L.,** D. Marinova and X. Guo, (2015) Resilience of social-ecological systems to human perturbation: Assessing Dongting Lake in China. *Journal of Sustainable Development*. 8(8): 185-200.

**Paper 7 (Peer reviewed book chapter):**

**Xu, L.,** X. Guo, M. Gollagher and D. Marinova, (2015) Managing social networks for community resilience from the perspective of bonding relationships. In Marinova, D. and Guo, X. (Eds) *Sustainability Issues in South Asia and Pacific*, Edward Elgar (forthcoming, acceptance date 30/09/2015).

**LIST OF ADDITIONAL PUBLICATIONS EXCLUDED FROM THIS THESIS**

**Peer reviewed journal papers:**

1. Sun, F., J. Shen, **L. Xu**, G. Xu, B. Liu and J. Ji, (2014) Multi-agent modelling of impacts from the Blue-green algae event in Taihu Lake on employees' income levels in Wuxi city. *BioTechnology: An Indian Journal*. 10(18): 10088-10095.
2. Shen, J., N. Chen, **L. Xu** and F. Sun, (2014) Cost-benefit analysis of impacts of Blue-green Algae incident on residents' environmental awareness of daily life in Wuxi City (in Chinese). *Journal of Economics of Water Resources*. 32(3): 1-5.
3. **Xu, L.**, J. Shen, D., Marinova, X. Guo, F. Sun and F. Zhu, (2013) Changes of public environmental awareness in response to the Taihu blue-green algae bloom incident in China. *Environment, Development and Sustainability*. 15(5): 1281-1302.

**LIST OF ACRONYMS AND ABBREVIATIONS**

<b>AOSIS</b>	Alliance of Small Island States
<b>CDM</b>	Clean Development Mechanism
<b>ED</b>	East Dongting Lake
<b>GS</b>	Governance Systems
<b>IPCC</b>	Intergovernmental Panel on Climate Change
<b>IW</b>	Inclusive Wealth
<b>NGOs</b>	Non-government organisations
<b>NOAA</b>	National Oceanographic and Atmospheric Administration, USA
<b>NWS</b>	National Weather Service, USA
<b>RS</b>	Resource Systems
<b>RU</b>	Resource Units
<b>SD</b>	South Dongting Lakes
<b>SER</b>	Social-ecological resilience
<b>SEs</b>	Social-ecological systems
<b>TGD</b>	Three-Gorges Dam
<b>U</b>	Resources Users
<b>UN</b>	United Nations
<b>UNCED</b>	United Nations Conference on Environment and Development
<b>UNFCCC</b>	United Nations Framework Convention on Climate Change
<b>UNHPGS</b>	United Nations High-level Panel on Global Sustainability
<b>WCED</b>	World Commission on Environment and Development
<b>WD</b>	West Dongting Lakes
<b>WMO</b>	World Meteorological Organisation
<b>YR</b>	Yangtze River

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# 1. INTRODUCTION

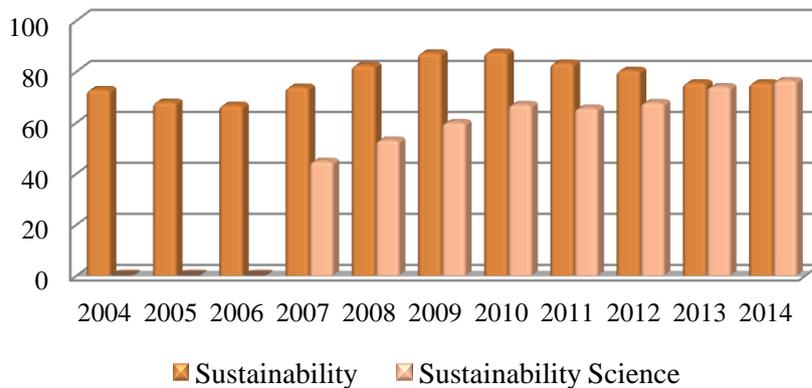
## 1.1. Background

One of the key missions of sustainability science is to detect possible changes that would occur in the future and find ways to maintain the environmental and socioeconomic systems in a desired sustainable trajectory. However, the growing changes and uncertainties facing the globe, including climate change, globalisation, political upheavals and changing demographics (Robinson and Berkes 2011), have become inevitable truths which make such a mission a big challenge and require more endeavours for it to be tackled. Sustainability research has therefore moved away from mainly theoretical concepts and transferred to problem-oriented areas in order to address these alarming issues.

In a transforming and uncertain world, the introduction of academic terms, such as: coupled human-environment systems (Turner II et al. 2003), ecosocial systems (Waltner et al. 2003), socioecological systems (Holmes 2001), and social-ecological systems (Berkes et al. 1998), demonstrates that sustainability science is not an area that can be suitably treated by any single discipline. It is “multiple things at once and navigates interesting territory – it is a goal, and ideal, and umbrella, and a sub-discipline of multiple disciplines” (Stock and Burton 2011, 1091). The goal of sustainability can only be achieved by the achievements of other objectives (Marcuse 1998). This requires sustainability science to shift its focuses to interdisciplinary areas as well as transdisciplinary discourses (Kates et al. 2001; Marinova and McGrath 2004; Hadorn et al. 2006; Koc 2010; Stock and Burton 2011; Lang et al. 2012), that is the involvement of multiple disciplines and different stakeholders is required.

Global calls for interdisciplinary and transdisciplinary research in sustainability science not only drew the attentions of academia (Kajikawa et al. 2014) but also generated the attention of the public as shown in Figure 1.1. According to *Google Trends*, the past decade has witnessed increasing global interest in sustainability and sustainability science. This trend is especially manifested through the gradual increases in sustainability science research since 2007.

**Monthly average Google search times for  
*Sustainability and Sustainability Science***



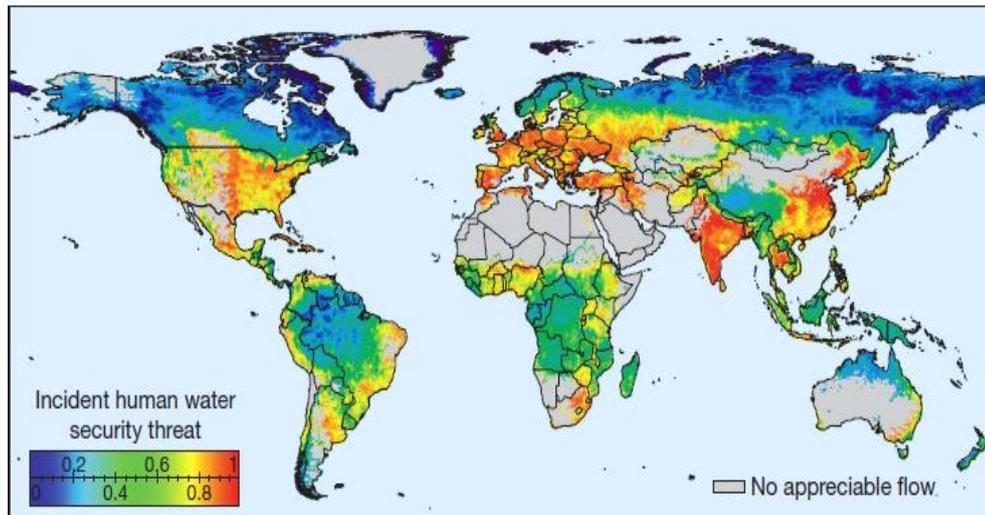
**Figure 1.1** Global interests in sustainability and sustainability science (2004-2014)

Note: the numbers are scaled on a 0-100 scale (<http://www.google.com/trends>).

The sustainability of water resources refers to “the ability to use water in sufficient quantities and quality from the local to the global scale to meet the needs of humans and ecosystems for the present and the future to sustain life, and to protect humans from the damages brought about by natural and human-caused disasters that affect sustaining life” (Mays 2007, 4). Freshwater is the most important water resource and is critical for the survival of the living world (Wetzel 2000). It is also seen as the prerequisite for the advancement of human societies (Postel and Carpenter 1997). Incremental scarcity of freshwater resources however emerged as an undisputable truth as these systems have being threatened by human activities and anthropogenic climate change (Gleick 2003).

Water availability and security have become major concerns in the 21st century (Biswas 1991; Vörösmarty et al. 2010) owing to the increasing demand, high pollution levels and declining freshwater ecosystems (Johnson et al. 2001). Growing human perturbations exert a wide range of threats to freshwater systems and destroy water security in many areas throughout the globe (Figure 1.2). According to Vörösmarty et al. (2010), there is around 4.8 billion (80%) of the world’s population facing the threat of water security. China is a typical example; water security is one of the major threats facing this country. The areas with higher population density and more developed economy experience a substantially higher threat of water shortage compared to arid areas within sparse population. This is the case even for places with high rainfall and dilution capacity such as the Yangtze River catchment. Two-thirds of the 669 Chinese cities are facing water shortage and 80% of

China's freshwater lakes suffer from eutrophication (Chinese Academy Sciences 2007; Liu and Yang 2012) which negatively impacts the availability of this precious resource.



**Figure 1.2** Global geographical map of incident threat to human water security<sup>1</sup> (Vörösmarty et al. 2010, 556 figure 1)

Although there is a dominant consensus about integrating socioeconomic dimensions in the sustainability context to address continuing environmental challenges, the coupled social and ecological systems are so complicated that our existing knowledge and ability are not enough to comprehensively understand them (Berkes 2007). The complexity of social-ecological systems (SESs) gives rise to varieties in variables for projecting the climate, which in turn increases the uncertainties of internal processes and external extremes (changes) in the systems. The changing impacts of climate extremes, such as flood, drought, and storm, on water systems depend not only on changes in the characteristics of climate-related variables but also on water-relevant non-climatic stressors, management characteristics, and adaptive capacity (IPCC 2012). For instance, climate change has potential impacts on river flood characteristics through changing the volume and timing of precipitation, or by changing evaporation and hence accumulated soil moisture deficits. However, there is considerable uncertainty about the magnitude, frequency, and direction of such changes.

One of the most important reasons for the complexity of nature-human systems is the interrelationship and non-linear dynamics between them. Social systems changes are

<sup>1</sup> Incident threat means pandemic impacts that caused by stressors including catchment disturbance, pollution, water resource development and biotic factors. All these incidents threaten human water security and biodiversity (Vörösmarty et al., 2010).

dependent on biophysical variables while changes in biophysical variables also depend on the degree and intensity of human activities (Berkes 2007). Those interrelationships sometimes are linear whereas under specific circumstances, and some might lead to a non-linear response and even to unanticipated consequences. There is need to know what and when the perturbation would lead to a non-linear response, especially social feedback in response to the human-induced environmental changes. There is also need to recognise how and to what extent the SESs can absorb and adapt to the external certain and uncertain perturbations without flipping into an undesirable state.

Since sustainability is not a “steady state” or “fixed target”, achieving this goal requires continued adjustments in responding to changing conditions, knowledge, and priorities (Dale et al. 2013). The extensive human perturbations have generated numerous uncontrollable changes and increased the uncertainties of water systems. Such trends are exacerbating future uncertainty. Climate warming is a typical example. The new task for water sustainability management is to find optimal ways of putting in place or adjusting appropriate actions to avoid the collapsing of systems faced with external shocks.

To deal with these challenges, both theoretical and technological innovation is essential along with continuing improvement and understanding of the uncertainties. Technological innovation provides the tool used to address the challenges and at its source is theory development and basic research. Starting from a theoretical point of view, this thesis uses bibliometric approaches to explore the new thinking for sustainability management in nowadays' growingly changing environment. Theory development is as important as technological innovation. Hence the thesis uses nano-biotechnology as an example to discuss the technological development of research on water resources sustainability issues.

There is also a growing consensus that building social-ecological resilience (SER) is an optimal way to enhance the likelihood of sustainability in the uncertain future (Adger et al. 2005; Folke 2006). The sustainability management of water resources requires a shift towards resilience thinking. This thesis hence concentrates on resilience thinking and its role in sustainability science using a freshwater lake in China as a case to show how this approach can be applied for water sustainability management and practices. Freshwater systems are particularly sensitive to external disturbances and their state is susceptible to changes in land coverage, vegetation distribution, hydrological conditions, and other

perturbations from human activities (Vörösmarty et al. 2010). The analysed Dongting Lake is a well-suited case to represent the complexities and importance of these issues.

## 1.2. Conceptualisation

Prior to proceeding with the research question, objectives and findings of this study, there is need to explain why this thesis concentrates on bibliometrics and resilience thinking in order to contribute to sustainability science by conceptualising the relevant contexts. In doing so, the discussion starts with the definitions of sustainability and explanation how its focus shifted to resilience since its first introduction in 1987; then it moves to clarifying how bibliometrics is used in sustainability discourse and after this, a detailed explanation of resilience and SESs is presented.

### 1.2.1. *The sustainability contexts*

Sustainability is often considered synonymous to sustainable development. Some researchers however stress that sustainability is a complex and multi-faceted concept which implies inclusiveness, connectivity, equity, prudence and security, while sustainable development is viewed as a process that embraces these multiple elements to achieve human development (Gladwin et al. 1995; Bebbington 2001). Despite these differences in interpretation of the concept, this thesis implies that the two meanings serve the same purpose. The general definition of sustainability that is most widely accepted is the one defined in *Our Common Future* (also known as Brundtland Report):

*“Sustainable development is development that meets the needs of present without compromising the ability of future generations to meet their own needs”*. It contains two key concepts:

- *The concepts of needs, in particular the essential needs of the world’s poor, to which overriding priority should be given; and*
- *The idea of limitations imposed by the state of technology and social organization on the environment’s ability to meet present and future needs”* (WCED 1987, Part I, Chapter 2).

Sustainability however is not a stable state of a system but evolves all the time through reacting with external and internal factors (Milestad and Darnhofer 2003). In recent years,

this research area generates about 12000 publications annually representing various disciplines and opinions (Bettencourt and Kaur 2011; Kajikawa et al. 2014). The term has experienced a dramatic rise in definitions and explanations. With sustainability being such a vague and broad concept, each study tends to provide an interpretation that suits its particular purpose. According to Mihelcic et al. (2003), diverse constituencies, including various academics and research groups, develop different visions of sustainability based on their needs and aspirations. It is impossible to cover all existing definitions and hundreds of them have been identified by other researchers in their studies. A detailed history and background for the concept of sustainability can be found in Fowke and Prasad (1996), Mebratu (1998), Lippert (2004), Mann (2009) and Quental et al. (2011), to name a few. Rather than reviewing the existing academic research on sustainability, the approach taken in this introduction is to present a roadmap of the development of the concept through exploring key global documents and reports. It is believed that these documents and accompanying forums have shaped the global understanding in a more distinctive way than individual studies have been able to achieve.

The influence of sustainability thinking emerged in the 1990s with the development of sustainability principles and action measures through the work of global environmental protection organisations. Notwithstanding this, their implementation has been surrounded with heated debates and challenges. For example, *Agenda 21* adopted at the 1992 UN Conference on Environment and Development (UNCED) in Rio de Janeiro laid out a list of measures for sustainable development. This legally non-binding and voluntary action plan however lacked the power to be enforced in all countries and failed to specify particular responsibilities and obligations. It was left to individual governments at national and local level to implement the priorities outlined in *Agenda 21*. The *Kyoto Protocol* of the UN Framework Convention on Climate Change (UNFCCC) put in place in 1997 drew specific goals and obligations for different countries to reduce greenhouse gas (GHG) emissions. More than 50 countries committed and signed the protocol successively while it was not supported by USA, the world's biggest economy and at the time also the largest GHG emitter. The 2012 Doha climate change negotiations delivered the extension of the Kyoto Protocol until 2020 but with a weakened support as Canada, Japan and Russia were reluctant to take on any further targets (The Guardian 2011; Arup 2012).

While sustainability is moving from conceptualisation to the development of analytical tools, human-induced disruptions are resulting in growing environmental shocks. The main mission in addressing sustainability while facing the growing changes and shocks has become how to build a resilient society. This requires the ability to quickly recover from problems at many levels. Resilience thinking, which is the emphasis in more recent global documents, such as UNHPGS (2012) and IPCC (2014), is becoming the mainstream in achieving such an objective. To capture these developments, it is essential to show how resilience thinking became an important conceptual framework in sustainability science along with the challenges which appeared at different stages. The bibliometric study on the other hand shows the quantitative trends in resilience thinking for sustainability science in the past decades.

### *1.2.2. Roadmap of sustainability: a focus on global documents*

The roadmap of the evolutionary path of sustainability as a conceptual framework is traced here through a number of global documents and reports. They represent policy milestones and are discussed chronologically below.

#### *1.2.2.1. Our Common Future (1987)*

Sustainability and sustainable development research was established as a well-defined academic area after the publication of *Our Common Future*, also known as the Brundtland Report, issued by the United Nations World Commission on Environment and Development (WCED) in 1987. This report was the first formal document with respect to the issue of sustainability and it also defined the term sustainable development. It should be acknowledged that the definition and conceptualisation of sustainability put forward in this report were building on many pioneering efforts outlining the interdependence between the environment and human development such as *Silent Spring* (Carson 1962) and *The Limits to Growth* (Meadows et al. 1972). In *Our Common Future* sustainable development was posed for discussion as a new policy agenda about the relationship and conflicts between human development and environmental protection.

The definition the Report provided is: “Sustainable development is development that meets the needs of present without compromising the ability of future generations to meet their own needs” (WCED 1987, Part I, Chapter 2). It further indicated that “sustainable development is a process of change in which the exploitation of resources, the direction of

investments, the orientation of technological development; and institutional change are all in harmony and enhance both current and future potential to meet human needs and aspirations” (WCED 1987, Part I, Chapter 2). More specifically, the Report analysed the concept of sustainable development from 12 aspects, which are: (1) societies must meet human needs both by increasing their productive potential and by ensuring equitable opportunities for all people; (2) the interventions from human development to natural systems must not, at minimum, endanger the life-support systems such as the atmosphere, waters, soils, and living beings; (3) humans must ensure equitable access to the constrained resources and change technology long before the carrying capacity of the resources reaches their limits; (4) social-environmental systems should be sustained at family, local, national and international levels; (5) the rate of depletion of non-renewable resources like fossil fuels and minerals should foreclose as few future options are possible; (6) biodiversity should be preserved for future generations; (7) the adverse impacts of development on the quality of air, water and other natural elements should be minimised for sustaining the ecosystems’ overall integrity; (8) sustainable development is a process of change in which human activities including exploitation of resources, investments, technological development and institutional change should be in harmony and are able to maintain current and future potential to meet people’s needs and aspirations; (9) although economic development inevitably involves changes in interlinked ecosystems, negative impacts can be minimised by taking into account system-wide effects of exploitation; (10) a society may compromise its ability to meet the needs of its people in the future in many ways; (11) sustainable development can only be pursued if demographic developments are in harmony with the changing productive potential of the ecosystem such as the population size and distribution of resources; (12) sustainable development requires the promotion of values encouraging consumption standards that are in the limits of ecological possibility.

The core of the Brundtland definition is “equity”. First of all, as the Report puts forward, sustainable development is a concept in respect to the permanent benefits of the contemporary and future generations. This definition gives a clear temporal boundary to sustainable development, namely sustainable development is not only a matter of intra-generational but also inter-generational justice and equity. Second, it accepts that development is essential for human living, which denies the extreme environmentalism views that call for restraining progress in order to preserve natural resources for future generations. Third, the Brundtland Commission emphasises the strong relationship between

poverty alleviation, environmental improvement, and social equitability through sustainable economic development. Specifically, sustainable development is an ideal developing way that maximises the efficiency of utilising natural resources in order to meet needs not only of the current generation but also of future generations and to alleviate poverty, promote the level of environmental quality and social equity as much as possible. Furthermore, it emphasises that development should happen on the condition that the current depletion of finite natural resources does not overweigh their thresholds which the next generation requires for its wellbeing. What is more, technological and institutional changes are essential for sustainable development. However, the definition did not refer to sustainable development or sustainability in terms of spatial scales such as land and marine environment (which were added later on in *Agenda 21*).

The *Our Common Future* definition has been widely accepted in sustainability science. Nevertheless, it has been difficult to capture the real meaning of sustainability. The reasons for this are sustainability being a vague notion on the one hand, and on the other, different visions being developed based on its researchers' diverse interests (Mihelcic et al. 2003).

### 1.2.2.2. Agenda 21 (1992)

*Agenda 21*, which was adopted by UN during the Conference on Environment and Development in 1992, i.e. the Earth Summit held in Rio de Janeiro, is another remarkable international programmatic document related to the issue of global environmental problems and economic development. This report further depicts and analyse sustainable development, with a main focus on social and economic dimensions and institutions, and its relation to environmental protection at the global, national, and local scales.

The document firstly discussed how to accelerate sustainable development, alleviate poverty, and enhance human health conditions through international cooperation. Then, it analysed conservation and management of resources for development by examining different resource systems and environmental problems such as land, agriculture, biodiversity, marine ecology, freshwater, deforestation, desertification, radioactive wastes and so on. It emphasised the importance of strengthening the different roles of the market and major stakeholder groups in bridging sustainable development. Those groups include women, children and youth, indigenous people, non-governmental organizations, workers and trade unions, local authorities' initiatives, business and industry, scientific and

technological community, and farmers. The report suggested means of implementing sustainable development through aspects of finance, technology, scientific research, education, national and international cooperation, institutional arrangements, and legislation (UNCED 1992).

*Agenda 21* focused on the contributions of economic, governmental, and social groups to sustainable development, which provided distinguished references to later research on sustainability, in particular the analysis of its various aspects. It came down to accepting that the limits to natural resources, especially biophysical limits, can be bypassed through increased efficiency and effectiveness in production. From then on, the notion of sustainable development was gradually accepted and advocated by most countries around the world. A growing number of regional and local organisations or initiatives concerned with putting sustainability into practice began to emerge, such as: President's Council on Sustainable Development, US (1993), Japanese Agenda 21 Action Plans (1994), Chinese Agenda 21 (1994), and the European Community environment programme: towards sustainability. While the Brundtland Report can be regarded as the contribution to theoretical research on sustainability, *Agenda 21* can be deemed to be a pioneering exploration in informing sustainability from theory further to practice. It directly defined neither sustainability nor sustainable development but used the terms interchangeably and discussed how to achieve sustainability objectives through actions.

### 1.2.2.3. Kyoto Protocol (1997)

The *Kyoto Protocol* came into realisation from the previous draft proposed by the Alliance of Small Island States (AOSIS) which called for a 20 percent reduction in carbon dioxide emissions from industrialized countries by 2005 (Dresner 2008). At the beginning, the draft protocol was opposed by most countries, including the United States and almost all Western countries. However, an agreement was reached in 1997 after rounds of negotiations and meetings and the so-called *Kyoto Protocol* was initiated.

The Protocol committed the industrialized countries to an overall reduction of 5.2 percent in their collective annual emissions of the main greenhouse gases in the period of 2008-2012 compared to the 1990 levels. By establishing a set of actionable mechanisms, the *Kyoto Protocol* formulised the implementation of direct measures to help countries reduce greenhouse gas emissions. Specifically, the Protocol asserted that emissions can be treated

as a new commodity that “was created in the form of emission reductions or removals...since the carbon dioxide is the principal greenhouse gas...carbon is now tracked and traded like any other commodity” which is known as “carbon market” (UNFCCC 1997a). Joint implementation in the Protocol allowed countries to pay for the measures to reduce or remove emissions in other Annex 1 (mainly developed, including former Eastern Europe) countries and count this towards meeting their Kyoto target. In addition, the Clean Development Mechanism (CDM) allowed a country to meet part of its targets by implementing emission-reduction projects or funding emissions reductions in developing countries. It is therefore seen as a “trailblazer” for “it is the first global, environmental investment and credit scheme of its kind, providing a standardized emissions offset instrument” (UNFCCC 1997b). The CDM from the *Kyoto Protocol* proved to be a win-win mechanism for countries in decarbonising. By the end of 2008, there were 4200 CDM projects registered and 8300 projects were expected by 2012 (ClimateAvenue 2010). As of August 2015, the number of registered projects was lower at 7664 but 2824 of them are already generating more than 4 billion of certified emission reduction units or carbon credits (UNFCCC 2015). Although aimed at achieving sustainability, the focus of the *Kyoto Protocol* was on a very specific area aimed at mitigating climate change through reducing greenhouse gas emissions. It is therefore viewed as a further programmatic document for actions to achieve the objective of sustainable development.

#### 1.2.2.4. Stern Review (2006)

The *Stern review: the economics of climate change* is well known for its economic perspective on the issue of global warming. This Review was announced by the Chancellor of the Exchequer (UK) in July 2005 and set out to provide a report to the Prime Minister and Chancellor in 2006. It assessed the impacts of climate change and analyses adaptation and mitigation to the warming temperatures from the viewpoint of economics. It posed that “reversing the trend to higher global temperatures requires an urgent, world-wide shift towards a low-carbon economy.” (Stern 2006, Introduction iv).

The *Stern Review* concluded that climate change could have serious impacts on growth and development but humans still have enough time to avoid the worse ones by adopting strong adaptations, such as building resilience, collective actions, minimise costs and strong, deliberate policy actions. Because of the global nature of climate change, all these must be

reached in an agreement at the international level. The delay in mitigating the climate problem would be dangerous and much more costly than the ways used to treat it.

This Review, based on the traditional economic cost-benefit analysis method, gave clear answers to questions about how much and how fast the world should reduce greenhouse gas emissions. It also provided insights about how to balance the costs of the reductions or carbon removals against the impacts of climate change, and contributed to offering nations more practicable action directions to sustainability. In particular, it looked at reducing the greenhouse gas emissions as well as providing reference to other sustainability problems such as water depletion, sea level rise, and population expansion from an economic perspective. The Review's radical revision of the economics of climate change is on the basis of the assumption of a near-zero time discount rate combined with a specific utility function. According to Nordhaus (2007, 701), "the Review's unambiguous conclusions about the need for extreme immediate action will not survive the substitution of assumptions that are consistent with today's marketplace real interest rates and saving rates".

### 1.2.2.5. Bali Road Map (2007)

*The Bali Road Map* was issued and adopted at the 13th Conference of the Parties to the UN Framework Convention on Climate Change and the 3rd Meeting of the Parties to the Kyoto Protocol in December 2007. It consists of a number of decisions that represent the various essential paths to a safe climate future (UNFCCC 2007).

The most important outcome of this meeting for sustainable development is known as the Bali Action Plan — a comprehensive process to enable the effective and sustained implementation of the Climate Change Convention through long-term cooperative action (UNFCCC 2007). The *Bali Road Map* charted the course for a new negotiating process designed to overcome climate change issues along with a number of other decisions and resolutions, such as building capacity for technology transfer and reporting on global observing systems for climate. The Bali Action Plan was expected to play an important role in paving the way for the negotiations towards a post-2012 Kyoto Protocol agreement at Copenhagen in 2009 (Ott et al. 2008).

The generation of the *Bali Road Map* can be seen as a historical landmark in the process of human efforts to cope with climate change. First of all, it for the first time emphasised that adaptation should be in parallel to mitigation of climate change. Secondly, it stood for the benefits of both developed and developing countries by defining the obligations and responsibilities individually. This enables efforts of resolving climate change to become a global participation issue. For instance, it appeals to developed countries to offer developing countries finance and technology. In detail, it requires developed countries to remove barriers to technology transfer, establish a sound mechanism for technology development, and collaborate to develop new technologies to adapt to climate change. On the other hand, it requires developed countries to provide sufficient financial assistance to developing countries for their actions to adapt to climate change. Thirdly, it involves almost all nations into the negotiation for collaborating to cope with climate change and received commitments from many countries, including the United States which refused to rectify the *Kyoto Protocol*. Although the *Bali Road Map* is an unprecedented international negotiation for dealing with climate change and achieving sustainable development in the coming years, there are still many ambiguous details which need further negotiations, such as how to define adaptations in operational terms in order to achieve political and financial outcomes.

### 1.2.2.6. Copenhagen Summit (2009)

The *Copenhagen Summit*, commonly known as the 2009 United Nations Climate Change Conference, was held in Copenhagen in December 2009. This conference aimed to negotiate further global plans and actions to replace the *Kyoto Protocol* after its first period of implementation. The conference included the 15th Conference of the Parties (COP 15) to the United Nations Framework Convention on Climate Change and 5th Meeting of the Parties (MOP 5) to the Kyoto Protocol. A framework for climate change mitigation beyond 2012 was to be agreed on the basis of the *Bali Road Map*.

The main outcome of this conference was the *Copenhagen Accord* accepted at the final plenary session. The *Accord* agreed and maintained the principles of collaborative action and common responsibility underpinning the *Kyoto Protocol* and the United Nations Framework Convention on Climate Change. It also made plans to force developed countries to reduce their greenhouse gas emissions and to activate developing countries to mitigate their emissions. In addition, a wide agreement was reached about global long-term objectives, financial assistance, and technology support.

### 1.2.2.7. UN High Level Panel Report on Global Sustainability (2012)

This report entitled *Resilient people, resilient planet: a future worth choosing* was released by the United Nations High-level Panel on Global Sustainability (UNHPGS) on 30 January, 2012. “Resilience” is used as the key logic basis and is regarded as the choice of future. The Panel was established by the UN Secretary-General with the aim at exploring approaches for adapting to changes and formulating a new blueprint for a sustainable future under increasing stress resulting from human activities, namely to build a low-carbon, green, and resilient economy.

The report consists of six sections: (I) The Panel’s vision; (II) Progress towards sustainable development; (III) Empowering people to make sustainable choices; (IV) Working towards sustainable development; (V) Strengthening institutions; and (VI) Conclusion: A call for action. It also contains 56 recommendations on what people, governments, organizations, and communities should do to put sustainability into practice. Specifically, the Panel emphasises that there are two possible answers to the question of why the concept of sustainable development is still hard to put into practice. It points out that the political will has failed to enhance sustainable development. There are “few incentives to put sustainable development into practice when our policies, politics and institutions disproportionately reward the short term” (UNHPGS 2012, 4). For another, “the concept of sustainable development has not yet been incorporated into the mainstream national and international economic policy debate” (UNHPGS 2012, 4). Secondly, the Panel appeals to the international community to establish “a new political economy” for sustainable development, including improving the interface between environmental science and policy, recognising ‘market failure’ exists in certain environmental problems (which require the pricing of ‘environmental externalities’ as many economists recognised) making explicit the economic, social and environmental costs of action and inaction, and so on. Furthermore, the impacts of the current production and consumption patterns and resource scarcity, innovation, demographic change, global economy changes, green growth, increasing inequality, changing political dynamics and urbanization are the main drivers for transforming towards sustainable development. Finally, the 56 recommendations aim at putting sustainable development into practice from the perspectives of people participation, multi-scale collaboration, education, employment, transparent policy choices, green technology revolution, and resources management.

It is clear from the report that the future sustainable development will be “green” and the main concern is how to mainstream sustainable deployment to economic growth as well as how to adapt to changes and uncertainties. The Report emphasises exploring approaches to alleviate poverty and formulate a political framework to ensure a sustainable future under the pattern of green development. Therefore, public participation, environmental accounting, institution management, green economy development, and broader cooperation are strongly recommended to meet the Millennium Development Goals and sustainable development objectives. This indicates that exploring sustainability has entered a further stage of much more specific actions.

The seventeen Sustainable Development Goals adopted by the United Nations in September 2015 (UN 2015) pave the road to making societies greener and safer with an ideal state of less vulnerability and higher resilience in responding to changes and uncertainties. They represent a culmination in the efforts on the international policy arena to firstly, mainstream sustainability and development, and secondly, the bridge the conceptualisation of sustainability with its immediate implementation. How the new Sustainable Development Goals will shape theory development and technological innovation is yet to be seen. What this thesis has been able to canvass is how resilience has permeated sustainability science from its inception to the point of establishing itself as a global development agenda. The section to follow clarifies the use of bibliometrics as an approach to accomplish this.

### *1.2.3. Bibliometrics and its applications in sustainability science*

Bibliometrics is a typical interdisciplinary research field. It uses statistical tools to analyse science policy and research management on the basis of publications (Smith and Marinova 2005). Bibliometric studies have been widely used to analyze various scientific fields ranging from mathematics to social sciences, natural sciences, engineering, medicine and life science. It is also applied to explore the linkage between science and technology (Glänzel 2003). Generally, bibliometric analyses contain basic measures and complex measures of publications including books, journal articles, and conference papers. The basic measures simply count numbers of publications, authors and co-authors, or citations of a set of publications on given study objects. Complex measures can be obtained by mathematical functions and bibliometric indicators (Glänzel 2003). There are numerous databases that can be used to collect bibliometric data. The most popular databases that are

used include Science Citation Index and Social Science Citation Index in the Web of Knowledge, Google Scholar, Scopus, Medline, and ProQuest. The fundamental of bibliometric analyses is the bibliographies of publications which include titles, abstract, keywords, and authors' information. By using such information, either basic or complex bibliometrics can be operated. An example below shows the general information that can be retrieved from such databases.

**TY-** JOUR|

**TI-** A framework for vulnerability analysis in sustainability science|

**T2-** Proceedings of the National Academy of Sciences of the United States of America|

**J2-** Proc. Natl. Acad. Sci. U. S. A.|

**VL-** 100|

**IS-** 14|

**SP-** 8074|

**EP-** 8079|

**PY-** 2003|

**DO-** 10.1073/pnas.1231335100|

**SN-** 00278424 (ISSN)|

**AU-** Turner, B.L.; Kasperson, R.E.; Matsone, P.A.; McCarthy, J.J.; Corell, R.W.; Christensene, L.; Eckley, N.; Kasperson, J.X.; Luers, A.; Martello, M.L.; Polsky, C.; Pulsipher, A.; Schiller, A.|

**AD-** Graduate School of Geography, Clark University, Worcester, MA 01602, United States; George Perkins Marsh Institute, Clark University, Worcester, MA 01602, United States; Stockholm Environment Institute, S-130 14 Stockholm, Sweden; Ctr. for Environ. Science and Policy, Institute for International Studies, Stanford University, Stanford, CA 94305-6055, United States; Dept. of Organismic/Evol. Biology, Harvard University, Cambridge, MA 02138, United States; Kennedy School of Government, Harvard University, Cambridge, MA 02138, United States; Dept. of Earth/Planetary Sciences, Harvard University, Cambridge, MA 02138, United States|

**AB-** Global environmental change and sustainability science increasingly recognize the need to address the consequences of changes taking place in the structure and function of the biosphere. These changes raise questions such as: Who and what are vulnerable to the multiple environmental changes underway, and where? Research demonstrates that vulnerability is registered not by exposure to hazards (perturbations and stresses) alone but also resides in the sensitivity and resilience of the system experiencing such hazards. This recognition requires revisions and enlargements in the basic design of

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vulnerability assessments, including the capacity to treat coupled human - environment systems and those linkages within and without the systems that affect their vulnerability. A vulnerability framework for the assessment of coupled human-environment systems is presented.

**KW-** article; biosphere; climate; decision making; global change; hazard; human; institutional care; priority journal; risk factor; social adaptation; social behavior; stress; Adaptation, Psychological; Animals; Conservation of Natural Resources; Decision Making; Disasters; Ecosystem; Humans; Models, Theoretical; Safety; Safety Management; Stress; Vulnerable Populations|

**N1-** Citation: 929; Export Date: 12 May 2015|

**DB-** Scopus|

**N1-** CODEN: PNASAJ|

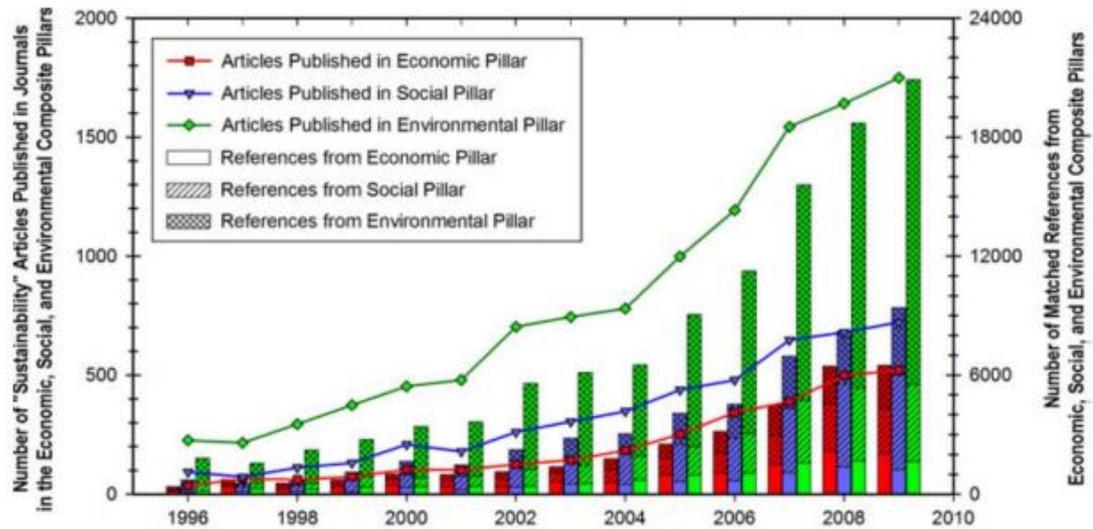
**C2-** 12792023|

**LA-** English|

**UR-**<http://www.scopus.com/inward/record.url?eid=2-s2.0.0037924465&partnerID=40&md5=117133bc8efe97f6da56a31aafaf3317>|

**ER-** ||

There is a growing literature focussing on bibliometric analyses of sustainability science. Dedeurwaerdere's analysis shows that the publications in all topics of sustainability (environmental, social and economic contexts) skyrocketed since the 1990s especially from the year 2002 (Figure 1.3). However, he did not consider sustainability research as an interdisciplinary and transdisciplinary field within many coupled terms. Thus, this study did not explain how sustainability research transferred to interdisciplinary and transdisciplinary domains. These domains can be reflected and termed by several coupled terminologies including human-environment systems, ecosocial systems, socioecological systems, and SESs.



**Figure 1.3** Bibliometric analyses on articles of sustainability (Dedeurwaerdere 2013, 72 figure 3.3)

Focusing on papers published in key journals in sustainability science, Kajikawa (2008, 2014) tracked the evolutionary pathways of sustainability science and categorised sustainability research into ten domains (climate, biodiversity, agriculture, fishery, forestry, energy and resources, water, economic development, health, and lifestyle). They used citation network and topological clustering to analyse the relationships among these domains and the inner structure of sustainability science (Kajikawa et al. 2007). Bettencourt and Kaur (2011) used bibliometric methods to analyse the development of the body of sustainability science and scholarly collections. They found the integration of perspectives created a new field with the emergence of scientific collaboration and a growing scientific field. For the analysis of the technology associated with sustainable development, patents were used as important indicators to represent the performance of technologies and their potentials in different countries (Marinova 2001; Marinova and McAleer 2003). Also, a citation network analysed the emerging technologies for renewable and sustainable energy (Kajikawa et al. 2008).

All these studies demonstrated that bibliometrics is a suitable approach to sustainability science not only in terms of the science and technology evolutions but also their trends and potential for future improvement. However, bibliometric analysis has limitations in terms of reflecting contributions to sustainability practice. It provides hints about science while sustainability requires not only research and development but also practical understanding as to how to achieve sustainable development. This is where sustainability science is

viewed as a use-inspired (Miller et al. 2013) interdisciplinary and transdisciplinary field of research which deals with issues related to resilience.

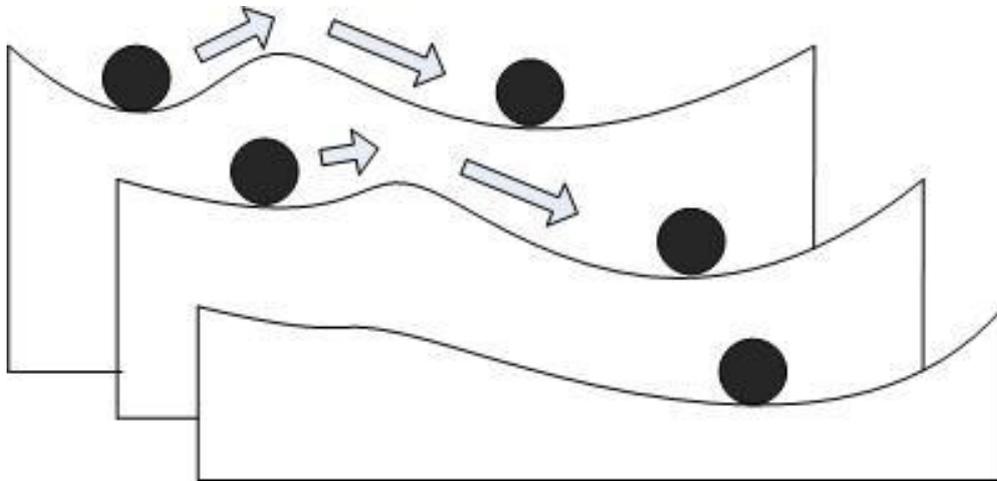
### *1.2.4. Resilience*

The term “resilience” is widely used in various areas. From a psychological point of view, resilience thinking is used to analyse the impacts of extreme situations on individuals, families and children as well as their responses to crises, risks, adversities and stress (such as poverty, familial mental illness, unemployment, etc.). From a systems point of views, the family is an open system that has its own social dynamics and evolves over a multi-generational life cycle (Carter and McGoldrick 1998). Family resilience seeks to identify and foster key processes that enable individuals to cope more effectively and emerge stronger from crises or persistent stresses, whether from within or without the family (Walsh 1996). In engineering, resilience is primarily used in materials science to describe robustness and elasticity as well as to understand what kind of materials are appropriate and/or better in meeting construction or mechanical requirements. For example, when an external force is applied to a rubber material, its shape will change, but will return to its initial shape if that force is lifted. In both these examples, resilience refers to plasticity – the ability of individuals (Masten 2009) and materials to bounce back to their normal state or not be negatively affected. It also implies robustness to withstand the changes and flexibility to return to normal functioning.

Ecological resilience differs from this understanding in the sense that it relates to transitioning between multiple equilibrium states of ecological systems. What this means is that there is an implicit assumption that multiple stable states (equilibriums) exist in ecological systems, thus resilience is the tolerance of the system to perturbations that facilitate transitioning between these stable states (Gunderson 2000, 2002). Hence it can be measured by the magnitude of disturbance that a system can absorb prior to its change of stable state (Holling 1973; Ludwig et al. 1997) or gauged by the size of the stability domains (Gunderson et al. 2010). From this perspective, ecological resilience “emphasizes conditions far from any equilibrium state, where instabilities can flip a system into another stability domain... and focuses on maintaining existence of function” (Holling 1996, 53, 54).

To better distinguish engineering and ecological resilience, a heuristic of a ball-and-cup

diagram and a similar one, termed stability landscape (Walker et al. 2004) were introduced. The ball and cup represent respectively the system state and the stability domain (Figure 1.4). When the ball is at the bottom of the cup, the system is in equilibrium. The ecosystems are assumed to have many stable states, which means that there is more than one cup for ecological resilience in the ball-and-cup diagram (Gunderson 2000). Engineering resilience refers to characteristics of the depth and slopes of the cup while ecological resilience refers to the width of the cup. The changes in the system's states are dependent on disturbance and the size of the attraction basin. If the cup (valley) is small, the state of the system can easily be changed even by a small perturbation (Gunderson 2000; Scheffer et al. 2001).



**Figure 1.4** Ball and cup heuristic of system stability (Gunderson 2000)<sup>2</sup>

As a common feature of complex systems, resilience is viewed as “the capacity of a system to survive, adapt, and grow in the face of unforeseen changes, even catastrophic incidents”, often self-organising and renewing itself into unexpected configurations (Center for Resilience at the Ohio State University 2015).

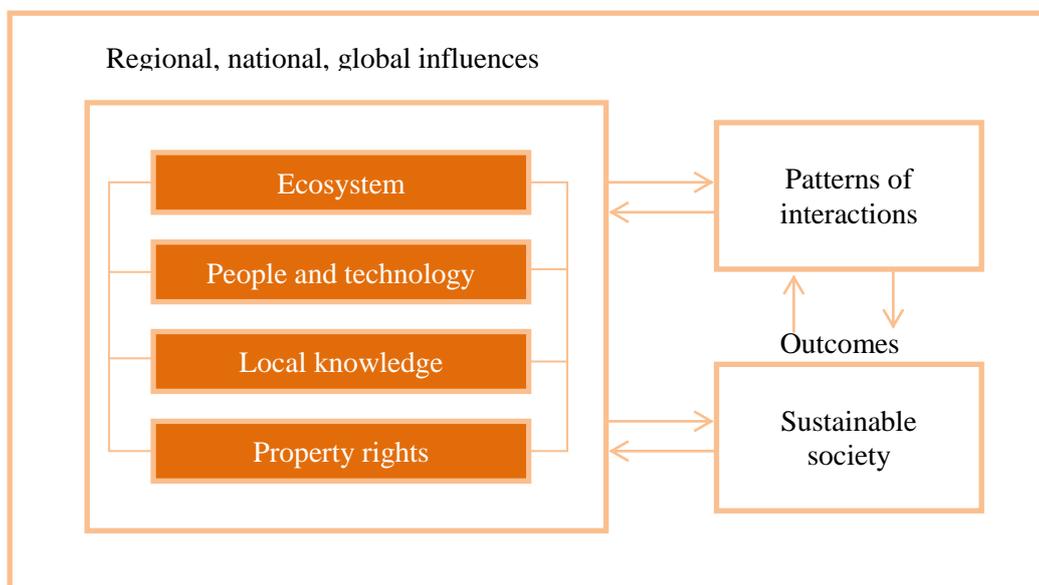
#### 1.2.5. *Social-ecological systems (SESs)*

The increasing closer interplay between human and nature has become a fact. A small disruption in a system may give rise to regime shifts or even collapse of other systems. While sustainability is shifting to enhance the resilience of societies to respond to the changes and uncertainties, the task for sustainability managers is not to better manage

<sup>2</sup> The valleys represent the cup and the arrows represent disturbances.

ecological resources but more important is to know more about coupled social and ecological dynamics so as to ensure their robustness (Anderies et al. 2004). In other words, for the purpose of sustainability resilience is no longer only a matter of ecological systems but coupled SESs. As Folke (2006) puts it, management that only focuses on social or ecological systems may generate breakpoints and narrow or wrong conclusions. Attempts to use resilience to integrate social dimension thus have emerged by focusing on understanding the SESs dynamics and social processes such as social learning, social memory, leadership, social networks, and local knowledge. However, the first question that needs to be addressed is to understand what a SES is.

The term SES was introduced to describe and emphasise the integrated reciprocal relations between nature and humans (Berkes et al. 1998). However, any SESs are complicated within ambiguous boundaries and their states are multi-stressors triggered. The study of SESs needs frameworks to understand their dynamics and forward-and-backward feedbacks. Berkes et al. (1998) framed a SES in a box within which ecosystem, people and technology, local knowledge, and property rights institutions are included as the key components that must be identified when considering resilience and sustainability issues (see Figure 1.5).



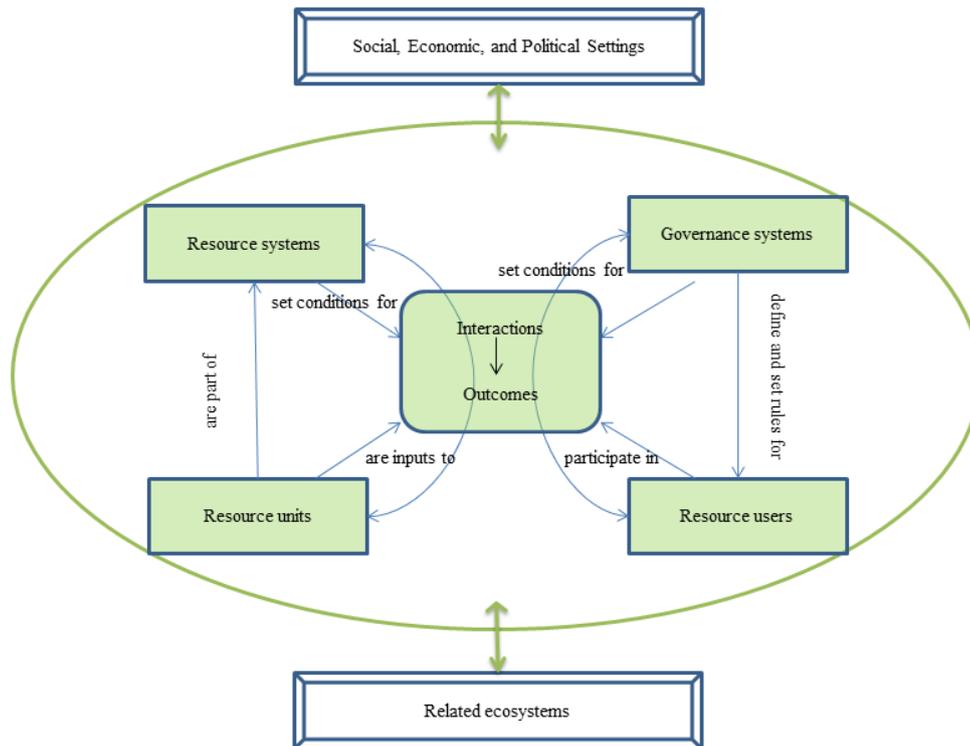
**Figure 1.5** Framework for analysing the relation between social and ecological systems for resilience and sustainability (Berkes et al. 1998)

According to the description by Berkes et al. (1998), the characteristics of ecosystems can be different in structure or function or both. The discussion of social systems should set on the people organised as user communities and the technology they use. Thus the analysis

must be on social groups or communities rather than only individual people or family. Technology is an important element for the SESs analysis not only because through it people may exert impacts on the ecosystems but also as the types available to potential users can affect their accessibility of resources. Also, the utility of types of technology could offer indication to differentiate user communities and the sustainability of their practices. In addition, different resources users have their own knowledge about the local environment including history, current situation, and reasonable management options. Such knowledge becomes particularly important for decision-making when it is transferred from older indigenous generations. Property rights cover state, private or common property. Developing flexible institutions is suggested to deal with resource management crises in terms of property rights (Berkes et al. 1998; Gunderson 1999). Understanding the patterns of interaction in SESs is a useful way to analyse dynamic changes based on other attributes such as use of local ecological knowledge to deal with the dynamics of the ecosystems and find out the social mechanisms behind these management practices. These analyses should be conducted in an evolutionary way and focused not only on external driving factors but also internal regulations that may cause changes in the systems and feedback mechanisms.

Following a similar logic, a general framework was developed to dissect SESs by Ostrom and her colleagues (Anderies et al. 2004; Ostrom 2009; Basurto et al. 2013). This framework views SESs as complex systems that consist of multiple core subsystems and internal variables at different levels. For example, for a SES for coastal areas, the subsystems can include a resource system (coastal fishery), resource units (lobsters), governance systems (organisations and rules that local government uses to manage fish stocks), and users (fishers). Below the first layer subsystems, there are multiple second and even deeper levels variables which belong to each subsystem such as size of a resource system and users' knowledge of the resource system (Figure 1.6).

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**Figure 1.6** The core subsystems in a framework for analysing social-ecological systems (combined Basurto et al. 2013 with Ostrom 2009)

In a SES, interactions occur among these subsystems and give rise to outcomes, which can be influenced by external drivers, including climate, markets, catastrophes, and social, economic and political settings. They interact with each other through the use of resources and management practice. Understanding the complex relations among these subsystems requires knowledge about different variables in each subsystem and how they are related to each other. Such framework is useful for data collection and conducting case studies by providing clues to identify relevant variables and their sub-variables. It also provides a diagnose logic for other studies on SESs. Paper Five of this thesis was conducted on the basis of this framework and further discussion can be found there.

Although there is a growing body of studies examining the coupled human-nature systems with a sustainability purpose, there is still little research informing how and in what direction management should develop in order to enhance the adaptability of systems to the changing environment and uncertain shocks triggered by human activities. Sustainability science is addressing critical issues from an integral point of view that incorporates different opinions from diverse areas. There is still a gap however between first, scientific research and practical implementation, and second, where sustainability science is and how

it should be developed further. This is particularly prominent in the case for water systems. Therefore, exploring answers of this gap requires not only an interdisciplinary approach that investigates the development trends in sustainability studies and brings up creative knowledge for coping with the complicated human-nature problems, but also a transdisciplinary method that integrates the detected creative knowledge and different social actors into practices for decision-makers.

### 1.3. Research question and objectives

The overarching research question of this thesis is:

*“How should sustainability management for water resources adapt to the growing changes and uncertainties?”*

Following this research question, major objectives of this thesis are to:

**Objective one:** Detect theoretical frontiers in sustainability science and the cutting-edged technological research in water sustainability.

**Objective two:** Integrate creatively knowledge into sustainability assessment of a freshwater lake in China as a practical case study and explore ways to enhance community resilience to adapt to changes.

The primary aims to achieve these two objectives are as follows:

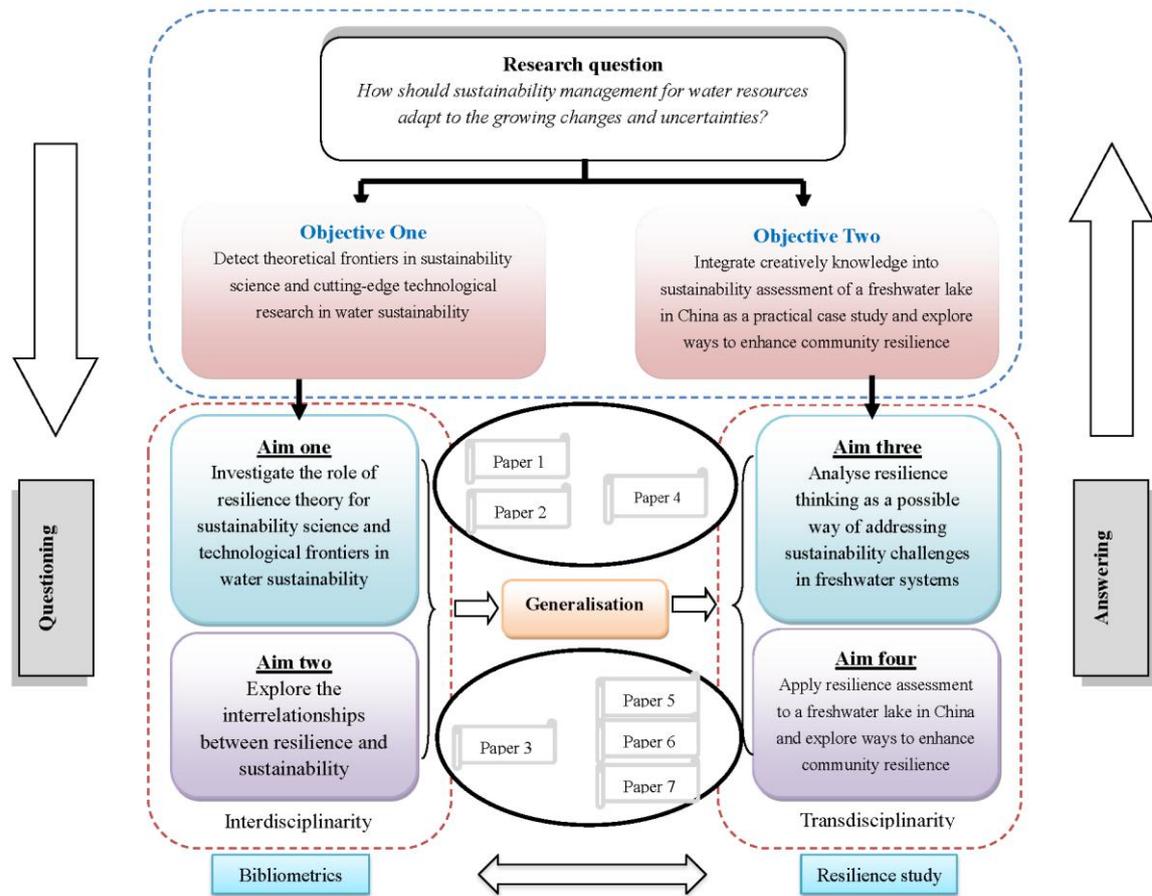
1. Based on bibliometric research, investigate the role of resilience theory for sustainability science and detect technological frontiers in water sustainability – this is achieved with Papers One and Two.
2. Explore the interrelationships between resilience and sustainability – this is achieved with Papers Three.
3. Analyse resilience thinking as a possible addressing way of addressing sustainability challenges in freshwater systems – this is achieved with Papers Four.
4. Apply resilience assessment to a freshwater lake in China and explore ways to enhance community resilience in adapting to the changing environment– this is achieved with Papers Five, Six and Seven.

The way these aims are achieved and the linkages between the research questions, objectives and aims are outlined in the section below.

### 1.4. Research design

This section contains the outline of the study and methodologies used to address its main research question.

#### 1.4.1. Research outline



**Figure 1.7** Schematic diagram of the research structure illustrating relationships among question, objectives and aims

As illustrated in Figure 1.7, the thesis comprises two parts: a bibliometric analysis and a resilience study. Bibliometrics and resilience thinking are seen as the breakthroughs in achieving the study’s aims thereby finding the answer to the research question. Sustainability science is an integrated area which requires both interdisciplinary and transdisciplinary studies and resilience thinking has been firmly established as a way of

conceptualising any policy and practical implications. Bibliometric analysis is used to demonstrate how resilience is becoming a new way of thinking about sustainability through interdisciplinary analysis. However, despite their high informative potential and ability to depict the latest trends and developments, bibliometric studies can make only limited contribution to transdisciplinary research. This study hence covers the theoretical base and evidence for the generalisation and application of resilience thinking to sustainability in order to fill such a gap. By using bibliometrics, the first two aims of this thesis can be achieved leading to the achievement of objective one. Furthermore, a case study which makes use of resilience thinking as its theoretical foundation helps achieve the second two aims and thereby the second objective of this thesis. In combination, the two approaches deliver the answer to the research question of this thesis.

### *1.4.2. Methodology*

The publications included in this study combined quantitative and qualitative approaches including several particular techniques. The quantitative methods used include bibliometric analyses and optimisation modelling for the case study while the qualitative methods composed of literature reviews and participatory approach. They are explained in detail below.

#### *1.4.2.1. Quantitative studies and data*

##### *(1) Bibliometric analysis*

Bibliometric approach is based on a statistical analysis on publications such as books and articles (OECD 2015). It has been widely used to present general trends in given research fields, to integrate crosscutting topics and present their factual structures, and to detect new methods and ideas emerging in various areas. Thus, bibliometrics is not only the publication and citation based gauging of scientific performance but a multifaceted approach that presents “structural, dynamic, evaluative and predictive scientometrics... Its methodology comprises components from mathematics, social science, natural sciences, engineering, and even life sciences” (Glänzel 2003, 5).

In Paper One included in this thesis, a bibliometric approach was taken to identify trends in resilience research in different contexts. The analyses include general statistics, journal output and cited paper statistics, spatial distributions of publications and case studies conducted by countries, intensity of resilience research worldwide, and prominent research

organisations in leading countries. The data used in this paper is based on desktop research conducted in July–August 2012 and information retrieved from Google Scholar, Web of Knowledge, and Scopus regarding cited publications between 1973 and 2011. Paper One starts with a comparison of general trends in the data retrieved from these three databases, then Google Scholar is used as the source to conduct the remaining analyses. The keywords used to collect the data are mainly associated with the word “resilience” and include the following combinations “ecological resilience”, “economic resilience”, “social resilience”, “resilience and sustainability”, “resilience and sustainable development”, “resilience and social-ecological systems”, “social-ecological resilience”, “resilience and environment”, “resilience and natural resources” and “resilience and assessment”. Journal articles, books, conference proceedings, working papers, comments, theses and reports which list the word “resilience” in the title or in their keywords or where it appears at least three times in the abstract were included for the analyses.

In Paper Two of this thesis, a similar study was conducted to demonstrate the cutting-edge research areas in water sustainability. Additionally, a co-occurrence analysis was used in this paper to identify the types of technologies emerging in nanotechnology and biotechnology for water sustainability. The raw data was collected from the Science Citation Index and Social Science Citation Index in the Web of Science and from Physical Sciences and Social Sciences & Humanities in Scopus by using nanotechnology and biotechnology as keywords. Then the publications retrieved from Scopus were taken up for further analyses. The co-occurrence analysis allowed detecting hot points and connections in the field of nano-biotechnology for water sustainability using co-word and co-authorship studies. Using open access software packages, such as Bibexcel and Pajack, the statistics and networks were presented in these two papers. ArcGis 10.2 was another technique used to better illustrate the bibliometric results.

### *(2) Optimisation modelling*

Another quantitative method employed in this thesis is the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) which is a multi-criteria decision analysis approach originally developed by Hwang and Yoon in 1981 (Hwang and Yoon 1981). It was used as a modelling approach on the grounds that the starting point of assessing resilience is similar to the core principle of TOPSIS. More specifically, the desirable state of SER is the one close to high resilience and far away from undesirable and

unsustainable regimes. This means that the desired state of the SES has the shortest distance from the positive state and the farthest to a negative state. This is consistent with the principle of TOPSIS that the optimal resolution should have the shortest distance from the ideal solution and farthest from the negative solution. Furthermore, this technique is a suitable method for complex environmental assessment especially for systems with insufficient data and SER is a typical example. Using fuzzy linguistic descriptions, TOPSIS is able to substitute for such a gap (Chen 2000).

The basic logic of TOPSIS is to compare a set of options by calculating the geometric distance between each option and the best option and worst alternative at the same time (Hwang and Yoon 1981). It assumes that each option has either monotonically increasing or decreasing tendency. As a method, TOPSIS is compensatory and allows trade-offs between different criteria of the options by using weighting and normalisation approaches, which are better suited for modelling complicated problems than non-compensatory methods (Huang et al. 2011). The usual procedure of TOPSIS modelling is:

- a. Construct a decision matrix  $(x_{ij})_{m \times n}$  which can be expressed as follows:

$$(x_{ij})_{m \times n} = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1j} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2j} & \cdots & x_{2n} \\ \vdots & \vdots & \cdots & \vdots & \cdots & \vdots \\ x_{i1} & x_{i2} & \cdots & x_{ij} & \cdots & x_{in} \\ \vdots & \vdots & \cdots & \vdots & \cdots & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mj} & \cdots & x_{mn} \end{bmatrix}$$

where  $x_{ij}$  denotes the performance of the  $i$ th option over  $j$  criterion under the given data either quantitative or qualitative,  $i=1,2,\dots,m$ ;  $j=1,2,\dots,n$ . The qualitative data can be transformed into quantitative by several fuzzy linguistic descriptions such as expert scoring.

- b. Develop a set of weights of relative importance  $w$  for each of the criteria.
- c. Construct the normalised decision matrix  $Y=(y_{ij})_{m \times n}$ ,  $y_{ij} = x_{ij} / \sqrt{\sum_{i=1}^m x_{ij}^2}$ ,  $i=1,2,\dots,m$ ;  
 $j=1,2,\dots,n$ .
- d. Determine the ideal and negative solutions  $S^+$  and  $S^-$  which can be given as:

$$S^+ = (y_1^+, y_2^+, \dots, y_n^+) = \left\{ \left( \max_i y_{ij} \mid j \in J \right), \left( \min_i y_{ij} \mid j \in J' \right) \right\}$$

$$S^- = (y_1^-, y_2^-, \dots, y_j^-) = \left\{ \left( \min_i y_{ij} | j \in J \right), \left( \max_i y_{ij} | j \in J' \right) \right\}$$

where  $i=1,2,\dots,m; j=1,2,\dots,n$ .  $J$  and  $J'$  are associated with the positive indicators set and the negative indicators set, respectively.

- e. Assign weights vectors and calculate the distance of each option from the ideal and negative solutions by:

$$D_i^+ = \sqrt{\sum_{j=1}^n \omega_j (y_{ij} - y_j^+)^2}; D_i^- = \sqrt{\sum_{j=1}^n \omega_j (y_{ij} - y_j^-)^2}, i=1,2,\dots,m; j=1,2,\dots,n$$

- f. Calculate the relative closeness ( $C^*$ ) to the ideal solution for any options using the following equation. After this, the options can be preference ranked according to the values of  $C^*$ .

$$C_i^* = D_i^- / (D_i^+ + D_i^-), 0 \leq C_u^* \leq 1, i=1,2,\dots,m.$$

In Paper Six of the thesis, an equal weighting approach was applied to the indicators and a TOPSIS model was developed and used to assess SER of Dongting Lake of China.

#### 1.4.2.2. Qualitative studies and data

##### (1) Literature review

Thorough literature reviews were carried out on resilience thinking covering its definition in engineering, psychology, sociology, economics, and coupled SESs as well as its evolutionary pathways to become an interdisciplinary domain. A particular focus in the literature reviews was given to sustainability science. Based on the existing literature, Paper Three investigated the interrelationships between resilience and sustainability. It begins with discussing the definition of resilience in different contexts ranging from psychological resilience to resilience engineering, engineering resilience, ecological resilience, social resilience, economic resilience, and SER. The paper then substantiates the argument that resilience thinking is becoming an important topic for sustainability science where it can play an important role. Similarities and differences between resilience and sustainability are outlined emphasising the contribution of resilience theory to sustainability, and deliberating on how resilience can be measured and managed for the achievement of sustainability.

### *(2) Participatory approach*

Participatory approach is based on shared ownership of decision-making and responding to traditional ecosystem-based “top-down” approaches (Campbell and Vainio-Mattila 2003). The participatory method was applied in this thesis for the case study of China’s Dongting Lake regions. Participatory approach was carried out as a two-stage procedure to assess the SER of the regions which are faced with human perturbations associated with the Three Gorges Dam. The first stage was conducted in December of 2013 and the second in December of 2014 following the four steps described below.

#### Step 1: Defining the purposes

Before conducting the participatory exercise, its main goals needed to be identified. Given the complexity of SESs, the changes that human perturbations have brought to the local regions and the responses of social systems are uncertain. In order to assess the SER, the purpose of the participatory technique was to identify changes that external perturbations had brought to local SESs and their abilities to withstand those changes. Therefore, the participatory approach was expected to provide information for these two purposes based on the participants’ “learning-by-doing” experience.

#### Step 2: Identifying the participants

At the first stage of this research, 38 participants were chosen, including 18 experts and 20 local stakeholders. The participating experts were from the fields of ecology – 3, economics – 2, environmental engineering – 2, hydrology – 3, limnology – 2, local governance – 4 and sociology – 2. Local stakeholders were people living in core areas of the case study and included economic developers – 3, farmers – 5, fishers – 5, indigenous people – 5 and members of local non-government organizations – 2.

At the second stage, 20 experts with expertise in the ecological and socioeconomic systems of the case areas were surveyed. Half of the experts were participants in a National Project of China (973 project) and the other half were experts from the Dongting Lake Station for Wetland Ecosystem Research of the Chinese Academy of Sciences. All participating experts were very familiar with the case area analysed in this thesis about which they have strong and specific experience and interest.

#### Step 3: Specifying local changes

At the first stage, a joint participatory exercise of both experts and local stakeholders was used to specify changes faced by the case areas in responses to the perturbations from the Three Gorges Dam (TGD) identified as the specific driver of vicissitudes. The expert surveys included two parts: online surveys and semi-structured face-to-face interviews. First, the online surveys were conducted in October 2013 with the aim of identify the core subsystems and the corresponding multiple variables of the local SESs. The surveys used questionnaires and were conducted via email contact. Previous studies on the dissection of SESs (Ostrom 2009; Baurto et al. 2013; Ernst et al. 2013) formed the basis for the development of the questions. The following semi-structured face-to-face interviews with experts were conducted in December 2013 with the aim of obtaining an agreement about the core subsystems and variables as well as identifying which variables have changed since the operation of the TGD and to what extent those changes happened to the local SESs. The participating experts were firstly given feedback from the online surveys and were requested to comment on differences, confirm or validate answers until an agreement was achieved. Furthermore, local stakeholders together with experts were engaged through individual interviews to gather their opinion and knowledge of local environmental changes – what they have witnessed, current abilities to adapt, what the governments should do, etc. The participatory technique involving experts and local stakeholders at the first stage helped the development of indicators for the assessment of the SER of the case areas. By using a joint expert and local stakeholder approach, local changes could be classified into different groups according to the degree to which the given variables happened according to their observation, experience and knowledge.

### Step 4: Exploring SER

At the second stage, an expert consultancy was undertaken in December 2014 on the basis of questionnaires with the aim of identifying possible regimes of the SESs and defining ranges for scales (criteria) of different levels of resilience. Experts were used due to the difficulties in identifying thresholds for some variables of SESs, especially when there is no evidence on whether or not there is a threshold and alternative regime for the system. Thus, expert questionnaires not only helped to identify the criteria for SER but also filled the gap of data limitation by scoring those indicators where data was not available. The questionnaire comprised two parts with 24 questions and a scoring table. The first part included multiple choices and filling in blanks and aimed to obtain expert knowledge about

possible regimes of the SESs and thresholds. The second part included a table in which the experts were asked to assign a score to a range of indicators. The questionnaires for both stages are attached as appendices at the end of the thesis.

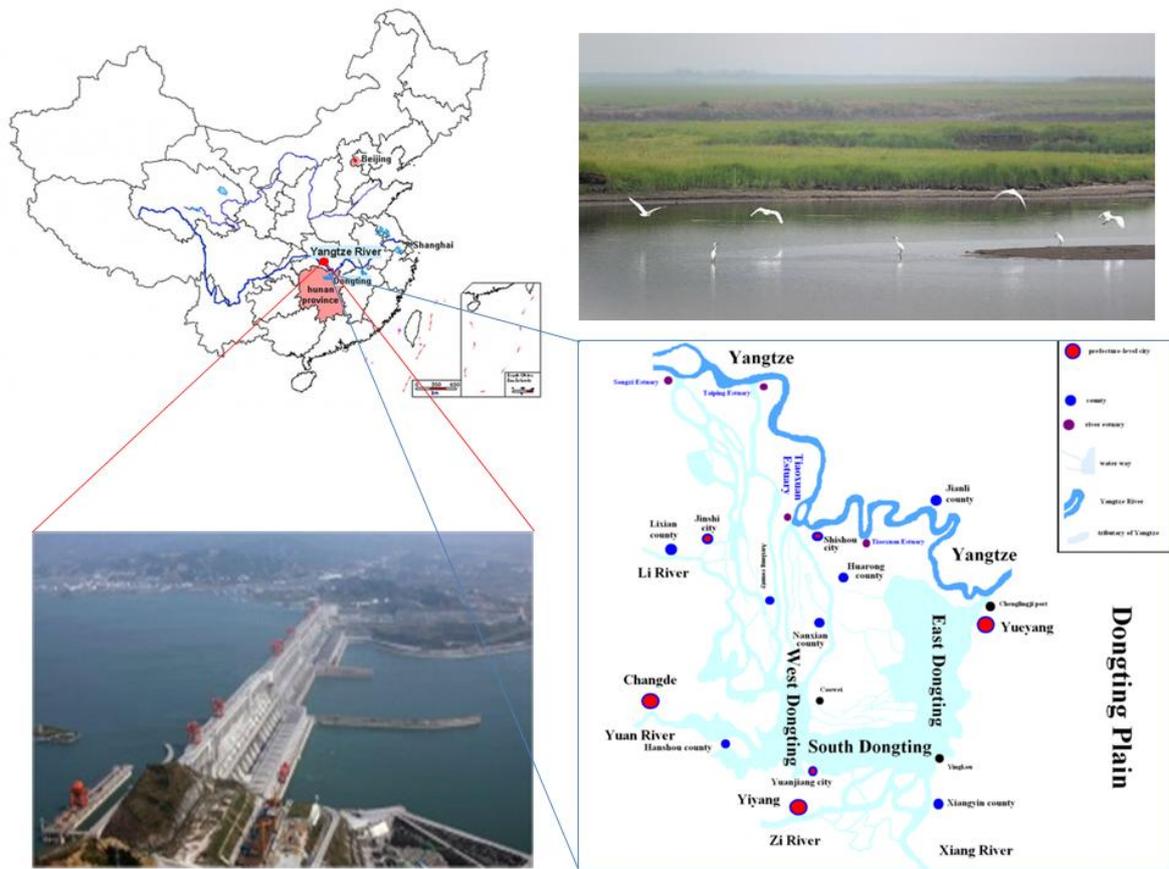
### 1.4.2.3. Case study

This thesis used Dongting Lake in China as the case to demonstrate how resilience can be incorporated into sustainability practice in the way of indicator-based assessment on SER. Dongting Lake is the second largest freshwater lake in China but is facing high perturbations from both climate change and human activities. In particular, recently increasing concerns about the disturbance to this lake caused by the TGD have placed it at the frontline of both academic and professional debates (Lai et al. 2013). As the focus of this study is SER, this specific resilience is emphasised in the thesis and the TGD was used as the main perturbation faced by the lake.

The TGD is the world's largest dam built in the upstream of Yangtze River (YR) and is located in Yichang city of China's Hubei Province. Its construction and operation started in 1994 and 2003, respectively. Since 2013, the dam generates more than 90 billion kWh (kilowatt-hours) of electricity each year (XinhuaNews 2015). Even though it has generated tremendous socioeconomic benefits (Liu et al. 2013a), the dam is now one of the world's most controversial engineering solutions because of its social and ecological impacts (Zhang et al. 2012).

Dongting Lake (Figure 1.8) is located in the north of Hunan Province and is connected with the YR in its middle and its area covers three prefecture-level cities – Yueyang, Yiyang, and Changde, four county-level cities – Miluo, Linxiang, Jinshi, and Yuanjiang, and eleven counties – Yueyang, Huarong, Xiangyin, Anxiang, Hanshou, Lixian, Linli, Taoyuan, Nanxian, Taojiang, and Wangcheng. The total population in the lake regions was 15.5 million in 2010 and accounts for 21% of Hunan Province (Li et al. 2014). It is the second largest freshwater lake in China with a drainage area of 262800 km<sup>2</sup> (Feng et al. 2013). It consists of three parts: East, South, and West Dongting lakes. East Dongting Lake (ED) which covers an area of 1328 km<sup>2</sup> is the biggest part of the lake followed by South Dongting Lake (SD) with an area of about 920 km<sup>2</sup>. West Dongting Lake (WD) is the smallest part with a coverage area of 443 km<sup>2</sup>. The water of the lake exchanges with the YR in its northern parts – the water of the lake comes from the YR through three inlets in the

northwest – Songzi, Taiping, and Ouchi, while it discharges to the YR through the Chenglingji outlet in the northeast of the lake. The lake is also fed by four joint rivers from the south – Xiang, Zi, Yuan, and Li rivers. The annual water inflows are about 312.6 billion m<sup>3</sup>, 38% of which comes from the YR. Thus, not only does the lake play a pivotal role in regulating water from the YR and providing habitat for numerous species, it is also one of the most important agricultural regions of China producing rice, cotton and fish. The regional cotton and fish production outputs in 1998 were 143.1 and 593.4 thousand tonnes accounting for 74.34% and 50.81% of the total outputs of the whole province (Li 2014, 3).



**Figure 1.8** Location of Dongting Lake and the Three Gorges Dam

However, due to the long-term unsustainable practices, the lake coverage has shrunk from 4700 km<sup>2</sup> in 1938 to 3082 km<sup>2</sup> in 2002 and to the current 2691.2 km<sup>2</sup> (Li 2014), even smaller in dry seasons when the water coverage is 500 km<sup>2</sup> (Lai et al. 2013). The impoundment of the TGD (upstream of the lake) worsened the hydrological conditions of the lake prolonging the duration of droughts in the lake regions and reducing resilience during dry seasons. The lake has been drying up since the TGD's impoundment (Feng et al. 2013). In October when the dam starts to store water, the flow of the YR is reduced causing

influx from the lake into the river. It is also reported (Chinanet 2011) that the TGD causes the lake's dry season to arrive earlier and span longer compared to the years prior to the operation of the dam. The altered river-lake interaction caused by the construction of the dam has increasingly drawn the attention of researchers (Liu et al. 2013b).

Taking into considerations data availability, economic development, sensitivity to the TGD and relative importance of the location, the spatial boundary of the system for the case study was identified as three geographically divided areas, i.e. ED, SD and WD with the surrounding counties and districts belonging to Yueyang City (ED), Yiyang City (SD), and Changde city (WD). They cover Junshan district of Yueyang City, Yueyang county, Miluo city, Xiangyin county, Yuanjiang city, Hanshou county, Anxiang county, and Nanxian county.

### **1.5. Discussion**

This thesis by publication is composed of seven articles, two of which are based on bibliometrics and the other five analyse how to apply resilience thinking into water sustainability practice. The PhD contains four peer reviewed journal articles and three book chapters. In this section, each published paper is firstly summarised. The research question, objectives and aims of this study are then revisited followed by a summary of the key research findings. In conclusion, five future directions are presented which emerged as continuation of the research in this thesis.

#### *1.5.1. Summary of the published papers*

Paper One, entitled "Resilience thinking: a bibliometric analysis of socio-ecological research", focuses on the development of resilience theory in the past decades. First, this paper compares the general trends in resilience publications in three main databases: Google Scholar, Web of Science and Scopus. It then moves to further investigate the 919 cited publications retrieved from Google Scholar. The analysis covers the following aspects: general statistics aimed at illustrating the development of resilience theory and its popularity growth in different disciplines as well as its role in fostering interdisciplinary studies; examination of journals, organisations and papers highlighting the important journals and papers and the leading organisations in resilience research; and the spatial distributions of the existing studies and global intensity of researchers showing research strength and weakness throughout the world.

Paper Two, entitled “Nano-biotechnology for water sustainability: bibliometric analysis”, conducts a bibliometric analysis for the cutting edge technological front in water sustainability. This investigation covers three critical directions of nano-biotechnology applied to enhance water sustainability, namely water supply, water treatment and water contamination. The bibliometric analysis is based on the data retrieved from Scopus because of its broader coverage of this studied area. Co-occurrence investigations, including co-word and co-authorship analyses, are used to detect the emerging technologies and scholarly networks in the area based on 4126 publications.

Paper Three, entitled “Resilience thinking: a renewed system approach for sustainability science”, is a literature review focusing on the interrelationships between resilience and sustainability. This paper firstly reveals the growingly popular of resilience research in environmental sciences and its potentials for sustainability science to address environmental changes and shocks. It then paper explores in more detail the relationships between resilience and sustainability, including their similarities and differences, contributions of resilience to sustainability as well as the measurement and management of resilience for sustainability.

Paper Four, entitled “What can we do better for sustainability in an uncertain future?”, aims to develop a general framework for the integration of resilience into sustainability. This paper starts with defining resilience for water sustainability and why and how resilience should be synthesised into water sustainability management. It then develops a procedure to achieve this, especially for assessment (with three main steps: systematic description, results analysis and decision-making) and post-assessment.

Paper Five, entitled “Resilience-based sustainability indicators for freshwater lakes with application for Dongting Lake, China”, conducts a case study for the integration of resilience as the source of thinking in sustainability assessment. The paper uses participatory approach to engage local stakeholders and experts to identify changes caused by the operation of the TGD. The SESs were dissected according to the framework suggested by Ostrom with expert consultancy used to develop a set of resilience indicators for the studied regions in the face of the changes.

As continuation of the work in Paper Five, Paper Six entitled “Resilience of social-ecological systems to human perturbation: assessing Dongting Lake in China”, carries out

an assessment on the SER of Dongting Lake to adapt to the perturbations of TGD. It uses the indicators developed in paper 5 and identifies different criteria for the SER of the region based on expert consultancy and scoring. The assessment is performed within an integral multi-criteria model.

Paper Seven, entitled “Managing social networks for community resilience from the perspective of bonding relationships”, treats social bonding relationships as critical capital for effective social connections to foster community resilience in the face of external disturbances. It starts with discussing how social networks are useful for community resilience. Four main components – social trust, leadership, social memory and social knowledge—that can affect the efficiency of social networks are then discussed. Finally it explains how social bonding can be used to enhance social networks at the local, regional and national scale.

#### *1.5.2. Addressing research question, objectives and aims*

The research question of this thesis was: “How should sustainability management for water resources adapt to the growing changes and uncertainties?”. Through the research in this thesis, the answer was found, namely: building up socio-ecological resilience (SER) is essential for enhancing the capacity of society to better adapt to changes and uncertainties related to and appearing in water systems.

The first two papers demonstrate the capacity of bibliometrics to capture renewed technological and theoretical studies in water sustainability science and how resilience thinking is dominating in the interdisciplinarity and sustainability studies. The other five papers make the argument why resilience should be, and how it can be, incorporated into water sustainability management in the face of environmental changes and uncertainties.

Revisiting the research objectives and aims, Table 1.1 below illustrates how they were addressed by the papers which form the essence of the PhD.

**Table 1.1** Links between research objectives, aims, and individual publications

<b>Research Objective</b>	<b>Research Aim</b>	<b>Publication</b>
<u><i>Objective One</i></u> Detect theoretical frontiers in sustainability	<u><i>Aim One</i></u> Investigate the role of resilience theory for	<u><i>Paper One (Journal article)</i></u> Resilience thinking: a bibliometric analysis of socio-ecological research

## Introduction

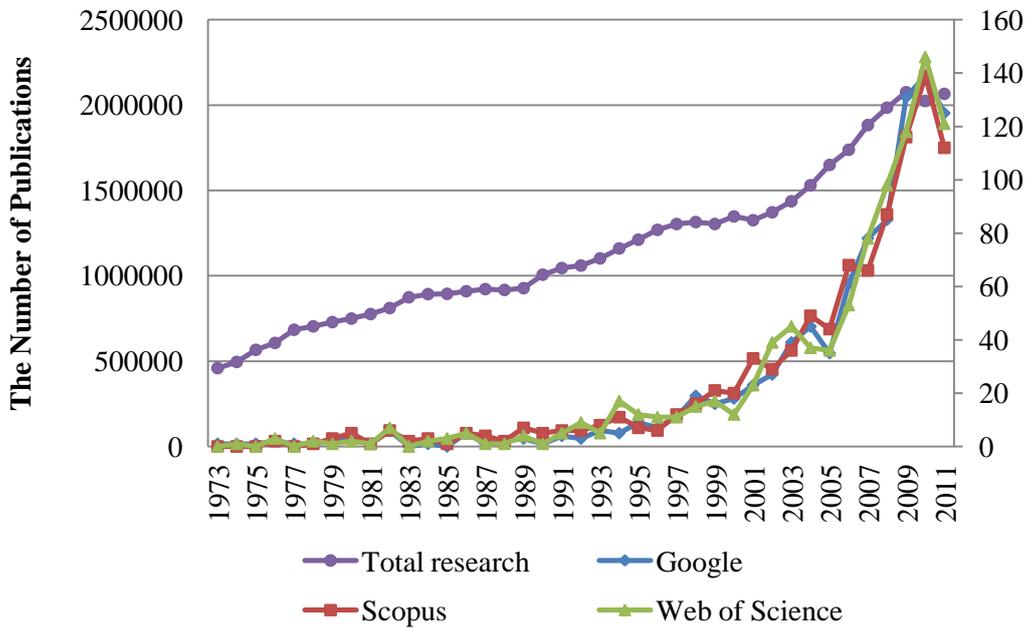
science and cutting-edge technological research in water sustainability	sustainability science and detect technological frontiers in water sustainability	<u><b>Paper Two (Book chapter)</b></u> Nano-biotechnology for water sustainability: bibliometric analysis
	<u><b>Aim Two</b></u> Explore the interrelationships between resilience and sustainability	<u><b>Paper Three (Journal article)</b></u> Resilience thinking: a renewed system approach for sustainability science
	<u><b>Aim Three</b></u> Analyse resilience thinking as a possible way of addressing sustainability challenges in freshwater systems	<u><b>Paper Four (Book chapter)</b></u> What can we do better for sustainability in the uncertain future?
<u><b>Objective Two</b></u> Integrate creatively knowledge into sustainability assessment of a freshwater lake in China as a practical case study and explore ways to enhance community resilience to adapt to changes	<u><b>Aim Four</b></u> Apply resilience assessment to a freshwater lake in China and explore ways to enhance community resilience in adapting to the changing environment	<u><b>Paper Five (Journal article)</b></u> Resilience-based sustainability indicators for freshwater lakes with application for Dongting Lake, China <u><b>Paper Six (Journal article)</b></u> Resilience of social-ecological systems to human perturbation: Assessing Dongting Lake in China <u><b>Paper Seven (Book chapter)</b></u> Managing social networks for community resilience from the perspective of bonding relationships

### 1.5.3. Key research findings

In general, bibliometrics is a reliable way to catch the evolutionary pathways of science and allows capturing up-to-date technological and theoretical developments. On the other hand, resilience is a very-well suited way to address changes and uncertainties in sustainability science.

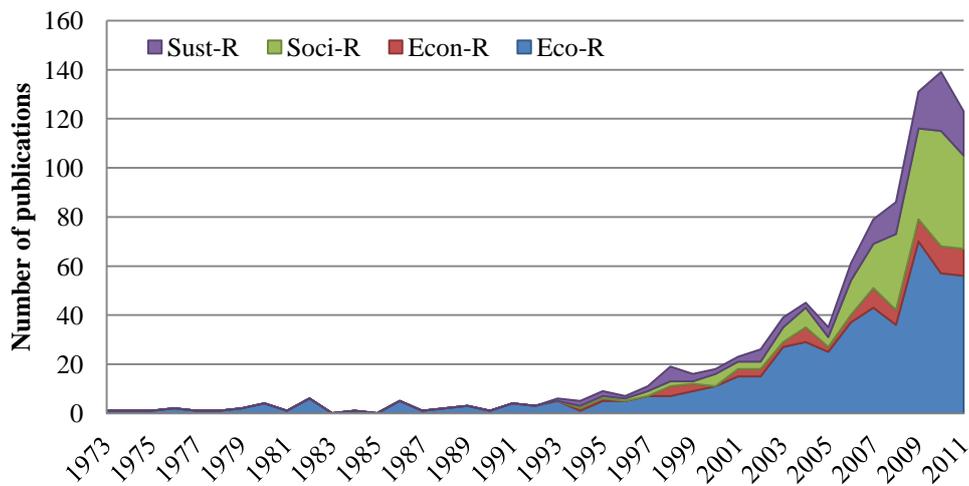
*Paper One* analysed the trends of resilience research in different environment-related contexts, i.e. resilience thinking in ecological, economic, social, and integrated socioecological systems. This bibliometric study found that the research in resilience thinking has experienced a dramatic increase in areas of environmental sciences since its introduction in 1973 and significantly sped up since 1999 (Figure 1.9). Further analysis in this paper also showed that the research in resilience thinking has shifted from emphasis on ecological systems to social and SESs as well as sustainability (Figure 1.10). Although the majority of research focuses on ecological systems, social resilience has also grown significantly while resilience regarding economic systems is still in the explorative stage.

The number of cited publications that apply an integrated sustainability approach has grown but it is still a very low share of all resilience output.



**Figure 1.9** Annual numbers of cited research publications in Web of Science and resilience publications in Scopus, Google Scholar and Web of Science, 1973–2011

This paper claims that the incorporation of resilience thinking into sustainability contexts should be the main research direction in the coming decades for addressing the growing environmental changes and uncertain shocks. This is especially significant for those countries where environmental issues are serious and where resilience research attracts very little attention, such as China.





such as USA and broader scopes of the applied nano-biotechnologies in water supply and treatment would be beneficial for better solutions of global water challenges in the future.

*Paper Three* investigated the relationships between resilience thinking and sustainability. The paper found that resilience thinking is becoming an important theory in sustainability science and it can be an optimal way to address changing environmental conditions and unanticipated environmental disturbances. First of all, resilience and sustainability share several similarities including objective, dependency relationship and starting point, but they also have differences such as in intergeneration equity emphasis, desirable state description, culture emphasis, and methodological approach. Thus, resilience cannot be used to totally replace sustainability as the final objective.

Secondly, resilience thinking has important contributions to sustainability from various aspects such as its specific views on coping with changes and uncertainties and its wide successful applications. Thirdly, measuring resilience for sustainability still remains a challenge as the difficulties in identifying thresholds of variables in the systems and the complexity of SESs. The main task is to identify the critical variables of different systems and generalise the dynamics of SESs by making use of different techniques such as surrogates indicators, scenario analysis, and modelling and simulation. Fourthly, the management of resilience for sustainability should pay more attention to engaging different stakeholders into practice and enhancing local understanding of the dynamics of SESs.

On the basis of the findings of the latter paper, *Paper Four* presented an overview of why and how resilience should be incorporated into sustainability practices for freshwater resources. The paper firstly defined resilience for water resources sustainability as: “The ability of water resources system, within the capacity to withstand and live with uncertainty and disturbance without shifting into an undesirable state by maintaining its ability of renewal, reorganization, learning, and adaptation, to provide sufficient quantities and good quality of water to meet the needs of humans and ecosystems for both current generation and next generations”.

One of the important ways to incorporate resilience into sustainability was argued in this paper is to assess resilience for sustainability. Following this logic, three general steps were proposed for the incorporation of resilience to water sustainability management and

practice, namely systematic description, results analysis and decision-making, and post-assessment.

*Paper Five* developed a framework for incorporating resilience into sustainability indicators by using freshwater lakes as the case. There are three key findings from this paper. First, the developed framework can help anticipate and understand the changing world. It described the process of resilience analysis and indicator identification by defining systems and external perturbations, depicting the systems' status and identifying indicators. In addition, this framework highlighted the importance of putting resilience thinking into sustainability policies and practices through identifying systems' boundaries, perturbations, systems' changes and feedbacks.

In addition, experts and local stakeholder interviews were used 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.

Thirdly, 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.

Building on the latter paper, *Paper Six* conducted an assessment on SER of Dongting Lake by specifying the TGD as the main perturbation. In other words, the assessment of resilience of this case study was specific resilience given the data and time limitation. The assessment found that ED has the highest resilience with most abilities to absorb the perturbations that TGD has brought or might exert to its social-ecological system. However, the policy responses are simple while more diverse strategies are needed to specify the perturbations of TGD such as strategies towards improving the power of social groups. The SER in SD and WD are at a relatively low level. More strategies are not only needed to enhance the systems' absorption abilities (including improvements on productions technologies, education and professional trainings for local people, and public participation

in policy makings), but also to diversify policy responses, such as supports available for local social groups and NGOs and plans for protecting the food chains of the lake.

*Paper Seven* focused on how to effectively manage social networks for the enhancement of SER. This paper argues that self-organising is a critical capacity for communities to live through the changes and shocks. Such self-organising must rely on good learning mechanisms and smooth information flows about the SESs, within which the systems are able to take advantage of the change as a chance to transform their state to a more desirable one. In the paper, it was claimed that using social networks as a capital therefore can enhance community resilience and help SESs to adapt to future changes and uncertainties.

Social trust and leadership of networks are advantageous for improving the systems' self-organisation by maintaining the information flows and affecting collaboration within the whole network. By focusing on these two aspects, this paper discussed how to use bonding relationships to analyse social networks at different levels. It is found that the information flows in local social networks should be organised by leadership networks which consist of leaders from each family. Managers have responsibilities to facilitate the work of leadership networks and their efficiency in relation to sharing power, funding and technological supports. Regional bonds are most important properties for social networks at regional and national levels. Such bridges comprising the core people of leadership networks from each community (area) can be the main sources to bridge the linkages at the regional level. The emphasis of enhancing social networks at the national level should be on dealing with duplications and overlapping of authority and policy inconsistencies. The recommended way is to share management power and responsibilities between communities, government agencies and non-governmental organisations.

#### *1.5.4. Recommendation for future research*

This thesis focussed on: (1) how to use bibliometrics to identify research and technological fronts in sustainability and water resources issues with the special attention on resilience thinking; and (2) how to apply resilience into sustainability practice by analysing coupled SESs. Although the presented publications representing the essence of this thesis have made a significant effort to address water resources sustainability issues in the face of growing environmental changes and uncertainties, the work is just starting and further research is most needed. For instance, the case study of this thesis developed a framework

to select resilience indicators for sustainability and was applied to Dongting Lake in China. However, the key perspective of the case study was a specific resilience of SESs of freshwater lakes, namely the SER of the lake to the specific perturbation of the big dam operation. The general resilience of SESs in freshwater lakes regions is also important to be addressed, including the SER to impacts of other external factors such as climate change, land use changes and pollution. Accordingly, a range of further questions is suggested for any future work on the basis of this thesis.

### *Future question one:*

What are the interrelationships between different domains of resilience research?

*Paper One* in this thesis shows the increasing trends in resilience thinking in social and sustainability contexts. However, the paper did not show whether there are any interrelationships between resilience in these contexts. In *Paper Three*, resilience was classified into seven groups according to their different definitions and emphases, namely psychological resilience, resilience engineering, engineering resilience, ecological resilience, social resilience, economic resilience, and social-ecological resilience. Future bibliometric analysis on citation networks within and across academic domains in these groups would help to specify whether there are any and what relationships between them and to find out how and what subtopics are dominating these areas as well as whether there are common principles that are applicable across fields.

### *Future question two*

What is the technological development for water resources sustainability?

In *Paper Two* of this thesis, nanotechnology and biotechnology are used as examples to present research on water resources sustainability issues. However, these are only two groups of technologies that are being used to address water sustainability. There could be other ways to deal with this issue. As many existing bibliometric studies focus on scientific fields such as the research conducted by Ho (2008), Wang et al. (2011), and Fu et al. (2013), a different way that uses bibliometrics on technological patents may be able to better show a development overview and inform about innovative theories and technologies in the area.

### *Future question three*

What could be the early warning signals for possible transitions of SESs?

Indicator-based measures for resilience are effective ways to put resilience into sustainable practices. However, existing resilience indicators are still dearth of early warning signals for regime shifts or critical transitions of SESs (Dakos et al. 2015). *Paper Five* of the thesis attempted to incorporate resilience into sustainability indicators. The paper treated uncertain changes of SESs in the way of using early warning signals such as using changes in the spatial pattern to indicate non-homogeneous distribution of units of the system. Those signals are able to show whether or not the changes could have happened but cannot indicate whether they are critical for the regime shifts of the system. Critical variables of SESs that underplay or control the different states of the systems have to be identified. To achieve this, more empirical studies are needed for different systems and general research on the dynamics of SESs in different kinds of systems would be helpful.

### *Future question four*

How to develop a general framework for the SER assessment of water systems?

*Paper Six* conducted a SER assessment for a Chinese freshwater lake (Dongting). Yet, the focus of this paper was from a specific resilience point of view, general resilience is also important for dealing with common disturbances to water systems such as climate warming, land use patterns, and contaminations and shocks such as floods and draughts. These common issues pose the question about how to develop a general framework that can be used to assess the SER for water sustainability. To this end, the suggested ways could be generalisation of the SESs dynamics in the face of different types of disturbances for one thing, and using topology approach to group various components of systems and the critical ones in responding to different disturbances for another. An example is to find out the ways in which ecological variations exert impacts on social systems and what feedback mechanisms social systems have in response to different ecological conditions.

### *Future question five*

Can and in what way social bonds facilitate social networks influence societal resilience for water systems and how better use social networks in water sustainability governance?

In *Paper Seven*, social bonds are recommended as the key social capital for building strong social networks in order to enhance community resilience in adapting to the changing environment. However, the discussion in the paper was not specifically focussed on water systems as more data and longer time observation are required. The paper put forward a general framework about using social bonding relationships as the core capital to establish

effective social networks in terms of information sharing and social learning. As stated in the paper, more empirical studies together with computer-based simulation and long-term observations are needed to improve the functions of this social capital for any specific systems. Future work in the area of water sustainability governance can focus on using and applying this framework to different water-based SESs, such as rivers and their catchments, lake areas, and coastal communities.

To sum up, this thesis uses bibliometric analysis and applies resilience thinking as a renewed systematic approach for water sustainability science to address a key question about how sustainability management for water resources should adapt to the growing changes and uncertainties. There is a lot more work to be done to fully address the challenges related to the sustainability of water resources. A sustainable future not only relies on efforts from academia but also on wider large-scale collective actions. What this thesis has been able to show is that the achievement of sustainable water (or in fact, any other natural) resources will depend on technological progress, innovation and theoretical advancement which are flexible and adaptable to the changing environment and unpredictable disturbances.

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Published papers

## **PUBLISHED PAPERS**

**PAPER 1: RESILIENCE THINKING: A BIBLIOMETRIC ANALYSIS  
OF SOCIO-ECOLOGICAL RESEARCH**

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**Statement of Contributions of Authorship**

To whom it may concern,

I, Li Xu, contributed 70% to the paper entitled above and cited as below:

Xu, Li, and Dora Marinova. 2013. "Resilience thinking: a bibliometric analysis of socio-ecological research." *Scientometrics* 9(3): 911-927. Doi: 10.1007/s11192-013-0957-0.

Signature of Candidate:



Date: 30 October 2015

I, as a co-author, endorse that this level of contribution by the candidate indicate above is appropriate.

Dora Marinova Signature:



Date: 2 November 2015

**This Chapter is an exact copy of the journal paper referred to above**

Published as:

Xu, Li, and Dora Marinova. 2013. "Resilience thinking: a bibliometric analysis of socio-ecological research." *Scientometrics* 9(3): 911-927. Doi: 10.1007/s11192-013-0957-0.

### **Resilience thinking: a bibliometric analysis of socio-ecological research**

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#### **Introduction**

The concept of resilience was firstly introduced by Holling in 1973 in an ecological context. He defined resilience as: "A measure of the persistence of systems and of their ability to absorb change and disturbance and still maintain the same relationships between populations or state variables...and it is concerned with persistence or probabilities of extinction" (Holling, 1973, p. 14). In recent decades, resilience thinking has been increasingly permeating sustainability debates in the context of social-ecological systems and the impact human activities have on the planet's physical environment. According to the Resilience Alliance, an interdisciplinary network of scientists and practitioners established in 1999, resilience in social-ecological systems has three defining characteristics: "the amount of change the system can undergo and still retain the same controls on function and structure, the degree to which the system is capable of self-organisation, and the ability to build and increase the capacity for learning and adaptation" (Resilience Alliance, 2002, n.p.). Resilience has also been identified as one of the most influential concepts in sustainability research (Quental and Lourenço, 2012).

The prevailing perspectives on sustainability and natural resources management focus on how to achieve stability, manage effectively and control change and economic growth (Adger et al., 2005; Folke, 2003 and 2006). However, this is not enough in a constantly changing globe and further research needs to allow for multidisciplinary (McMichael et al., 2003), interdisciplinarity (Bjurström and Polk, 2011) and transdisciplinarity (Marinova and McGrath, 2005; Buns and Weaver, 2008) in order to better understand any occurring transformations. Jappe (2006) describes this as mutual task dependence of all scientific fields. Resilience as a new concept and way to look at the world was introduced in order to analyse how complex systems are adapting to climate change and human disturbance. Many argue that resilience thinking for social-ecological systems will be the optimal way to enhance the likelihood of sustainability in the uncertain future (Walker et al., 2004; Adger et al., 2005; Folke, 2006).

The main purpose of this study is to identify trends in resilience research using a bibliometric analysis. In particular, we identify the prevailing patterns of influence resilience research has in different contexts and the geographical distribution of this research output. The paper consists of four sections as follows. Section 2 describes the bibliometric analysis (procedures) used in the study, including data source, applied keywords, types of publications and limitations to data collection. Statistical analysis, ranking and distribution mapping of the resilience research outcomes are presented in section 3. The last section contains concluding remarks about the outcomes from this analysis.

#### **Methodology and data**

The study is based entirely on bibliographic desk-based research conducted in July-August 2012. It uses data sources available to almost all academic institutions in western countries. As the aim is to analyse the impact

Published as:

Xu, Li, and Dora Marinova. 2013. "Resilience thinking: a bibliometric analysis of socio-ecological research." *Scientometrics* 9(3): 911-927. Doi: 10.1007/s11192-013-0957-0.

and importance of resilience research, we opted to investigate only publications that have been cited (instead of providing a general description of all resilience publications irrespective as to how valuable they have been to other researchers). The main imperative that triggered this choice are the concerns of the scientific community associated with climate change and the need to see fast considerable real changes in order to address the deteriorating state of the planet. Despite the many questions and valid points raised around the use of citation analysis (MacRoberts and MacRoberts, 1996), the fact remains that cited research is a valid indicator for the influence of any work, at least on other researchers (Cole and Cole, 1972). Small's (2004) study identifies interest, novelty, utility and significance – all linked to research importance, as interrelated reasons stated by academic authors for their research to be cited.

Analysing only numbers of cited publications, rather than the actual number of cites they have attracted on the other hand, helps deal with problems associated with citation counts, such as biased over-citing, citing of a well-recognised body of literature, socio-psychologically motivated reasons to increase cites, different citation rates across disciplines as well as institutional and self-citations. More information about the methodology of the study is presented below.

#### *Data sources*

The data in this study was retrieved from three widely used databases, namely:

- (1) Google Scholar – a freely available web-based tool in operation since 2006 that allows search for scholarly literature across disciplines and sources, including theses, books, papers and abstracts (Google Scholar, 2012, n.p.);
- (2) Web of Science – an academic citation indexing and search service of Thompson Reuters' Web of Knowledge (formerly operated by the Institute for Scientific Information, ISI) launched in 2002 which claims to be "today's premier research platform for information in the sciences, social sciences, arts, and humanities" (Thompson Reuters, 2012, n.p.) and covers journals, conference papers, websites, patents and chemical structures; and
- (3) Scopus – launched by SciVerse in 2004 to facilitate library searches around the world with an easy access to "the world's largest abstract and citation database of peer-reviewed literature" (Elsevier, 2012, n.p.) covering journals, trade publications, book series and conference papers.

The period of examination spans from 1973 to 2011, i.e. from the year when resilience was first introduced to the most recent year. The data from these different databases is analysed but also compared between the three sources with the aim to identify the general trends in resilience research. According to Aguillo (2012), Google Scholar provides the largest coverage of sources. Its free-of-charge availability also makes it accessible to all researchers, including outside the western academic system. These are the reasons why we opted to use Google Scholar to further analyse the geographical spatial distribution of research outputs related to resilience.

#### *Keywords used*

In order to identify resilience related publications, we applied keyword searches within the titles, keywords and abstracts of the various research outputs. The keywords used to search for such publications are mainly associated with the word "resilience" and also include the following combinations "ecological resilience", "economic resilience", "social resilience", "resilience & sustainability", "resilience & sustainable development",

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"resilience & social-ecological systems", "social-ecological resilience", "resilience & environment", "resilience & natural resources" and "resilience & assessment". The targeted coverage was intended to provide insights not only about ecological resilience but also how the concept relates to sustainability and the integration of its social, economic and environmental tenants.

#### *References selected*

The publications selected in our study are those cited journal articles, books, conference papers, working papers, comments, theses and reports that list the word "resilience" in the title or as their keyword. In addition, if "resilience" does not appear in any of the above, we included the publication in the dataset only if "resilience" appears at least three times in the abstract. In other words, we have applied a very strict and generally limiting way of categorising a publication's belonging to our sample in order to accurately reflect the penetration of resilience thinking in academic research. A less restrictive approach would probably have expanded the size of the sample but would have raised questions as to how reliable any claims are.

#### *Limitation of the data selection*

It should be acknowledged that some limitations exist in the dataset used for this analysis. The publications counted in the study include only those containing "resilience" either in their title, keywords or abstract whilst publications based on possible synonyms, such as stability, adaptability, resistance, reliability and robustness, or antonyms, such as vulnerability, susceptibility and defencelessness, are excluded. Also, the selected publications include only documents in English which have been cited by other publications in English, and non-English publications were not considered.

Thus the publications counted in this paper do not include all publications in resilience research. The existing publications and research outcomes no doubt overweigh what we could find and access in this study. There are certainly other scholarly papers that are making their contribution to this area, particularly in languages such as Chinese, German, Spanish and French and this study is not trying to undermine the work done by these researchers. Any limitations should be seen as a deficiency in the current web-based data search engines rather than a deliberative decision by the authors. It will be interesting to compare the results from this study with any further work as the capacity of search tools expands.

## **Results and discussion**

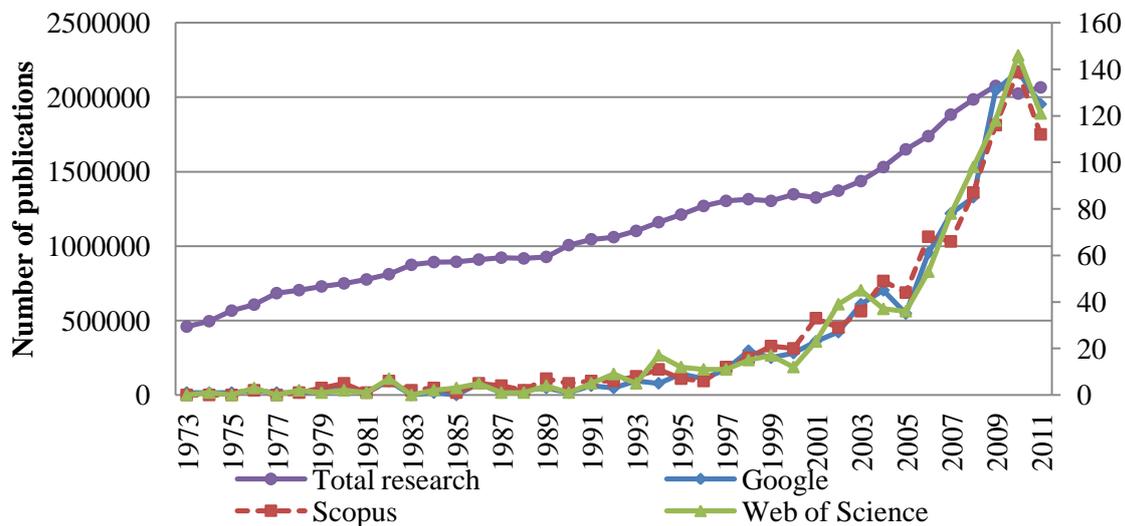
The analysis in this section is organised around five research directions. The first one is general statistics which describe the total number of cited publications on resilience and the particular context that has been the focus of this resilience research. In addition, we compare the data obtained from Google Scholar, Scopus and the Web of Science to illustrate the total trend in resilience thinking. Journal output and paper citation analyses of resilience publications represent the second research direction. The third direction engages with the spatial geographical distribution of the studies and particular case studies represented in the cited resilience publications. This is followed by an analysis of the national affiliations of the publications' authors and how different countries around the world are represented in resilience research. The last aspect shows the leading research institutes in the top 15 productive countries in the area of resilience.

#### *General statistics*

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Resilience thinking has come a long way since its 1973 inception with the number of publications steadily on the increase. The annual numbers of cited publications for the 1973–2011 period are shown on Figure 1. In total 919, 939 and 942 cited publications were found through the respective databases of Google Scholar, Scopus and Web of Science. It is interesting to observe that contrary to popular believes and earlier studies (e.g. Yang and Meho, 2006), the largest amount of resilience publications are captured by the Web of Science which is the most academically oriented database. In other words, there are many highly specialised scholarly publications that target the scientific community and are not necessarily captured by the more popular Google Scholar and Scopus search engines. On the other hand, the discrepancy between the three databases is relatively low, at around 2%. Most importantly, the overall trend and fluctuations appear to be very similar, irrespective as to which database is used. Hence, resilience research is very well represented by any of the three databases which does not seem to be the case in other research areas, such as for example medicine Falagas et al. (2007) or social sciences (Harzing, 2012).



**Fig. 1** Annual numbers of cited research publications in Web of Science and resilience publications in Scopus, Google Scholar and Web of Science, 1973–2011

In addition to resilience publications (right vertical axis), Figure 1 also shows the total number of cited publications for all research fields (left vertical axis) for the 1973–2011 period. Against the overall consistently increasing trend in total research outputs, resilience publications show a significant surge in relatively recent years. This indicates that resilience is becoming a robust research field.

The number of cited resilience publications reached a peak in 2010; however they seem to constantly fluctuate around a strong upwards trend and 2011 may just be one of these fluctuations, rather than a significant drop. Between 1973 and 1999, there was a stable increase in resilience publications, but this was followed by a very strong increase between 1999 and 2005 and an even further sharp increase since 2005. The study by Janssen et al. (2006, p. 10) already provided reliable evidence that the area of resilience has experienced “a major and still continuing increase in the number of published papers” (Janssen et al., 2006: 10). It is also encouraging to see the increasing trends in the uptake of these research findings as expressed in citations. The

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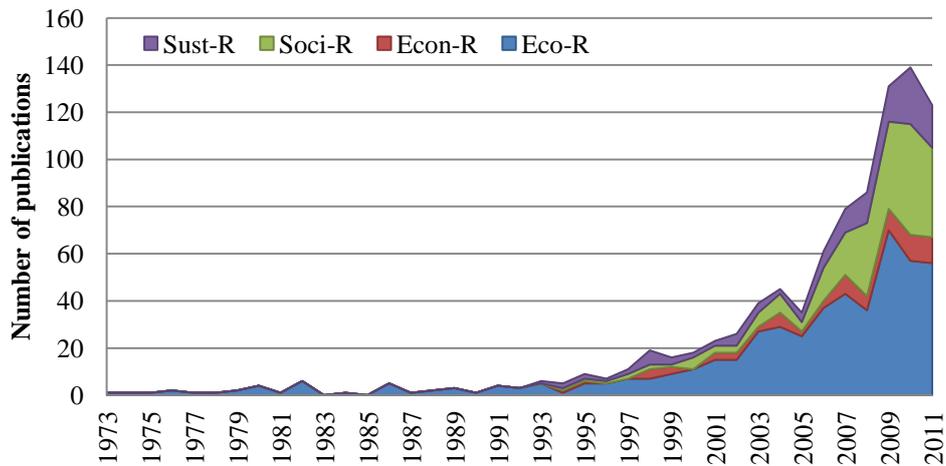
dramatic increase since 1999 in the number of cited publications has partly benefitted from the establishment of the outstanding global Resilience Alliance network with its academic journal *Ecology and Society* (Janssen et al., 2006) as well as from the increased interest in global environmental changes during 1990s. Activities on the global political arena since 2005, such as the release of the Millennium Ecosystem Assessment Reports in 2005, the Stern Review in 2006, the Intergovernmental Panel on Climate Change (IPCC)'s 4th Assessment Report in 2007, as well as the continuing regular international climate change meetings and negotiations, all stimulated researcher interest in resilience.

Figure 2 breaks down the Google Scholar data to provide a more detailed overview of the specific areas of interest of resilience research as it relates to ecological (Eco-R), economic (Econ-R) and social systems (Soci-R) as well as to an integrated sustainability (Sust-R) approach. This original categorisation was done arbitrarily based on the research topics of the papers. Although we are not aware of any other similar classification, almost all resilience publications explicitly state their area of interest which varies vastly from conceptualisation to more narrowly oriented ecological, economic or social analysis. For instance, studies which are focused on conceptual development, such as "Resilience, adaptability and transformability in social-ecological systems" (Walker et al., 2003) and on ecological systems such as "Regime shifts and ecosystem services in Swedish coastal soft bottom habitats: when resilience is undesirable" (Troell et al., 2005) were classified as Eco-R; studies which stated economic perspectives, such as "Resilience in the dynamics of economy-environment systems" (Perrings, 1998), or which concentrate on economic resilience, such as "Economic resilience to natural and man-made disasters: multidisciplinary origins and contextual dimensions" (Rose, 2007) were categorised as Econ-R; research which mainly discusses resilience from social perspectives, such as "Social and ecological resilience: are they related?" (Adger, 2000), was categorised as Soci-R; while those studies which discuss resilience in terms of sustainability, such as "Resilience and sustainable development: building adaptive capacity in a world of transformations" (Folke et al., 2002), or in the context of integrated social, economic and ecological systems, such as "Incorporating resilience in the assessment of inclusive wealth: an example from South East Australia" (Walker et al., 2010) were classified as Sust-R.

The total number of 919 cited publications includes journal articles (661 or 71.9%), books (63 or 6.9%), conference papers (61 or 6.6%), working papers (54 or 5.9%), book chapters (41 or 4.5%), reports (23 or 2.5%), theses (9 or 1.0%), and short comments (7 or 0.8%).

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**Fig. 2** Comparison of resilience research in different contexts

Note: Sust-R – resilience thinking in the context of sustainability; Soci-R – resilience thinking for social systems; Econ-R – resilience thinking for economic systems; Eco-R – resilience thinking for ecological systems

The number of studies embracing resilience thinking in relation to ecological, economic and social resilience as well as in the context of integrated sustainability has been steadily growing since its emergence with a clear further increase since 1995. The majority of cited publications focus on ecological systems while social resilience has also grown significantly while resilience in relation to economic systems is still in the explorative stage. This situation largely differs from the area of sustainability research where economics (mainly through ecological economics) has been largely overrepresented (Quental and Lourenço, 2012). The number of cited publications that explore an integrated sustainability approach has also grown but it is still a very low share of all resilience output. With human induced climate change and other environmental problems, it is important to have the right perspective on any resilience research but we are yet to see more prominence of the integrated sustainability resilience research.

Resilience thinking for economic systems is a very important case and there needs to be a strong warning that such research can only be beneficial if it is based on interdisciplinarity. As the main external factor affecting the health of the planet's ecosystems, acceleration of human activities across the globe makes it difficult to continue to separate any ecological, social and economic impacts and "try to explain them independently, even for analytical purposes" (Folke et al., 2010, n.p.). Another warning is that while in isolation, socially and ecologically resilient systems have a very high probability to also be sustainable, a solely economically resilient system can be extremely detrimental to sustainability. In other words, we can learn how to efficiently and effectively destroy the environmental and social foundations of human life. Assessing and evaluating sustainability in the context of complex systems in a transforming world requires a shift in thinking and perspective (Ludwig et al., 2001) and resilience thinking seems to have started to deliver some changes but there is still a long way ahead.

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This part answers questions, such as: which journal is the most popular in the realm of resilience research, which articles are highly cited on the topic of resilience thinking, who has produced those articles and where have they been published. Hence the analysis here examines only the 661 cited journal articles according to Google Scholar. They have been published in 269 academic journals and Table 1 lists the top 10 journals in which they have appeared. The top journal with 85 cited papers in the area of resilience thinking is *Ecology and Society* (which replaced *Conservation Ecology* in 2004). This journal published by the Resilience Alliance is relatively new but has proven a strong outlet for resilience research. With a very significant drop in the number of articles cited, this is followed by *Global Environmental Change* (16 articles) and *Ecosystems* (15 articles).

**Table 1** Top 10 journals with the largest number of articles (1973-2011)

Rank	Journal	Year of first publication	No. of articles
1	Ecology and Society (formerly Conservation Ecology)	2000	85
2	Global Environmental Change	1990	16
3	Ecosystems	1998	15
4	Ambio	1972	13
5	Ecological Economics	1989	12
	Ecology	1920	
6	Environmental Education Research	1995	11
	Water Resources Research	1965	
7	Environment and Development Economics	1996	10
	Natural Hazards	1988	
8	Environmental Hazards	2007	9
	Climatic Change	1977	
9	Coral Reefs	1984	8
	Ecological Applications	1991	
	American Naturalist	1972	
	Ecological Modelling	1978	
10	Ecological Monographs	1972	7
	Ecology Letters	1998	
	Human Ecology	1972	

We further looked at the actual number of Google Scholar citations that each cited resilience article has attracted. Table 2 presents the top 10 journal articles with the most citations and their authors, citation times, year of publishing, title of the journals and the context of the papers. It is not surprising that the top cited article is the original 1973 paper by Holling which for the first time introduced resilience thinking to ecological systems. The most prominent contributor in the area is Folke who comes from Sweden and is the author or co-author of the six of the top 10 cited journal articles. Similarly, Holling (Canada), Carpenter (USA) and Walker (Australia) have also achieved excellent recognition with their names appearing as authors or co-authors of five of the top 10 papers. This indicates that resilience thinking has produced a list of very noticeable and influential researchers and thinkers who have contributed to the shaping of ideas and research directions in this field. Furthermore, seven of the top ten cited articles are in the area of ecological systems with a strong interest in theory development. The economic context is represented with one article and so are the social and integrated sustainability approaches. Overall, it appears that since its inception the focus on the ecology continues to

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dominate resilience research. This has enabled it to produce a strong body of environmental findings but this knowledge still needs to be integrated with the socio-economic aspects of human presence on Earth.

**Table 2** Top 10 articles with the most citations and the authors, year, journals and the context (1973-2011)

Rank	Title	Year	Author (s)	No. of citations	Journal	Context
1	Resilience and Stability of Ecological Systems	1973	Holling, C. S.	4216	Annual Review of Ecology and Systematics	T-E
2	Catastrophic shifts in ecosystems	2001	Scheffer, M., Carpenter, S., Foley, J.A., Folke, C. and Walker, B.	2348	Nature	T-E
3	Economic growth, carrying capacity, and the environment	1995	Arrow, K., Bolin, B., Costanza, R., Dasgupta, P., Folke, C., Holling, C. S., Jansson, B., Levin, S., Maler, K., Perrings, C. and Pimentel, D.	1538	Science	ECO
4	Climate change, human impacts, and the resilience of coral reefs	2003	Hughes, T. P., Baird, A. H., Bellwood, D. R., Card, M., Connolly, S. R., Folke, C., Grosberg, R., Hoegh-Guldberg, O., Jackson, J., Kleypas, J., Lough, J. M., Marshall, P., Nystrom, M., Palumbi, S. R., Pandolfi, J. M., Rosen, B. and Roughgarden, J.	1437	Science	T-E
5	Resilience, adaptability and transformability in social-ecological systems	2004	Walker, B., Holling, C. S., Carpenter, S. and Kinzig, A.	975	Ecology and Society	T-E
6	Resilience and sustainable development: building adaptive capacity in a world of transformations	2002	Folke, C., Carpenter, S., Elmqvist, T., Gunderson, L., Holling, C. S. and Walker, B.	940	Ambio	I-S
7	Regime shifts, resilience, and biodiversity in ecosystem management	2004	Folke, C., Carpenter, S., Walker, B., Scheffer, M., Elmqvist, T., Gunderson, L. and Holling, C. S.	902	Annual Review of Ecology Evolution and Systematics	T-E
8	Resilience: the emergence of a perspective for social-ecological systems analyses	2006	Folke, C.	888	Global Environmental Change	T-E
9	Social and ecological resilience: are they related?	2000	Adger, W. N.	856	Progress in Human Geography	SOC

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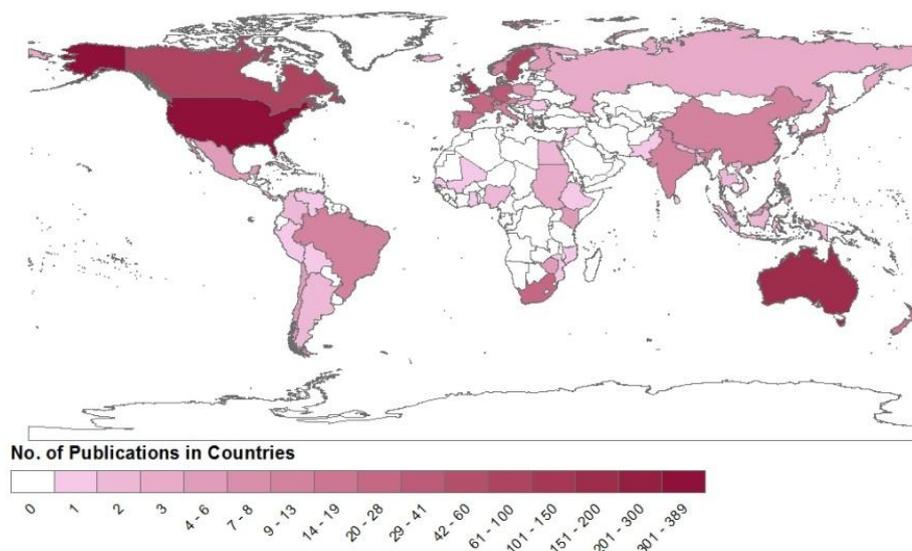
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10	From Metaphor to Measurement: Resilience of What to What?	2001	Carpenter, S., Walker, B., Anderies, J. M. and Abel, N.	834	Ecosystems	T-E
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Note: T-E, ECO, SOC and I-S represent respectively that the research was conducted in the context of ecological systems or focused on theoretical studies, economic systems, social systems, and integrated ecological, social and economic systems or sustainability in terms of resilience.

### *Spatial distribution*

In this part, we explore the geographical distribution of the 919 cited Google Scholar publications on the topic of resilience to analyse how much output has been generated in different countries, and which areas throughout the world have been used as case studies. Country performance in resilience research is represented through a mapping approach where the authors' affiliations in the publications were used as the criterion to locate the place of their origin. Publications were counted more than once if they had authors from more than one country. For instance, a paper with authors from USA and UK is counted twice – once for each country irrespective as to how many authors are from USA and UK as the main interest is to highlight the geographic spread of resilience thinking throughout the world (see Fig. 3). The most productive country in this respect is USA with 389 cited publications followed by Australia, UK, Sweden and Canada with 162, 135, 95 and 91 publications, respectively. Very few and even no authors come from Central Asia, the Middle East, North and Middle-West Africa. The spatial geographic distribution indicates the dominance of western researchers. Despite the evidence of China's growing contribution to the global scholarly knowledge (Veugelers, 2010), resilience thinking is yet to make its mark in influencing Chinese researchers as far as their publications in English are concerned.

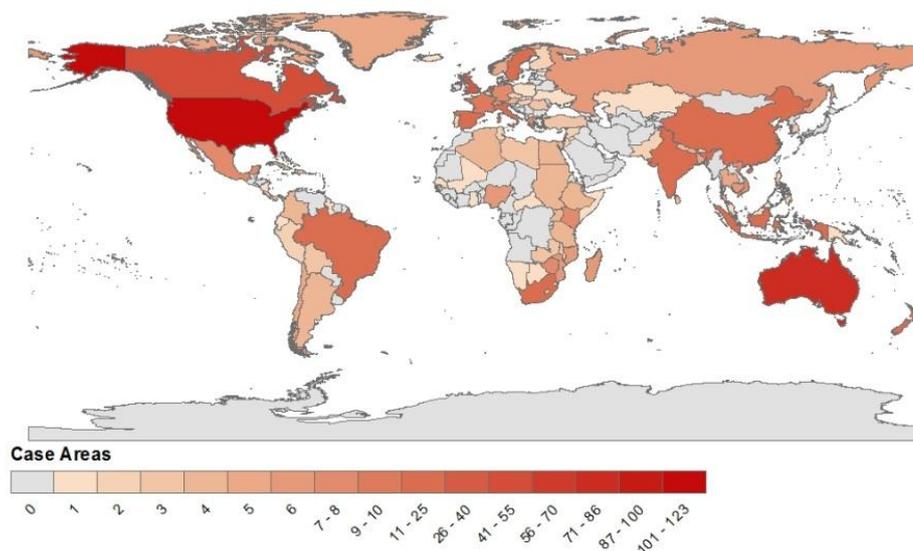


**Fig. 3** Distribution of publications by country

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Fig. 4 shows the areas which have been used as case studies in the cited publications on resilience thinking throughout the world. There are about 646 case studies within the 919 Google Scholar cited publications, which include 164 in North America (25.4%), 141 in Europe (21.8%), 104 in Oceania (16.1%), 89 in Africa (13.8%), 57 in South Asia (8.8%), 38 in South America (5.9%), 18 in Middle America (2.8%), 15 in East Asia (2.3%), 11 in West Asia (1.7%), 5 in the Arctic (0.8%) and 4 in Middle Asia (0.6%). This is a more balanced geographic spread but large areas of Central and West Africa, the Middle East, Central Asia and Eastern Europe continue to be underrepresented. In terms of specific countries, the largest number of case studies, namely 123, have been carried out in USA, followed by Australia – 85, Canada – 40 and UK – 26. It is interesting to note that Japan – one of the largest countries on earth in terms of population and the size of its economy, has not yet generated any case study for resilience research.



**Fig. 4** Distribution of case areas covered in resilience publications

The spatial analysis demonstrates that USA, Australia, UK and Sweden are the scholarly leading countries in the realm of resilience research in social-ecological systems. The USA is both the most productive country and with the largest number of case areas, followed by Australia. However, not many studies have been undertaken in other large countries such as Russia, China and India. As resilience thinking seems to be an important, if not the main approach in adapting to climate change and human disturbances issues with the objective of sustainability in a highly uncertain future (Walker et al., 2004; Adger, 2005; Folke, 2006), more research is urgently needed. In particular, China and India which are currently experiencing high economic growth and already have large populations, are being ecologically threatened with serious environmental issues and resilience thinking may prove a useful way to re-examine such development. It may well be the case that Chinese researchers have resilience related publications in Chinese or other than English languages, which this research does not capture. Nevertheless, in order to respond to the urgent need for practically-oriented scholarly research, it is important to

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be able to easily communicate results, findings and exchange scientific ideas as well as understand the experiences of other countries. For the time being, English publications remain the main medium to achieve this.

#### *Intensity of resilience research*

This part examines the intensity of resilience research as represented by the share of resilience researchers within total researchers by country. This is indicative of the popularity of resilience thinking in the research arena of the various countries. Furthermore, the dominant resilience context is presented through the percentage of resilience researchers working respectively on ecological, economic, social and integrated systems (see Table 3).

The two African countries of Lesotho and Ghana appear to be at the top of the list according to resilience research intensity, however they both have relatively small numbers of researchers and the respective 1 and 3 cited resilience publications have drastically increased the share of researchers in this area to respectively 21.6 per thousand and 7.2 per thousand. Among the remaining countries, resilience research is most popular in Australia and Sweden with about 2.6 and 1.8 per thousand researchers with cited publications in this area. The majority of researchers in most countries focus on resilience thinking in ecological systems and theoretical analysis. Among the countries with more than 10 cited resilience researchers, social resilience is dominant in South Africa and Japan, there is no country where economic resilience has attracted the highest interest and the integrated systems or sustainability approach is prevalent only in Columbia (where 100% of the studies fall in this category) and Austria.

**Table 3** Numbers and shares of researchers with cited resilience publications (1973-2011)

Country	No. of researchers in resilience	Share in total researchers (%)	Percentage of resilience researchers in different contexts (%)			
			T-E	ECO	SOC	I-S
USA	605	0.43	63.31	4.79	16.69	15.37
Australia	246	2.57	58.94	6.10	23.58	11.38
UK	218	0.93	57.80	6.42	22.48	13.30
Canada	99	0.65	57.58	2.02	25.25	15.15
Sweden	88	1.78	45.45	15.91	15.91	22.73
Netherlands	62	1.12	53.23	11.29	22.58	12.90
France	58	0.25	79.31	5.17	12.07	3.45
Germany	53	0.16	54.72	9.43	16.98	18.87
Spain	33	0.24	66.67	0	15.15	18.18
China	29	0.02	68.97	10.34	20.69	0
Switzerland	29	1.13	62.07	6.90	17.24	13.79
New Zealand	29	1.33	55.17	3.45	37.93	3.45
Italy	21	0.20	38.10	19.05	23.81	19.05
South Africa	21	1.07	38.10	4.76	42.86	14.29
Norway	18	0.68	50.00	27.78	16.67	5.56
Japan	17	0.03	35.29	0	47.06	17.65
India	16	0.10	31.25	18.75	31.25	18.75
Denmark	15	0.42	60.00	6.67	20.00	13.33

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Israel	14	N/a	91.00	0	0	9.00
Austria	13	0.36	15.38	23.08	23.08	38.46
Brazil	12	0.09	83.33	8.33	8.33	0
Columbia	11	1.48	0	0	0	100.00
Sudan	11	N/a	9.00	0	54.56	36.36
Mexico	10	0.23	60.00	0	10.00	30.00
Finland	10	0.24	70.00	10.00	0	20.00
Portugal	9	0.20	44.44	22.22	33.33	0
Greece	8	0.36	75.00	0	12.50	12.50
Solomon Islands	7	N/a	100.00	0	0	0
Malaysia	6	0.58	100.00	0	0	0
Argentina	6	0.14	50.00	0	33.33	16.67
Hungary	6	0.28	0	16.67	83.33	0
Kenya	6	2.65	66.67	0	16.67	0
Poland	5	0.08	80.00	0	20.00	0
Chile	4	0.66	25.00	0	75.00	0
Singapore	4	0.13	75.00	0	25.00	0
Zimbabwe	4	N/a	50.00	0	50.00	0
Philippines	3	0.41	66.67	0	33.33	0
Indonesia	3	0.14	66.67	0	33.33	0
Nigeria	3	0.49	33.33	66.67	0	0
Russia	3	0.01	33.33	0	33.33	33.33
Romania	3	0.15	100.00	0	0	0
Ghana	3	7.23	0	0	0	100
Syria	3	N/a	100.00	0	0	0
Nepal	2	1.24	0	0	50.00	50.00
Senegal	2	0.42	100.00	0	0	0
Panama	2	4.88	100	0	0	0
Belgium	2	0.05	50.00	0	0	50.00
Egypt	2	0.06	50.00	0	50.00	0
South Korea	2	0.01	100.00	0	0	0
Iceland	2	0.74	100.00	0	0	0
Cuba	2	0.41	100.00	0	0	0
Slovenia	2	0.26	100.00	0	0	0
Slovakia	2	0.13	0	0	0	100.00
Pakistan	1	0.04	0	0	100.00	0
Mozambique	1	2.67	0	0	100.00	0
Peru	1	0.19	100.00	0	0	0
Sri Lanka	1	0.20	100.00	0	0	0
Bolivia	1	0.70	0	0	100.00	0
Venezuela	1	0.19	0	0	0	100.00
Costa Rica	1	0.64	100.00	0	0	0
Vietnam	1	0.10	0	0	0	100.00
Thailand	1	0.05	0	0	0	100.00
Lesotho	1	21.65	0	0	0	100.00

Published as:

Xu, Li, and Dora Marinova. 2013. "Resilience thinking: a bibliometric analysis of socio-ecological research." *Scientometrics* 9(3): 911-927. Doi: 10.1007/s11192-013-0957-0.

Ethiopia	1	0.27	0	100.00	0	0
Mali	1	1.71	100.00	0	0	0
Bangladesh	1	N/a	100.00	0	0	0
Belize	1	N/a	100.00	0	0	0
Bhutan	1	N/a	100.00	0	0	0
Fiji	1	N/a	100.00	0	0	0
Guam	1	N/a	100.00	0	0	0

Notes: 1. The source of data for research numbers is UNESCO's database (<http://www.uis.unesco.org/Pages/default.aspx?SPSLanguage=EN>).

2. T-E, ECO, SOC and I-S represent respectively that the research was conducted in the context of ecological systems or mainly on theoretical studies, economic systems, social systems and integrated ecological, social and economic systems or sustainability in terms of resilience.

3. N/a – information not available.

Overall, the geographic distribution of resilience thinking appears to indicate that despite very small numbers, this research is highly important for two categories of countries: (1) African (Lesotho, Mozambique, Ghana, Kenya, Mali and South Africa), a couple of Latin American (Panama and Columbia) countries and Nepal, all of which are aspiring to improve the living standards of their people; and (2) strong western type small economies (Australia, Sweden, the Netherlands, Switzerland and New Zealand) which have already achieved higher living standards. It is a warning sign to see that resilience research communicated in English is yet to increase its importance for the world's largest and emerging economies, such as US, Japan, Germany, France, China, India, Brazil and Russia.

#### *Research organisations*

This final part looks at which research institutes or universities are leaders among the top 15 most productive resilience research countries (see Table 4). The research organisation with the largest number of author affiliations in the cited resilience papers is considered to be the leading institution for the respective country. Figure 5 shows the respective national shares that the leading resilience research holds.

**Table 4** Leading institutes in top 15 most productive countries (1973-2011)

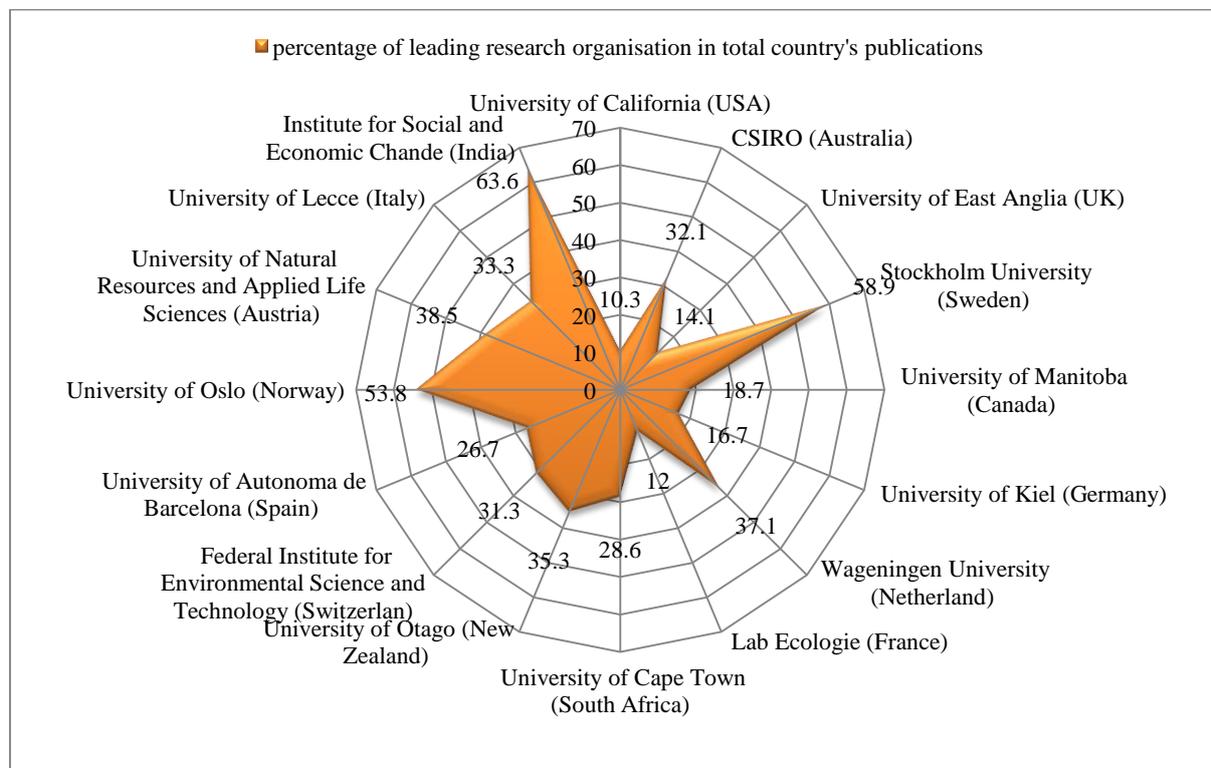
Rank	Country	Publications involved	Most productive institute		
			Name	Number	Percentage (%)
1	USA	389	University of California	40	10.3
2	Australia	162	Commonwealth Scientific and Industrial Research Organisation (CSIRO)	52	32.1
3	UK	135	University of East Anglia	19	14.1
4	Sweden	95	Stockholm University	56	58.9
5	Canada	91	University of Manitoba	17	18.7
6	Germany	36	University of Kiel	6	16.7
7	Netherlands	35	Wageningen University	13	37.1
8	France	25	Laboratoire Ecologie	3	12.0
9	South Africa	21	University of Cape Town	6	28.6
10	New Zealand	17	University of Otago	6	35.3
11	Switzerland	16	Swiss Federal Institute for	5	31.3

Published as:

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			Environmental science and Technology		
12	Spain	15	University of Autonoma de Barcelona	4	26.7
13	Norway Austria	13	University of Oslo University of Natural Resources and Applied Life Sciences	7 5	53.8 38.5
14	Italy	12	University of Lecce	4	33.3
15	India	11	Indian Institute of Technology, Institute for Social and Economic Change	7	63.6

Notes: Because of multiple authorship the number of publications is higher than the total number of Google Scholar cited publications (919). Publications are counted more than once if their authors affiliate with more than one country (see main text for further explanation).



**Fig. 5** Percentage of the leading resilience research organisation for the top 15 countries

The USA is overall the most productive country in resilience research, but its top institution – University of California, is responsible for 10% of the total research output in this area. This indicates that there is not a lot of concentration and resilience thinking has penetrated a larger number of American research organisations. The situation is very similar for the other larger developed economies, namely UK, Germany and France as well as for Canada where the shares of the respective leading organisations are below 20%. By comparison, the situation in India, Sweden and Norway is very different – the leading Institute for Social and Economic Change, Stockholm University and University of Oslo are respectively responsible for 64%, 59% and 54% of total national resilience output. In the remaining countries, the leading research organisations account for around a third of all cited resilience publications.

## Conclusion

Published as:

Xu, Li, and Dora Marinova. 2013. "Resilience thinking: a bibliometric analysis of socio-ecological research." *Scientometrics* 9(3): 911-927. Doi: 10.1007/s11192-013-0957-0.

This paper examined the trends of resilience research using a bibliometric approach based on 919 cited English publications from 1973 to 2011 identified through Google Scholar. The analysis of resilience thinking shows that this area experienced a dramatic increase since it was introduced for ecological systems in 1973. This increasing trend substantially speeded up since 1999 with the establishment of the global Resilience Alliance network, which also publishes *Ecology and Society* – the top and most influential journal in this area, responsible for the largest number of cited resilience papers. Although the bulk of the research in resilience is conducted for ecological systems, there is an increasing interest in socio-economic systems and even more importantly, in integrated socio-ecological systems which facilitates sustainability research. How to incorporate resilience thinking to respond to sustainability challenges in the constantly changing world highly influenced by human activities, should be the main research direction of this area.

The paper also shows that resilience research is dominated in size by USA, Australia, UK and Sweden. In absolute numbers, USA is the most productive country in terms of resilience output; however, its importance is much higher for relatively smaller western economies, such as Australia and Sweden. Similarly, the case study areas covered in the cited publications demonstrate more attention to the parts of the world from where resilience research originates with many important areas attracting very little attention. Consequently, there is need for urgent practically-oriented scholarly research to concentrate on those particular regions where environmental issues have been seriously on the rise, such as in China.

Given the English language limitation of the study, it may be the case that there are other resilience publications, not captured by this analysis. Nevertheless, communication in English of environmental and sustainability concerns as well as resilience thinking remains highly important for the development of ideas and measures of adaptation to any future uncertain disturbances across the globe.

### **Acknowledgements**

We would like to thank Dr. Roman Trubka and Cole Hendrigan for their assistance with GIS mapping and helpful suggestions. The second author also acknowledges the financial assistance by the Australian Research Council. We are also thankful to the Journal's Editor and referees for helpful and constructive comments which improved the quality of the paper.

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**PAPER 2: NANO-BIOTECHNOLOGY FOR WATER  
SUSTAINABILITY: BIBLIOMETRIC ANALYSIS**

**Statement of Contributions of Authorship**

To whom it may concern,

I, Li Xu, contributed 80% to the paper entitled above and cited as below:

Xu, Li, and Dora Marinova. 2015. "Nano-biotechnology for water sustainability: bibliometric analysis." in *Technology–Society–Sustainability: Selected Contemporary Issues, Concepts and Cases*, edited by Lech W. Zacher, Springer. (forthcoming, acceptance date 27/07/2015).

Signature of Candidate:



Date: 30 October 2015

I, as a co-author, endorse that this level of contribution by the candidate indicate above is appropriate.

Dora Marinova Signature:



Date: 2 November 2015

**This Chapter is an exact copy of the journal paper referred to above**

Published as:

Xu, Li and Dora Marinova. 2015. "Nano-biotechnology for water sustainability: bibliometric analysis." in *Technology–Society–Sustainability: Selected Contemporary Issues, Concepts and Cases*, edited by Lech W. Zacher, Springer. (forthcoming).

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## **NANO-BIOTECHNOLOGY FOR WATER SUSTAINABILITY: BIBLIOMETRIC ANALYSIS**

**Li Xu**

**Dora Marinova**

### **Abstract**

Nano-biotechnology is regarded as having high potential for solving challenges related to water, food and biodiversity. Of particular interest to sustainability is its promising ability to enhance the supply and security of water resources for human use. The chapter applies bibliometric analysis to describe the trends in the development of nano-biotechnology for issues related to water supply, contamination prevention and treatment. A co-occurrence analysis is used to identify the types of technologies emerging in this area, namely related to bio-engineering, chemical engineering, microbiology and material sciences. The majority of the new knowledge comes from USA but researchers from China, South Korea, the Netherlands, India and Australia are also making their mark.

### **Keywords**

Technological innovation, water supply, water contamination, water treatment, research trends, nano-biotechnology, bibliometric

## **INTRODUCTION**

Water is vital for life on our planet but expanding population, industrialisation and industrial agriculture put immense pressure on this important resource. Taken for granted in developed countries, nations in the developing world are still struggling to provide clean and safe water. Security and scarcity are two major challenges. While the problems across the globe may vary, many regions face multiple changes in water supply and water quality that undermine its accessibility and safety thereby destabilising human wellbeing.

Access to clean and safe drinking water and sanitation is a human right and a pre-requisite for adequate standards of living (UNESCO 2011). Yet 884 million people have limited drinking water and 2.6 billion people live without proper sanitation (UNESCO 2011). Although the quantity of water on Earth has been stable for millions of years, its quality has deteriorated progressively due to a combination of human demographic and activity factors (PWC 2012). Climate change coupled with degradation of the quality of surface and groundwater reserves exacerbates the already serious global and region-specific issues.

Technological solutions have always been compelling in assisting with water challenges, ranging from construction of dams, piping and drainage to desalination, filtering devices and wastewater treatment. According to PricewaterCooper (PWC 2012), R&D and innovation can

Published as:

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generate solutions related to water production, including alternative sources from seawater and marginal quality water, reuse, intelligent consumption and optimised sanitation. In recent years nanobiotechnology, a technological field combining nanotechnology and biotechnology solutions, is seen as having significant potential to solve water challenges across the globe and enhance the supply of clean water for human use (Diallo and Brinker 2011). Nanobiotechnology is the branch of nanotechnology that deals with biological and biochemical applications and uses (Venkatesh, 2009) or in other words, it represents "the use of nano-science for specific biological applications" (Gazit 2007, p. 13). Research in nanobiotechnology (also referred to as nanobiology) developed in embryonic stage in the mid 2000s and is still in its infancy. A search of published papers in Scopus up to year 2013 generates only 9 entries pertaining uniquely to water sustainability and nanobiotechnology. This small number indicates that although nanobiotechnology is promising its overall impact is still negligible. The two areas from which nanobiotechnology emerged, namely nanotechnology and biotechnology, however have been going strongly for decades. Immediate and fast solutions related to water sustainability need to rely on the progress and advancement of knowledge made in these two individual classes of technologies.

How can these new technologies contribute to dealing with water security and scarcity? What is the scientific evidence that they can offer useful and working solutions? Diallo and Brinker (2011) point out the potential of nanotechnology solutions for safe environment and water resources in efficiently supplying potable water for human use and clean water for agricultural and industrial applications. Similarly, many argue the potential biotechnology holds for biotreatment and bioremediation to control water quality, decontaminate wastewaters, monitor and prevent pollution (e.g. Zechendorf 1999; Gommen and Verstraete 2002). Both nanotechnology and biotechnology can be used in water treatment, for example nanofiltration membranes for producing potable water from brackish groundwater (Hillie and Hlophe 2007) or biofilm bioreactors for wastewater treatment (Van Loosdrecht and Heijnen 1993).

Using a bibliometric approach, we analyse in this chapter how active the nanotechnology and biotechnology research field is in relation to water. We describe this as nano-biotechnology. While several bibliometric studies have examined nanotechnology and biotechnology through patent or publication activities (Meyer 2001; Marinova and McAleer 2003; Schummer 2004; Leydesdorff and Rafols 2009; Rafols and Meyer 2010; Thursby and Thursby 2011), not much is known about issues related to water sustainability. Despite their promising potential in relation to water, the links between nano- and biotechnology are yet to be firmly established. In order to address water sustainability priorities in the time being, we need to understand the individual trends within the two individual technology groups and this is where a bibliometric analysis of nano-biotechnology can be very informative. It is also important to see how researchers connect with each other in collaborative efforts to address the water challenges.

Hence, we conduct a study of nano-biotechnology research on water sustainability issues with the aim to present the global trends in the area and give direction for future quantitative

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studies. We firstly screen publications indexed by the Web of Science (Thompson Reuters ISI) and Scopus to describe the general trends in nano-biotechnology research in the past decades. This allows for the more appropriate database for further analysis to be selected. The methods, data used and scope of the analyses are presented in section 2. Section 3 presents the results from the bibliometric investigation based on co-occurrence analyses. We conclude the study with a discussion and further research directions in section 4.

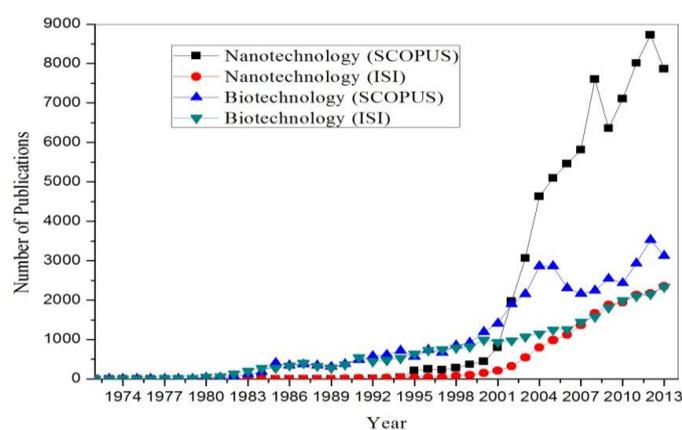
## METHODOLOGY AND DATA

Bibliometrics aims to quantitatively analyse the publications covered in scientific sources (De Bellis 2009). Described as the foundation for the science of science (De Solla Price 1963), it applies the methods of science to examine scientific output. The two most commonly used bibliographic databases of academic work are Web of Science established by the Institute for Scientific Information (ISI) and more recently acquired by Thompson Reuters, and Scopus owned and operated by Elsevier.

### *Data collection*

#### *Choice of bibliographic database*

In order to determine which of the two databases has a better coverage and is better suited for this study, we firstly conduct queries, using nanotechnology and biotechnology as search words in the total number of publications in Scopus and Web of Science. We search for publications which contain these two words separately in either their titles or lists of keywords. The specific journal databases that we use for the search are Science Citation Index and Social Science Citation Index in Web of Science and Physical Sciences and Social Sciences & Humanities in Scopus (see Fig. 7.4.1).



**Fig. 7.4.1** Number of publications per year with “nanotechnology” and “biotechnology” in the title or keywords (data accessed July 2014)

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The total numbers of publications in Scopus and Web of Science are 74,361 and 42,375 respectively for nanotechnology and 18,038 and 29,482, respectively for biotechnology. The peak numbers for nanotechnology publications are 8,719 for SCOPUS in 2012 and 2,351 for ISI in 2013 while for biotechnology they are 3,529 for SCOPUS in 2012 and 2,333 for ISI in 2013. The historical trends in the two databases show that biotechnology research preceded nanotechnology – the first two biotechnology publications appeared in 1972 in Web of Science while the first nanotechnology publication was registered in 1978 in Scopus. Although there might be earlier publications in both areas in other bibliographic databases, overall research in biotechnology started prior to that in nanotechnology.

Given the broader coverage of publications by Scopus on both technologies, this bibliographic database is chosen for further analysis and we believe it represents well the progress made in the respective fields. We are particularly interested in research and advancement of knowledge through these two types of technologies in relation to water sustainability. This requires narrowing down the publication fields using specific keywords.

#### *Keywords and dataset*

Growing demands for water and increasing agricultural and industrial pollution continuously intensify the stress on surface and groundwater resources and on supply systems. The three main issues related to water sustainability are supply, contamination and treatment (Gray 2010). These are the three retrieval keywords that we used to examine the research progress made in nano-biotechnology in relation to the sustainability of water resources. Hence the keyword combinations are: nanotechnology & water supply, nanotechnology & water contamination, nanotechnology & water treatment, biotechnology & water supply, biotechnology & water contamination and biotechnology & water treatment (see Fig. 7.4.2). In order to ensure data integrity, we manually cleaned the obtained dataset by deleting any repeated publications to avoid double counting and removing all documents for which author(s) names were not available.

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The screenshot displays the Scopus search interface. At the top, there are navigation links: "Document search" (underlined), "Author search", "Affiliation search", and "Advanced search". On the right, there are links for "Browse Sources" and "Analyze Journals". The main search area contains a search bar with "nanotechnology" and a dropdown menu set to "Article Title". Below this, there are several rows of search criteria, each with an "OR" or "AND" operator, a text input field, and a dropdown menu. The criteria are: 1) "nanotechnology" (Article Title), 2) "nanotechnology" (Keywords), 3) "biotechnology" (Article Title), 4) "biotechnology" (Keywords), 5) "water treatment" (Article Title, Abstract, Keywords), 6) "water supply" (Article Title, Abstract, Keywords), and 7) "water contamination" (Article Title, Abstract, Keywords). There are "Add search field" and "Reset form" buttons. Below the search criteria, there is a "Limit to:" section with "Date Range (inclusive)" set to "Published All years" to "2013", "Document Type" set to "ALL", and "Added to Scopus in the last 7 days". The "Subject Areas" section has checkboxes for "Life Sciences (> 4,300 titles.)", "Health Sciences (> 6,800 titles. 100% Medline coverage)", "Physical Sciences (> 7,200 titles.)", and "Social Sciences & Humanities (> 5,300 titles.)".

**Fig. 7.4.2** Keywords combinations used in Scopus

### *Data analysis*

Co-occurrence analysis is applied to identify research hot points and connections in the field of nano-biotechnology for water sustainability. The linguistic term “co-occurrence” refers to analysis of related words (Kroeger 2005) and in this case, the mutual occurrence of two units in the same metadata field, e.g. “climate change” or “Newman and Kenworthy”. This type of bibliometric analysis has been previously used to describe research development, including to explore concept networks and reveal research themes (Courtial 1994; Ding et al. 2001; Ronda-Pupo and Guerras-Martin 2010; Hu et al. 2013). One of the first studies applying a co-word analysis is that by Rip and Courtial (1984) who mapped developments in biotechnology.

This study is the first to specifically examine water related issues. The co-occurrence method here comprises two sections, namely co-word and co-authorship analyses, and is employed to reveal on which topics nano-biotechnology researchers focussed their studies on water sustainability and how well they connected with one another. Bibexcel is used for the bibliometric analysis and Pajek (a software for large networks representation) combined with ArcMap is applied to visualise the networks of dominant topics and co-authorship<sup>1</sup>.

### *Co-word analysis*

The co-word analysis reveals the research hot points. It is based on the keywords appearing in the lists provided by the authors assuming that they were properly scrutinised and describe the content well. Extended keywords provided by indexers are excluded as they not always

<sup>1</sup> Original data and routine files are available from the authors.

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indicate exactly what the authors have done and lead to double counts. The higher the co-occurrence frequency of two words, the closer the relationship they have.

The co-word dataset is built by cleaning meaningless publications according to two criteria: (1) when the extracted keywords from the list overlap with the ones used as searching criteria to identify the publication (see Fig. 7.4.2); and (2) when the keywords from the list are not representatives of a well-defined topic (e.g. being too general, such as "water" or "modelling"). For example, the frequency distribution extracted 114 "nanotechnology" and 16 "modelling" from the keywords lists of all publications. These publications are excluded from the sub-dataset because "nanotechnology" is a keyword we used in the search to identify the publication and "modelling" does not reveal any specific subject domain. We use words which appear more than ten times in the co-occurrence matrix and co-words which appeared more than five times in the matrix to build the descriptive networks. This avoids having too many vectors and arcs in the graphic representation which might make the visualisation unclear.

### *Co-authorship analysis*

The co-authorship analytical method is a good way to discover social networks, scholarly collaborations, scientific evolutions and the research performance of various fields (Barabasi et al. 2002; Liu et al. 2005; Abbasi et al. 2011). We constructed global co-authorship networks for nano-biotechnology research in water sustainability to reveal the scholarly connections among leading authors around the world. To visually present the global connections through the authors' networks, they are graphed onto a world map according to the places with which the researchers affiliate.

Similar rules as for the co-word analysis are applied for the data cleaning in this part. That is, all authors are firstly counted up from the dataset of the names appearing in the publications. Then we conduct frequency distribution analyses in the order of the list. We use five as the minimum number of times an author's name has to appear in the documents to establish a co-occurrence matrix. However, all co-authors are included in the co-occurrence matrix because of the higher complexity in authorships than in keyword use. According to the rules we adopted, the matrix of co-authors is smaller than that of co-words, which is easier and clearer to visualise in the networks. The nodes in the networks represent authors and the line between two nodes (authors) denotes that they co-authored a publication. The more lines a node has, the more collaborations that author has with others.

Although this way presents well the most productive authors and collaborations between researchers, some links may be missing because of the emphasis on larger number of publications. For example, some authors may have strong relationships with others who are not included in the networks because of their publications' number not matching the rules, e.g. author A and author B are both in the networks and they have two collaborations; author A

Published as:

Xu, Li and Dora Marinova. 2015. "Nano-biotechnology for water sustainability: bibliometric analysis." in *Technology–Society–Sustainability: Selected Contemporary Issues, Concepts and Cases*, edited by Lech W. Zacher, Springer. (forthcoming).

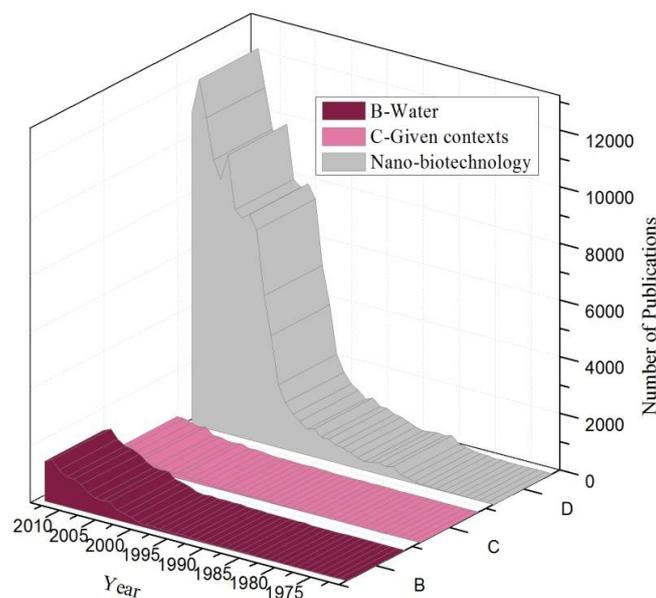
however has four collaborations with author C who is not in the networks because of having only four documents in the defined contexts. This limitation similarly occurs in the co-word networks; however it does not create significant effects on revealing the relationships between leading scientists as all authors in the networks have more than 5 publications.

## RESULTS AND DISCUSSION

A general description of the trends is first provided. Following this, we present the results from the two co-occurrence analyses.

### *Research trends in nano-biotechnology for water sustainability*

A total of 4,126 publications in nano-biotechnology research were found in Scopus in the contexts of water supply, contamination and treatment, which account for 36% of all nano-biotechnology research on broader water issues (11,469) and 3.5% of all nano-biotechnological studies (Fig. 7.4.3).



**Fig. 7.4 3** Comparison between “nano-biotechnology” in total water research and within sustainability context

The earliest study on nano-biotechnology addressing water issues was published in 1971. Since then, the publication rate grew steadily until the first rise in 1985, following which it continued to increase gradually and later on witnessed a dramatic jump in 2000. A similar trend happened in research on water sustainability problems (namely supply, treatment and contamination). After the first study on water sustainability problems in 1981, there was a steady growth reaching a peak of 548 in 2013. The number of publications which apply nano-

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biotechnology to water supply, contamination and treatment rose dramatically after 2001. Afterwards it experienced a period of seven years (2002-2008) of relatively stable development prior to the next soar between 2009 and 2013.

### *Co-occurrence analysis*

After 43 documents were removed from the dataset during data clearing, the final number of publications for the co-occurrence analysis is 4,083. The results from the two co-occurrence analyses based on these publications are presented below.

### *Co-word analysis*

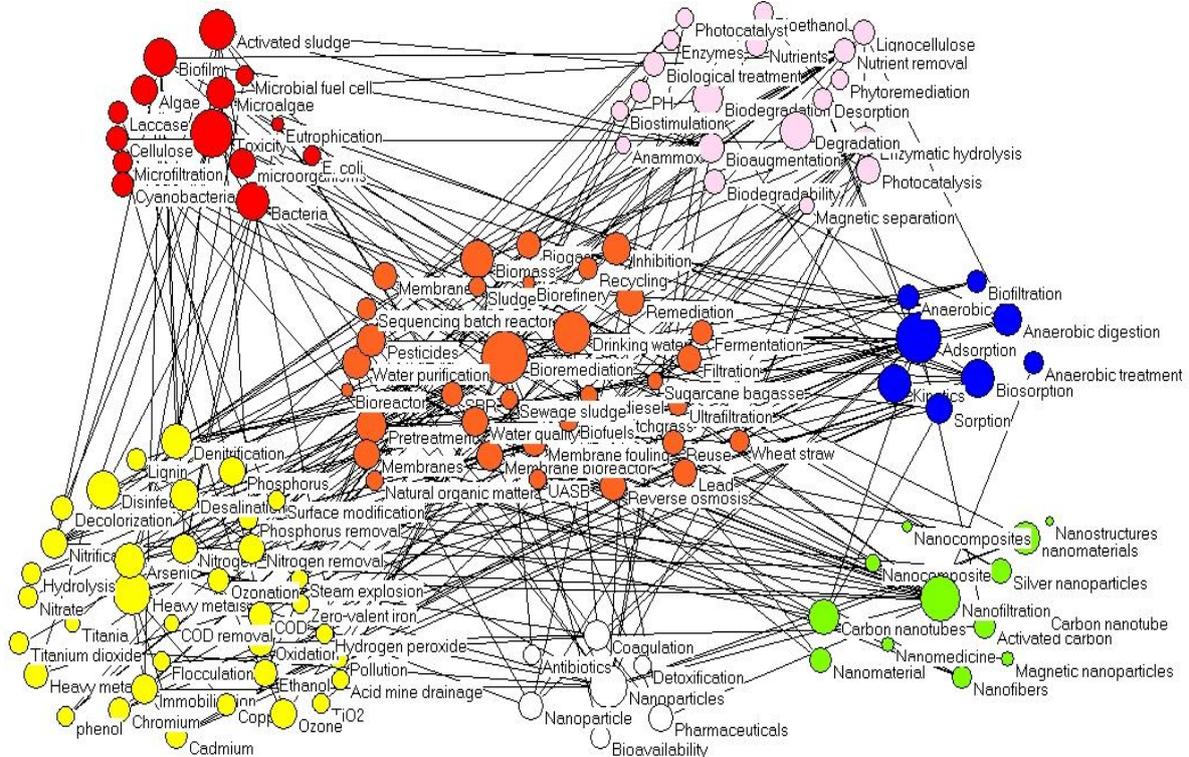
Overall 131 key vertices and 1,186 lines constitute the network of co-words for all publications. Lines with a value of less than two were removed from the dataset to make the visualisation of the networks clearer. Using a manual semantic analysis, the keywords were firstly classified into three groups, namely water treatment – yellow nodes, water supply – red nodes, and water contamination – green nodes (see Fig. 7.4.4). This is in line with the keywords used originally to identify the publications combined with the keywords in the titles and abstracts of the articles in which they appeared.



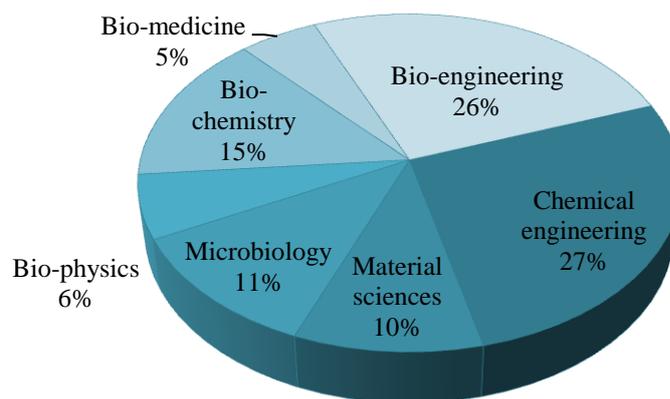
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nodes, microbiology – red nodes, material sciences – green nodes, and chemical engineering – yellow nodes. This is also diagrammed in the pie chart on Fig. 7.4.6.



**Fig. 7.4.5** Co-word networks by keyword subjects in water sustainability research



**Fig. 7.4.6** Composition of studies of nano-biotechnology on water sustainability by subject

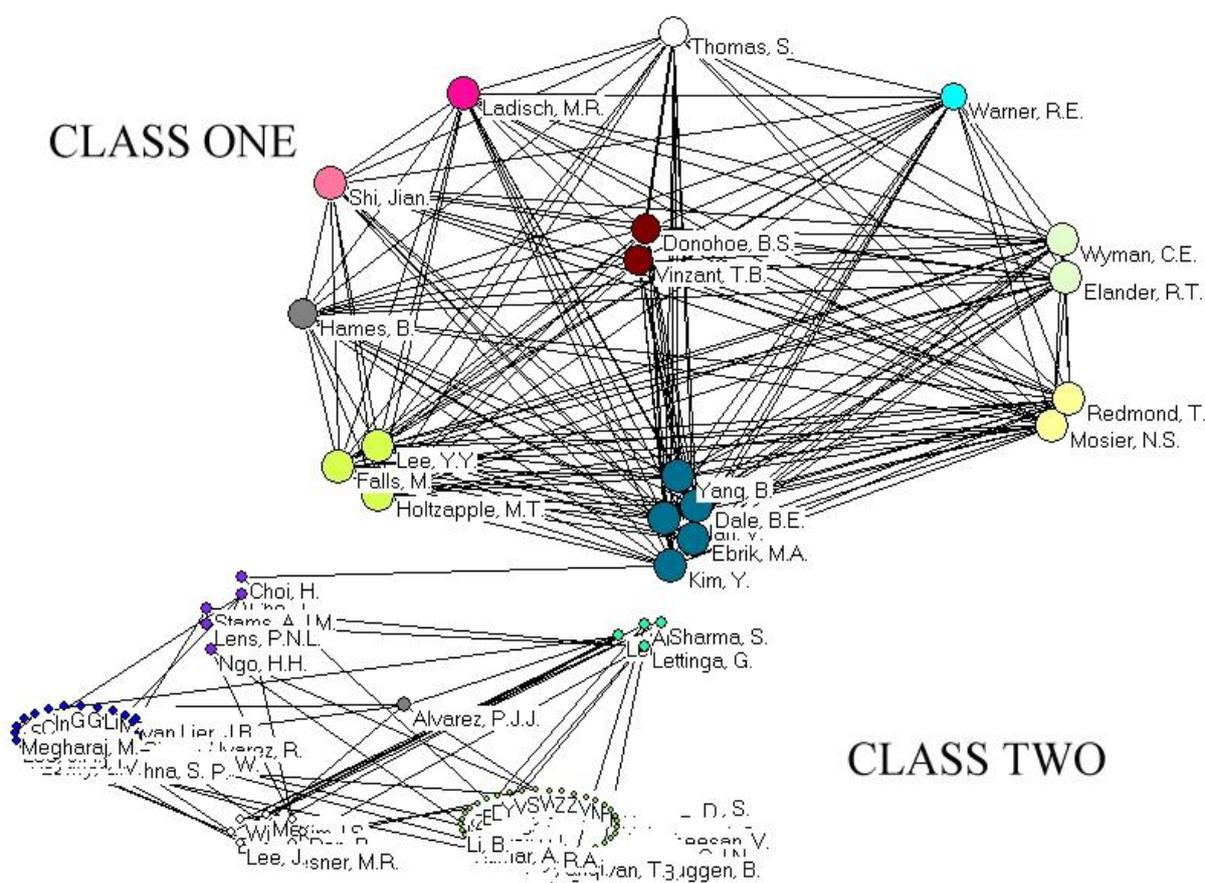
Similar numbers of studies have been published in bio-engineering and chemical engineering in the field of nano-biotechnology for water treatment, supply and contamination. They also have strong connections with the other topics. Microbiology and material sciences have again similar but smaller contributions while limited research has been conducted in bio-medicine and bio-physics. On the other hand, bio-physics and bio-medicine have weak connections in the whole network.

Published as:

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### Co-authorship analysis

Based on the 4,083 articles, 16,496 authors in total conducted research on either nanotechnology or biotechnology related to water specific issues. After data cleaning for publications without stated authors and elimination of authors whose names appear less than five times in the documents, the 97 most productive authors were identified for inclusion in the co-authorship analysis. The networks are shown in Fig. 7.4.7 and are classified in 16 groups according to the degree of the connections between the authors. They are further organised into two classes (see Fig. 7.4.7): high collaborations (Class One) and low collaborations (Class Two).



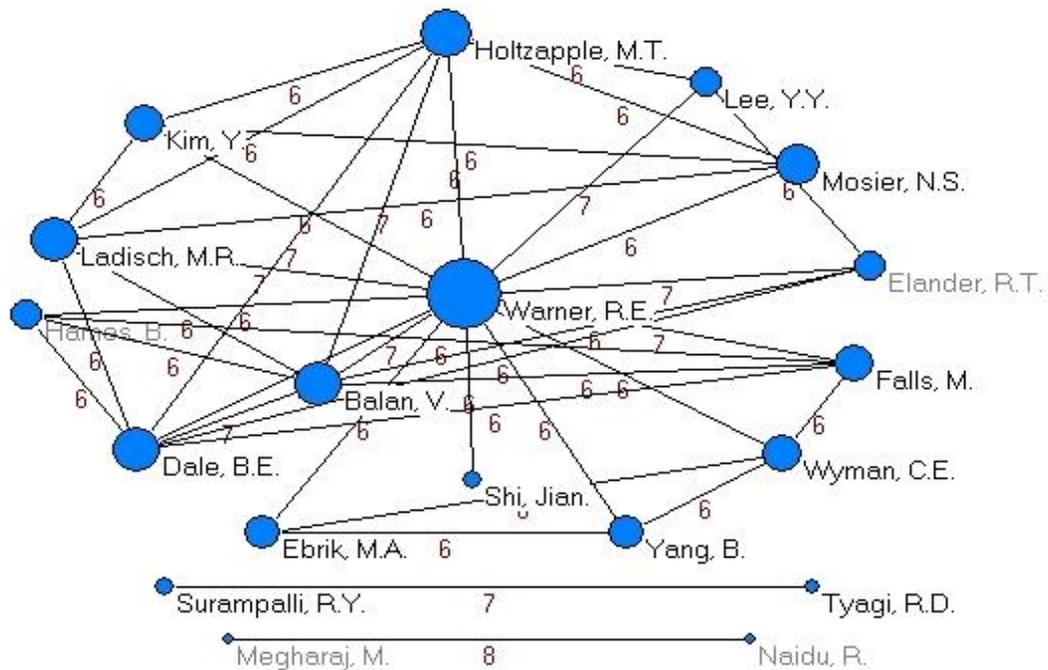
**Fig. 7.4.7** Co-authorships grouped by degrees of connections

The collaborations in Class One are more than those in Class Two meaning that the relationships between authors are closer in Class One. There is a gap between the two classes. Choi, H. is the only author from Class Two linked to Class One by publications (collaboration between Choi, H. and Kim, Y.). In Class One, the connections between authors are closer than those in Class Two. To further assess the relationships between the most active authors, we removed those whose names occurred together with others in the documents less than 6 times

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and generated new networks (see Fig. 7.4.8).



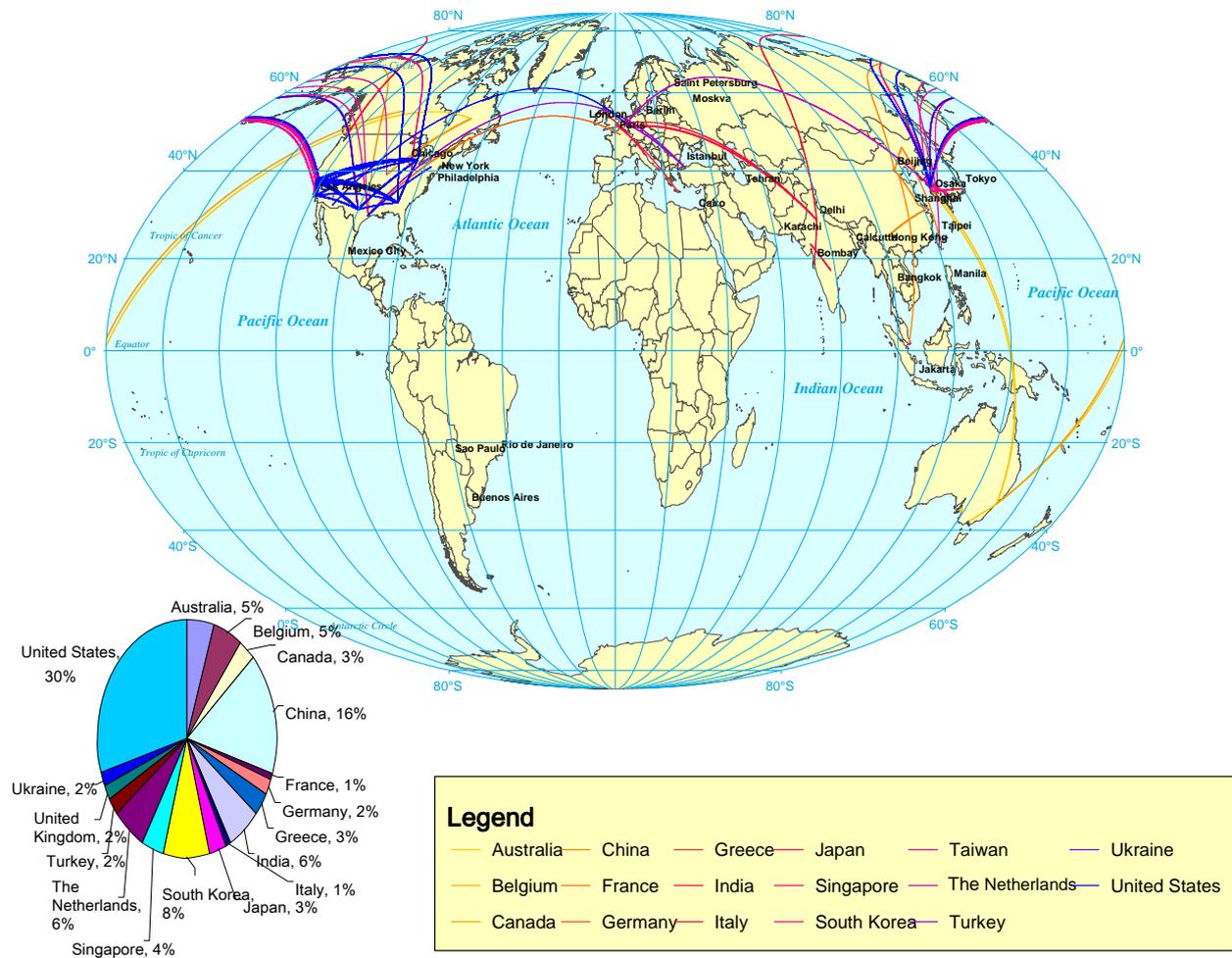
**Fig. 7.4.8** Closely connected authors' networks

Fig. 7.4.8 shows the close relationships between the active authors with nodes representing authors and a line between two nodes meaning that the respective two authors have joint publications. The values on the lines denote the number of publications the authors have co-authored. Warner, R. E. has the most relations with others than any other active author in the networks. Although Megharaj, M. and Naidu, R. have co-authored the most, neither of them has collaborations with other researchers. Similarly, Surampalli, R. Y. and Tyagi, R. D have high numbers of publications (11 and 10 respectively) and are respectively the second and the third most productive authors in the dataset; however, they have less collaborations with others.

Within the co-authorship networks, it is also interesting how authors are linked to each other amongst the various countries as this reveals the global collaboration picture in nano-biotechnology. The locations of the 97 authors were determined from the affiliations listed in their publications. For authors with multiple affiliations, the telephone number and mailing address (if applicable) were used to determine the country in which they are based or, if these do not provide a clearly indication, we used the first affiliation as the location base. The spatial distribution of the linked authors is presented in Fig. 7.4.9. It shows the various productive authors and their closer relations with others who have a similar status in terms of publication numbers and with whom they have collaborated.

Published as:

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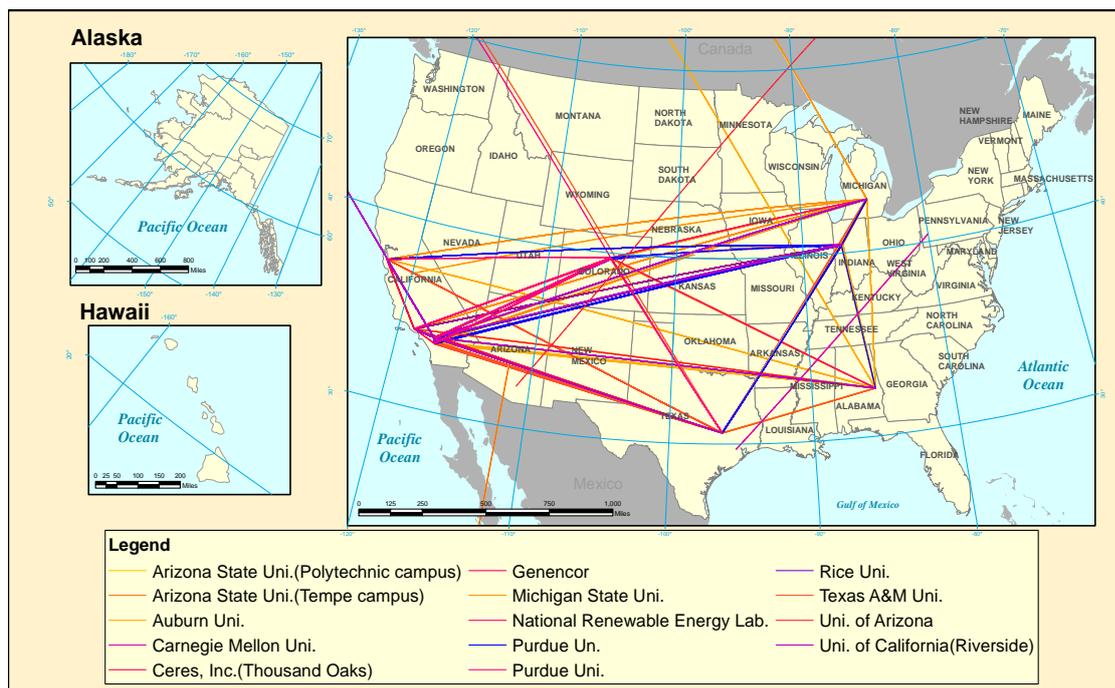


**Fig. 7.4.9** The global spatial networks of linked authors

At a regional scale, USA is the leading country in nano-biotechnology studies on water sustainability. The USA authors have the majority of collaborations in this field, followed by China, South Korea, the Netherlands, India and Australia. Notwithstanding this, the collaborations conducted by the USA researchers were mostly within their own country (see Fig. 7.4.10).

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Xu, Li and Dora Marinova. 2015. "Nano-biotechnology for water sustainability: bibliometric analysis." in *Technology–Society–Sustainability: Selected Contemporary Issues, Concepts and Cases*, edited by Lech W. Zacher, Springer. (forthcoming).



**Fig. 7.4.10** Co-authorship network distributions in USA

The main collaborating organisations are Michigan State University, National Renewable Energy Laboratory, University of California (Riverside), Texas A&M University, Auburn University, Ceres Inc. in Thousand Oaks and Purdue University in the USA, with the University of California (Riverside) being the most involved organisation (accounting for 18% of the total US authors in the dataset). On an individual level, Warner, R.E. from Genencor participated in the largest number of collaborations. External connections were built by the University of California (Riverside), Texas A&M University, Auburn University and Michigan State University (the stretching left purple lines, middle red lines and right light yellow lines in Fig. 7.4.10).

## CONCLUSION

In the last three decades, the world community recognised water as a global issue which needs to be approached on a planetary scale and that negligence and ignorance could lead to problems threatening human survival (PWC 2012). Progress made in research related to nano-biotechnology represents humanity's ability to respond to these global challenges.

The bibliometric analysis conducted in this study shows that the specialised nanobiotechnology field is yet too small to make a meaningful contribution towards addressing water challenges. More promising technological solutions are emerging from the broader combined nano-biotechnology field whose publication output is consistently growing. The most active publication areas relate to bio-engineering, chemical engineering,

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microbiology and material sciences confirming that water sustainability is a truly interdisciplinary and transdisciplinary research field. Despite the relatively large number of very active researchers, the bulk of the new knowledge is generated within USA. The contributions by researchers from China, South Korea, the Netherlands, India and Australia are also making their mark.

With continuing population growth and expansion in human activities, water supply, contamination and treatment are likely to remain highly active areas of technological endeavour. Research in nano-biotechnology will also remain important but further internationalisation and concerted effort are required for society to be able to address the global water challenges and priorities.

#### **ACKNOWLEDGEMENTS**

The second author acknowledges the support of the Australian Research Council.

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Xu, Li and Dora Marinova. 2015. "Nano-biotechnology for water sustainability: bibliometric analysis." in *Technology–Society–Sustainability: Selected Contemporary Issues, Concepts and Cases*, edited by Lech W. Zacher, Springer. (forthcoming).

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**PAPER 3: RESILIENCE THINKING: A RENEWED SYSTEM  
APPROACH FOR SUSTAINABILITY SCIENCE**

**Statement of Contributions of Authorship**

To whom it may concern,

I, Li Xu, contributed 75% to the paper entitled above and cited as below:

Xu, Li, Dora Marinova, and Xiumei Guo. 2015. "Resilience thinking: a renewed system approach for sustainability science." *Sustainability Science* 10(1): 123-138. doi: 10.1007/s11625-014-0274-4.

Signature of Candidate:



Date: 30 October 2015

I, as a co-author, endorse that this level of contribution by the candidate indicate above is appropriate.

*Dora Marinova Signature:*



Date: 2 November 2015

*Xiumei Guo Signature:*



Date: 2 November 2015

**This Chapter is an exact copy of the journal paper referred to above**

Published as:

Xu, Li, Dora Marinova, and Xiumei Guo. 2015. "Resilience thinking: a renewed system approach for sustainability science." *Sustainability Science*. 10(1): 123-138. Doi: 10.1007/s11625-014-0274-4.

## **Resilience thinking: a renewed system approach for sustainability science**

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**Abstract** This paper examines the contribution of resilience thinking for social-ecological systems (SESs) in understanding sustainability and the need to preserve natural resources in the face of external perturbations. Through qualitative and quantitative analysis, the literature survey shows the increased importance of resilience and its integration into the interdisciplinary area of sustainability studies. By exploring the links between resilience and sustainability the analysis finds that these two concepts share some similarities but also highlights the differences. The discussion of resilience indicators, measuring criteria, models and management issues reveals how resilience contributes to sustainability science and in what ways the concept can be used to measure resilience in terms of sustainability. Most existing studies emphasise the ecological aspects of resilience, but only by including human activities in the modelling can resilience thinking inform sustainability in a meaningful way. The paper concludes defining issues requiring further investigation, such as identifying and managing the drivers and key elements of resilience in SESs, exploring the dynamics between critical variables of SESs and the system feedbacks to external perturbations, as well as evaluating policies and engaging stakeholders for building resilience.

Published as:

Xu, Li, Dora Marinova, and Xiumei Guo. 2015. "Resilience thinking: a renewed system approach for sustainability science." *Sustainability Science*. 10(1): 123-138. Doi: 10.1007/s11625-014-0274-4.

**Keywords** Social-ecological systems (SESs), resilience, sustainability, literature review, measurement, management

## 1. Introduction

With strong interest in preserving the natural environment, sustainability research is a very complex and highly productive field that brings together scholarship and practice (Clark and Dickson 2003). This "use-inspired basic research" (Clark 2007:1737), also referred to as metadiscipline (Mihelcic et al. 2003), transcends the boundaries of economics, environmental science, climate science, sociology, behavioural and policy studies and many other disciplines.

While sustainability is moving from conceptualisation to the development of analytical tools, human-induced disruptions are resulting in growing environmental shocks. Global problems such as climate change and natural catastrophes are the inevitable truth to which we have to adapt (Barnosky et al. 2012). In the face of such continuing environmental challenges, the context of sustainability thinking changed from questions about avoiding or mitigating climate change to finding out how resilient society is. This reflects the need to integrate the social dimensions in dealing with the abundant empirical observations of ecosystem dynamics (Folke 2006), particularly how people react to changes. Resilience thinking for ecosystems and social-ecological systems (SESs) is asserted to be one of the active focuses within sustainability (Xu and Marinova 2013). It is also regarded as the optimal way in adapting to global environmental change and dealing with human impacts as well as hazards characterised by surprises and unknown risks (Walker et al. 2004; Adger et al. 2005; Berkes 2007; Folke 2006 & 2010).

The link between resilience and sustainability thinking however is multifaceted and the interpretation of its various dimensions is not always straightforward. What this paper

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sets to address is: 1) how important is resilience in sustainability studies?; 2) what are the similarities and differences between resilience and sustainability?; 3) in a growingly uncertain future, can resilience help the goal of sustainability?; 4) how can resilience be measured?; and 5) how can resilience be managed? Looking for answers to these questions, the paper conducts a literature survey to provide a better understanding of the place of resilience in sustainability studies.

## 2. Methodology

A combination of qualitative and quantitative approaches is used in this investigative review. We first start with conceptually explaining the definitions of resilience. A quantitative analysis of the publications in this area follows with the aim of this bibliometric inquiry being to show the importance of resilience in sustainability science.

Secondly, we analyse the similarities and differences between resilience and sustainability. The comparison demonstrates the conceptual connections between the two. After this, the contribution of resilience to sustainability is revealed through a discussion of its role in enhancing the main pillars of sustainability, that is environmental, social and economic sustainability.

A further investigation is undertaken on aspects related to measuring resilience, including indicators, thresholds of different systems and modelling. The last facet of this review is around managing the systems' resilience to achieve sustainability goals which includes building up resilience as well as managing resilience in terms of people, social capital and economic means.

## 3. Resilience: a prevailing thinking

Published as:

Xu, Li, Dora Marinova, and Xiumei Guo. 2015. "Resilience thinking: a renewed system approach for sustainability science." *Sustainability Science*. 10(1): 123-138. Doi: 10.1007/s11625-014-0274-4.

Resilience thinking shifted the sustainability concept from the early focuses on how to achieve and maintain stability, manage effectively resources, control change, pursue economic growth and increased human wellbeing, to how to deal with changes, disturbances and uncertainties (Berkes 2007; Ahern 2011). In this section, we explain the concept of resilience and then analyse publication trends which show that resilience is becoming an increasingly prevalent thinking for sustainability.

### **3.1 Defining resilience**

The term "resilience" originated from the technical area of mechanical and engineering sciences to describe the properties of materials, such as timber or iron, and their ability to withstand severe conditions (Hollnagel et al. 2006). It is now used across many academic fields with different interpretations ranging from engineering to psychology, economics and social sciences to ecology and environmental science (Bhui 2014) with its more recent meaning related to SESs. The conceptual similarities lie in understanding the responses to shocks, surprises, unforeseen or hazardous disturbances. The specific lens of the analysis however differs (Table 1).

Published as:

Xu, Li, Dora Marinova, and Xiumei Guo. 2015. "Resilience thinking: a renewed system approach for sustainability science." *Sustainability Science*. 10(1): 123-138. Doi: 10.1007/s11625-014-0274-4.

Table 1 Definitions of resilience in different contexts

Term	Definition	Interpretation/Example	Reference
Psychological resilience	A set of combined abilities and characteristics that interact dynamically to allow a person (especially children and a family) to bounce back, handle successfully, and function above the norm in spite of significant stress or adversity.	Family resilience seeks to identify and foster key processes that enable families to cope more effectively and emerge harder from crises or persistent stresses, whether from within or without the family.	Rutter (1993); Tusaie and Dyer (2004); Walsh (1996)
Resilience engineering	The intrinsic ability of a system to adjust its functioning prior to, during, or following changes and disturbances, so that it can sustain required operations under both expected and unexpected conditions.	Refers to the ability to perform without failure; the focus is on expected and unexpected conditions of functioning for a material or system; it is also used as an alternative or a complementary view of safety.	Hollnagel et al. (2006); Hollnagel et al. (2011)
Engineering resilience	The ability of systems to anticipate, recognise, adapt to and absorb changes, disturbances, surprises and failures.	It focuses on the stability of systems near an equilibrium state and maintaining efficiency of system functions; in this case resilience can be measured by the stability of the system, i.e. the time the system takes to return to the previous steady state.	Holling (1973); Ludwig et al. (1997);
Ecological resilience	The measure of the persistence of systems and their ability to absorb unforeseen changes and disturbances and still maintain the same relationships between populations or state variables as well as essential functions, structures, processes, and feedbacks.	It assumes that there exist multiple stable states (equilibria) in ecological systems, thus ecological resilience means the tolerance of the system to perturbations that facilitate transitions among those stable states.	Holling (1973); Gunderson (2002); Walker et al. (2004)
Social resilience	The ability of communities to withstand external shocks, mitigate and recover from hazards.	It emphasizes the time it takes to recover from stress and also most importantly the access community has to critical resources such as water, land, finances and human skills.	Adger (2000); Bruneau (2003); Langridge et al. (2006)
Economic resilience	The ability of the system to withstand either market or environmental shocks without losing the capacity to allocate resources efficiently, or to deliver essential services.	It emphasizes the functionality of the market and supporting institutions as well as the production system to recover from shocks.	Perrings (2006)

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Social-ecological  
resilience

The capacity of a system to tolerate disturbance without collapsing into a qualitatively different state that is controlled by a different set of processes

It points out that resilience is an essential property for societies to survive from changes. The system needs to keep this property by retaining its functions, structure, and capacity of self-organisation and learning.

Carpenter (2001);  
Resilience Alliance  
(2002: n.p.)

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In this review, we examine resilience only in ecologically related contexts with resilience thinking applied to the ecological, social and economic dimensions of change and their integration for future development. The emphasis in social resilience is not just on the time it takes to recover from stress, but most importantly the access community has to critical resources (Langridge .. 2006), such as water, land, finances and human skills. Economic resilience refers to "the ability of the system to withstand either market or environmental shocks without losing the capacity to allocate resources efficiently...or to deliver essential services" (Perrings 2006:418). Ecological resilience describes the ability of an ecosystem to absorb environmental disturbances as well as its capacity for renewal, reorganization, learning, adaptation and development, hence reflecting the degree of self-organization (Berkes et al. 2003; Folke et al. 2004; Folke 2006). The way in which economic, social and ecological characteristics are integrated is extremely important in order to permit systems dynamics and change. Analysing the resilience of SESs, Le Maitre and O'Farrell (2008: 371) point out that human-constructed resilience ultimately fails because of two important reasons: firstly, it locks social and economic systems in specific states and trajectories (as demonstrated in the use and development of technologies, market mechanisms, or ways of governance) which reduce the overall resilience and capacity to renew and reorganize; and secondly, it typically also reduces the resilience of the supporting ecological systems, often to the point that they can no longer provide essential services required by society and other populations (as are the cases of climate change and freshwater availability).

The need to understand the relationships between people and nature without the barriers and divides created by specific disciplines and knowledge holders led to the establishment of an interdisciplinary network of scientists and practitioners in 1999, the

Published as:

Xu, Li, Dora Marinova, and Xiumei Guo. 2015. "Resilience thinking: a renewed system approach for sustainability science." *Sustainability Science*. 10(1): 123-138. Doi: 10.1007/s11625-014-0274-4.

Resilience Alliance. Their resilience explanation and characteristics are widely accepted and form the basis of the definition adopted by the Intergovernmental Panel on Climate Change (IPCC 2014: 5), namely: "The capacity of... systems to cope with a hazardous event or trend or disturbance, responding or reorganizing in ways that maintain their essential function, identity, and structure, while also maintaining the capacity for adaptation, learning, and transformation". The Resilience Alliance emphasises explicitly that resilience is an essential properties of the linked social-ecological systems (Resilience Alliance 2012) and this is the approach taken here.

### **3.2 Increasing importance of resilience**

To present the growing concerns and importance of resilience research, we examined the annual numbers of cited publications from 1973 (when Holling introduced the notion) to 2013. The publications (including books, journal articles, working papers, theses, conference papers and reports) are directly related to the term in the contexts of sustainability, ecological systems, SESs and eco-economic systems, or any combination between them. We opted to examine cited publications rather than just publications as they can better represent the use and prevalence of resilience research among scientists. Further, we did not consider the number of cites as a more informative statistics. The keyword search to identify publications in *Web of Knowledge*, *Scopus* and *Google Scholar* is based on the word "resilience" and combinations of "ecological resilience", "economic resilience", "social resilience", "resilience and sustainability", "resilience and sustainable development", "resilience and social-ecological systems", "social-ecological resilience", "resilience and environment", "resilience and natural resources", "resilience and assessment" in the title, keywords or abstract.

Published as:

Xu, Li, Dora Marinova, and Xiumei Guo. 2015. "Resilience thinking: a renewed system approach for sustainability science." *Sustainability Science*. 10(1): 123-138. Doi: 10.1007/s11625-014-0274-4.

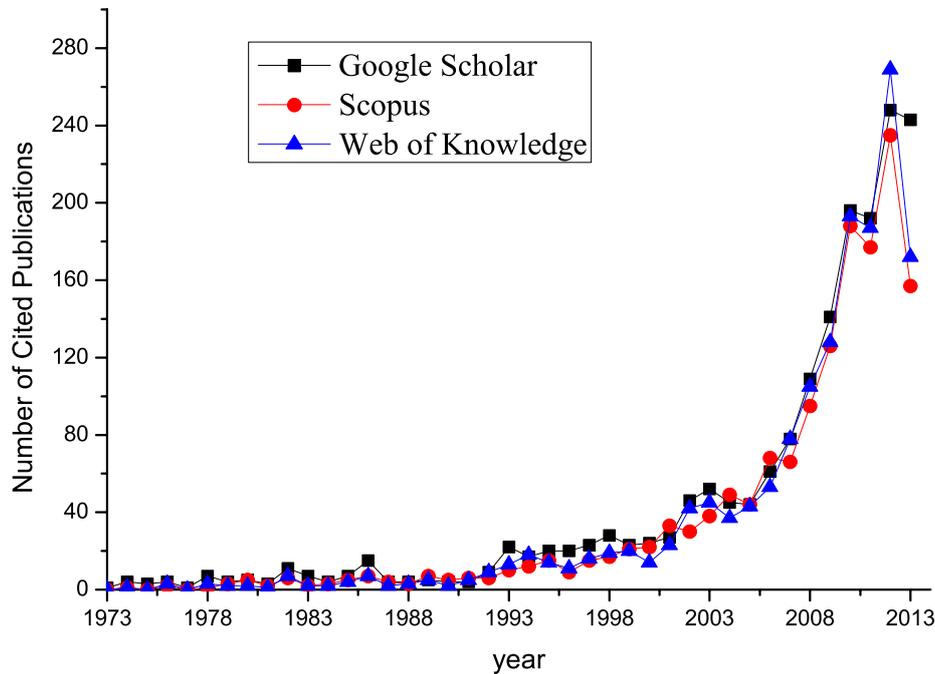


Figure 1 Number of cited resilience publications in three databases per year, 1973–2013

In total, there are 1765, 1495 and 1560 cited resilience publications in the *Web of Knowledge*, *Scopus* and *Google Scholar* databases respectively (see Figure 1). There is a clear increase in the annual figures which reached their peak at 269 in 2012. Sharp increases occurred in 1999 and more clearly after 2005. Despite the overall upward trend, numbers for individual years fluctuate. This is not surprising due to the fact that the newer the publications are the less citations they have. The dramatic decrease in 2013 is such an example. The observed trend is consistent with the findings by Janssen et al. (2006) who argue that the sharp increase since 1999 has partly benefited from the establishment of the Resilience Alliance network with its academic journal *Ecology and Society* coupled with the increased interest in global environmental change during 1990s. The active international political arena since 2005, including the release of the

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Millennium Ecosystem Assessment Reports in 2005, the Stern Review in 2006, the IPCC's 4th Assessment Report in 2007, as well as the continuing regular international climate change meetings and negotiations, all stimulated research interest in resilience.

The trends obtained from the three databases are similar (Figure 1), which shows consistent interest across commercial academic outlets and the freely available *Google Scholar* reference sources. Therefore we further investigated only *Google Scholar* scrutinising all publications one by one to identify the resilience focus, namely ecological, economic, social or integrated sustainability, each has adopted.

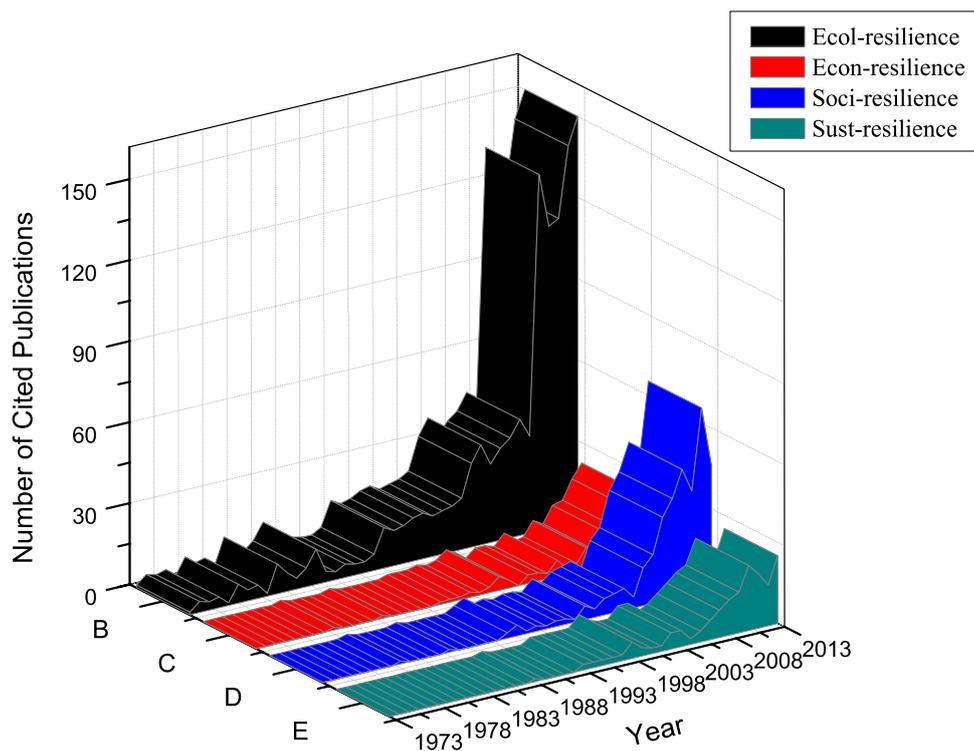


Figure 2 Cited resilience publications in different contexts

As shown in Figure 2, all four resilience contexts grew steadily since 1995 with the ecological aspects vastly overshadowing social, economic and sustainability integration. Overall, economic resilience attracted the least number of cited publications. Social

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resilience and integrated sustainability context publications have become quite important in recent years.

The above analysis is indicative about the trends in resilience research but may contain some deficiencies. Firstly, we made arbitrary judgement and applied our interpretation when classifying the publications into the four contexts groups to avoid double counting. We also did not use keywords that are considered synonymous, complimentary or characteristic of resilience, such as stability, adaptability, reliability and robustness, and antonyms of resilience, such as vulnerability and susceptibility. Non-English language publications were similarly excluded which maybe under-represent resilience research.

The findings show that resilience analysis experienced significant development and continues to increase. Nevertheless, the strong prevalence of ecological resilience indicates that more work needs to be done in the integration of environmental, social and economic knowledge in order for humanity to understand the occurring changes, self-organize to respond to them and increase its ability to learn and adapt.

#### **4 Resilience thinking and sustainability**

Assessing sustainability in the context of complex systems in the changing world requires a shift in thinking and perspective (Ludwig et al. 2001). The acceleration of human activities is the main external factor affecting the planet's ecosystem. This makes inappropriate the continual separation of ecological, social and economic impacts "even for analytical purposes" (Folke et al. 2010). Resilience represents such a shift in thinking and is described as a change from "fail-safe to safe-to-fail" (Ahern 2011:341) for sustainability management. The review below covers the conceptual connections between resilience and sustainability by discussing what resilience means for

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sustainability, how resilience contributes to sustainability, how a resilient system can be sustainable, and how to maintain the resilience of SESs in order to improve their sustainability.

#### 4.1 What resilience means for sustainability

What resilience means for sustainability is the first step in bridging the conceptual connection between the two. We discuss similarities and differences (Table 2) in their objectives, relationships, starting points, cultural aspects, and in relation to intergenerational equity.

Table 2 Similarities and differences between resilience and sustainability

	Resilience	Sustainability
<b>Similarities</b>		
<i>Objective</i>	A desirable ecological resilience can sustainably supply sufficient resources and keep its functions to meet the demands of social and economic wellbeing without shifting the regimes in the face of perturbations and unforeseen shocks	Strong definition of sustainability includes an important criterion, namely that the stocks of natural capital are maintained at or above existing threshold levels for humans wellbeing
<i>Dependency relationship</i>	The basic ecosystem functions should not be affected by human activities or other disturbances beyond their thresholds and socio-economic systems would not collapse because of changes in the states of ecosystems (precondition of sustainability)	The sustainability of a system relies on its own resilience while such resilience depends on a wide range of properties which affect the system itself (goods and services that ecosystems can provide)
<i>Starting points</i>	The first important thing for applying resilience thinking to practice is to define resilience in terms "of what to what"	The sustainable state of not only social systems but also environmental systems (sustainability of what) to both present and future generations (sustainability to what)
<b>Differences</b>		
<i>Intergeneration equity</i>	Resilience thinking does not conceptually emphasise equity, meaning the resources for next generations are not less than for the current generation	Intergenerational equity is the core concept of sustainability, whose concerns are about previous injustices and the future generations' unreduced accessibility to resources as the current generation has
<i>Desirable state</i>	Resilience thinking does not specify	Sustainability is interested in the

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	explicitly the desirability of a particular state	desirability of any state the system is and how it transitions to another more desirable state
<i>Culture emphasis</i>	Culture is considered as a part of social mechanisms	A strong body of sustainability research exists that acknowledges culture as the fourth pillar and capital distinctive from the natural, physical and human capital
<i>Methodological approach</i>	Resilience relates to responses to external factors	Sustainability relates to the evolution, and co-evolution, of complex systems that embed natural, social and environmental components and dimensions

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#### 4.1.1 Similarities

Resilience thinking is similar to the objective of sustainability. With a resilience capacity, the system is able to keep its current equilibrium state and endure external perturbations – either from nature or human activities. This equilibrium not only relies on the stock of natural resources but also on the degree of social and economic wellbeing which consist of the three sustainability pillars. The advocated strong definition of sustainability includes an important criterion, namely that the stocks of natural capital are maintained at or above existing threshold levels. This is germane to ecosystem resilience as resilient ecological systems are important for human life and the strong sustainability criterion should be an indispensable guideline for sustainability (Ott 2003).

In other words, the loss of resilience can lead to the loss of adaptive capacity of SESs, thereby the loss of the opportunity during periods of re-organization and renewal, which will take them on an undesirable trajectory termed unsustainability (Folke et al. 2002). By contrast, a desirable resilience of an ecosystem can sustainably supply sufficient resources to meet the demands of social and economic wellbeing without

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reducing their stock below the thresholds. This desirable resilience is in accord with the goal of sustainability that a harmonious development between nature and human society. Besides, the central aspects of resilience are the "environmental basis for human activity and the temporal dimensions of development and wellbeing" (Adger 1997:3). Consequently, some argue that resilience thinking is equivalent to sustainability, and resilience is the preferred way to consider sustainability in social as well as natural systems (Levin et al. 1998; Derissen et al. 2011).

Secondly, resilience is a crucial condition for sustainability in that sustainable development requires both ecosystems and socio-economic systems to be resilient (Gunderson and Holling 2002). This is due to the fact that the relationship between ecosystems and human socio-economic systems is complex and interdependent, i.e. a dependency relation (Adger 1997 & 2003). The sustainability of a system relies on its own resilience while such resilience depends on a wide range of properties which affect the system itself (Perrings 1998). Socio-economic development is based on the goods and services (capacity) that ecosystems can provide, whilst such development in turn affects the state of the ecosystems. That is, if those goods and services are able to serve development over extended periods of time meanwhile the development does not jeopardise or collapse the functions of the ecosystems, then sustainability can be achieved. What resilience means to sustainability here is that the basic ecosystem functions should not be affected by human activities or other disturbances beyond their thresholds and socio-economic systems would not collapse because of changes in the states of ecosystems. Sustainability management, therefore, needs to be focused on building resilience (Folke et al. 2002) so as to secure societal development and avoid vulnerability.

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It is clear that resilience thinking and sustainability have the same starting point. The first important thing for applying resilience thinking to practice is to define resilience in terms "of what to what" (Carpenter et al. 2001). This can also be interpreted as resilience over what time period, to whom and at what scale. Resilience "of what" can be regarded as what system state is being considered, and resilience "to what" is what perturbations are of interest (Carpenter et al. 2001). For example, the desired resilience of a lake is to be in a clear-water state over a long time period and the perturbations are all industrial, water utilities, transport and recreational activities around the lake combined with climatic, environmental, geological and other natural events. Similarly, sustainability emphasises the sustainable state of not only social systems but also environmental systems (sustainability of what) to both present and future generations (sustainability to what), i.e. achieving intergenerational equity.

Although resilience does not directly highlight intergenerational equity, it implies that a resilient system should be able to maintain a desirable configuration over a long time period in the face of external perturbations – a prerequisite for intergenerational equity. The fairness of intergenerational welfare distribution relies on the planet's life-support systems and could be enhanced by resilience management. If a system collapses from external shocks, intergenerational equity would never be reached. Hence, both resilience and sustainability are achieved on the basis of temporal (i.e. present and future generations and long-term functionality) and spatial (i.e. consideration of all connections and feedbacks between systems) integrity. However, while the temporal integration is expected to be homogenous, namely equal opportunities and continuing provision of services, the spatial integration is heterogeneous and highly dependent on the unique circumstances of any particular SES.

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#### 4.1.2 Differences

In spite of similarities between resilience and sustainability, they are not identical notions and cannot replace each other. The main difference is that resilience thinking does not emphasise the long-term time dimension and equity, meaning the resources for next generations are not less than for the current generation. By contrast, intergenerational equity is the core concept of sustainability, whose concerns are about previous injustices and the future generations' unreduced accessibility to resources as the current generation has (Golub et al. 2013). Resilience places more focus on the state of a system when facing disturbances. In fact, in some cases the system remains resilient as long as the critical tipping points are not passed, even though the stock of resources is reduced and less available than previously. Such a system is not sustainable based on the principle of intergenerational equity. In other words, unlike sustainability, resilience does not always stand for the desirable state of SESs; a system could be highly resilient for those systems (especially ecosystems) with multiple equilibriums without achieving the goal of equity that sustainability requires. Carpenter et al. (2001) show that system states that decrease social welfare, such as polluted water supplies or dictatorships, can be highly resilient.

Another difference relates to the approach towards culture. In resilience, culture is considered as a part of social mechanisms, covering social belief, values, knowledge, and behaviours as well as social norms formed in relation to ecological health (Folke et al. 2000; Berkes et al. 2000; Walker and Salt 2012). In sustainability, however, there is a strong body of research that acknowledges culture as the fourth pillar and capital distinctive from the natural, physical and human capital (Throsby 1999 & 2009). Throsby (1999) distinguishes between two forms of cultural capital: tangible (e.g. buildings, art

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works and locations with cultural significance) and intangible (intellectual capital, e.g. social ideas, practices, beliefs and values). Both tangible and intangible capital is inherited from former generations; in terms of equity, sustainability requires us to hand it on to the next generations.

Sustainability is an overarching goal that includes assumptions or preferences about which system states are desirable. Hence when applying resilience in sustainability research, it needs to make sure the system does not flip from a desirable into an undesirable state, or alternatively moves from one undesirable into another undesirable state (Carpenter et al. 2001; Derissen et al. 2011). Critics of resilience, such as Nadasdy (2007) and Homborg (2009), even argue that maintaining capitalist social-ecological relations as a goal for resilience is undesirable as it means continuing the exploitative economic imperatives of modern extractive and agricultural industries. Similarly, the resilience of outdated technological systems could represent barriers to the introduction of better innovations as is the case of fossil fuel based energy systems. According to Jerneck and Olsson (2008: 170), resilience "depicts incremental changes and capacity to preserve systems within given frames but does not recognise that social change mainly implies transitions to renewed forms of production, consumption and distribution with new combinations of organisation, institutions and technology" which represent important areas of research in sustainability.

There are also methodological differences in the way the two notions are conceptualised. Resilience relates to responses to external factors while sustainability is associated with the evolution, and co-evolution, of complex systems that embed natural, social and environmental components and dimensions (Todorov and Marinova 2011).

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Hence, resilience thinking is not sufficient for sustainability and cannot be used to totally replace sustainability as the final objective.

#### **4.2 How resilience contributes to sustainability**

Sustainability is not a perpetual state of a system but evolves through reacting with external and internal factors, thus "sustainability implies not only an enhanced capacity to adapt in the face of changes, but also cope with unexpected events" (Milestad and Darnhofer 2003:83). Building resilience for SESs is the vital pathway to achieve such long-term sustainability as a way to deal with changes and uncertainties (Folke et al. 2002; Milestad and Darnhofer 2003; Quinlan 2003; Berkes 2007). Ecosystem resilience can be regarded as a clear and operational concept of sustainability (Perrings 1998). Human activities can only be seen as sustainable on the condition that the ecosystems where they are occurring and on which these activities rely are resilient (Arrow et al. 1995). Sustainability can be deemed to be the desirable objective of human development whilst resilience thinking is the way to get to this goal. The greatest contribution of resilience thinking to sustainability therefore is its role in linking the visionary and broad theory of sustainability into practices in more specific ways, namely the applications of resilience thinking to different realms for pursuing sustainability.

Resilience contributes to social sustainability. Community resilience is one of the important indicators of social sustainability (Magis 2010); social and ecological resilience have a clear link, in particular for social groups or communities reliant on ecological and environmental resources (capital) for their livings (Adger 2000). From a sociological perspective, building resilience for SESs is beneficial for adapting to globalization, diminishing vulnerability, alleviating poverty and promoting social

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justice (by accounting for resource allocations and policy decisions) thereby for long-term sustainable development (Adger 2003; Quinlan 2003; Berkes and Folke 2000). That is, a resilient SES is able to provide natural capital for human development and is capable of tolerating the stress imposed by environmental change and human activities, which no doubt enhance intra-generational justice in the short term and inter-generational justice in the long run by balancing human demands and natural carrying capacity. This kind of relative balance state (equilibrium) and social justice are the utopian aspiration of sustainability.

On the other hand, as one of the dispensable components of social systems, economic systems similarly have close relations with ecological resilience. Perrings (2006) conceives that two aspects of resilience change might jeopardise the sustainability of economic development. The first is the importance of systems' thresholds, irreversibility and hysteresis for resilience on the grounds that the loss of resilience in ecological-economic systems implies a change in the range of socio-economic or environmental conditions over which the system can maintain the flow of services. The second aspect is the role of heterogeneity or diversity. Perrings (2006:418-419) explains that the resilience of ecological systems in any state is dependent on "the economic use of the system... the connection between economic usage and resilience lies in the impact of either extraction (habitat destruction, harvesting, pest control) or waste disposal (pollution of air, soils and water) on the composition of the species that support ecosystem functioning and process". In this sense, market-based management can be the effective way to ensure ecological resilience for economic sustainability but some missing markets for properties of the system such as carbon pollution or species preservation must be taken into

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consideration carefully because they may affect resilience (Perrings 2006). Hence, the use of price mechanisms alone may push the system to undesirable states and closer to thresholds invisible for the market. While ecological resilience improves economic sustainability, the reverse is rarely the case.

The studies applying resilience thinking to global issues at multiple scales, in particular in interdisciplinary analysis, are also paving the way for sustainability research and practice. For instance, studies on resilience of ecosystems have been widely carried out on lakes and aquatic systems that can flip from clear water to turbid water (Scheffer 1993; Carpenter et al. 1999; Scheffer et al. 2001; Gunderson et al. 2006; Baudo 2002; Folke 2003), forests (Steneck et al. 2002; Hirota et al. 2011), coral reefs (Nyström et al. 2000; Mumby et al. 2007), fisheries (Bueno and Basurto 2009), agricultural systems (Perrings and Stern 2000; Cabell and Oelofse 2012), and catchment management (Walker et al. 2009). However, these studies lack an integration perspective, and largely adopt ecological points of view. Other research has examined different community systems. For example, Adger et al. (2005) focused on social-ecological resilience of coastal areas; Newman et al. (2009) used resilience as one of the scenarios to analyse the future of cities; Anderies et al. (2002) developed a stylized mathematical model to explore the effects of physical, ecological and economic factors on the resilience of rangelands; other focused on urban ecosystems (Muller 2007; White and Stromberg 2011). Analysing the social aspects of systems' resilience is more difficult than examining a single distinctive ecosystem because of the complex interplay between socio-economic and ecological systems. Research led by the Resilience Alliance has stimulated interdisciplinary investigations through using resilience thinking as an overarching framework and focusing more on the socio-economic aspects

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of the systems. Examples of these are books, such as "Panarchy" (Gunderson and Holling 2002), "Resilience thinking" (Walker and Salt 2006), "Foundations of ecological resilience" (Gunderson et al. 2010), "Principles of ecosystem stewardship", and many articles (Endfield 2011; Adger 2000; Adger et al. 2005; Perrings and Stern 2000). They explore in depth issues, such as how communities absorb disturbance and maintain function, why social systems are not just ecosystems, how to build resilience for ecological and socio-economic systems, all of them are contributing to promoting our understanding of sustainability.

### **4.3 How can a resilient system be sustainable**

The first thing in exploring how a resilient system can be sustainable, particularly for SESs, is to measure its resilience. Below we briefly discuss indicators, criteria and models to this end.

#### *4.3.1. Indicators for social-ecological resilience*

Measuring resilience in SESs ought to start with thinking about the abilities of reorganization, learning, and adaptation of the systems combined with adaptive cycle analysis (Carpenter et al. 2001; Walker et al. 2002) or with systems' capacity of motivation, knowledge (information, knowledge and creativity) and capacity (Lambin 2005; Pierce et al. 2011). For example, the indicators developed for SESs' resilience of river basins on the basis of key subsystems that include biophysical (surface hydrology, climate, groundwater, native vegetation, river channels, wetlands and floodplains), economic (market values, non-marketed values, intrinsic values, bequest values and option values) and social (governance system, social networks, organizations and human capital) aspects (Walker et al. 2009). For SESs in agricultural regions, productive land use, agricultural establishments, farmer age, farmer terms of trade and

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wheat yield were selected (Allison and Hobbs 2004) and 13 behaviour-based indicators around aspects of the ability to meet food, fuel and fibre needs of humans in the future (Cabell and Oelofse 2012) were developed to diagnose agro-ecosystems' resilience. From a sociological perspective, resilience should be captured by social and ecological aspects with empirical indicators, such as institutional structures, population displacement, migration and mobility which may be affected by environmental variability like extreme events and resource dependency (Adger 2000).

Yet, the indicators of SESs' resilience have not reached common usage partly because the data are usually hard to collect. Some social ecologists (Carpenter et al. 2001 & 2005; Scheffer et al. 2000; Walker and Salt 2006; Darnhofer et al. 2010) suggest that the insights of measuring resilience can be transferred to identify "surrogate indicators" which are inversely related to the resilience of the system. For instance, the desirable resilience of lake systems (a clean water state) can be measured by indicators, such as the ability of farmers to reduce nonpoint pollution from their lands, if they can afford to leave wetlands undisturbed; public support for controlling pollution; economic indicators, including externalities captured by market means such as phosphorus or quotas determined by the market, phosphorus pollution costs in the market; social indicators, including social networks or groups that facilitate collaborative actions.

Existing sustainability indicators lack the propensity to present information about the ability of systems to improve their current state to become sustainable over time in the face of growing uncertainties. To fill such gap, research endeavoured to incorporate resilience directly into sustainability with the purpose of measurement (Milman and Short 2008; Walker et al. 2010b; Mäler and Li, 2010). As one example, Milman and Short (2008) developed a Water Provision Resilience index to fill the deficiency of the

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existing indicators, which can only measure the current state of human wellbeing rather than the capacity of maintaining water accessibility over time and absorbing external stresses, for sustainable water provision in cities. Despite the contribution of this study to linking resilience thinking to sustainability assessment, there is still room for new knowledge. For example, the assessment of this study was conducted by an expert participation way and the data was on the basis of qualitative analysis. However, quantitative data may provide more reliable source for any sustainability assessment but data about natural systems is difficult to gather (even non-observable) in many cases. Appropriate surrogate indicators, which may be easier to collect in terms of data, thus need to be explored. Also, limitations of resilience indicators are that they are unpredictable and there are still gaps in our understanding of how they would behave in more complex situations. Indicators should allow to be used as early-warning signals in future stochastic shocks (Scheffer et al. 2012). The work has begun but much more needs to be achieved.

#### 4.3.2. *Measuring criteria*

It is an important question to recognise whether the resilience of SESs is increasing or decreasing thereby determining how far it is to sustainability. A well-defined threshold (or a magnitude that a system can absorb before it flips to another state; or a breakpoint between different regimes) can be used to achieve this goal (Walker and Meyers, 2004; Walker et al. 2010a). Because of the complexity of SESs, the thresholds of their components are influenced by many factors. It is important to identify the crucial variables or drivers (fast and slow) together with their thresholds which determine the dynamics of the system as well as the interacting processes evidenced in the SESs (Walker et al. 2002; Walker and Meyers 2004; Kinzig et al. 2006; Walker et al. 2009).

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When the critical threshold level of an underlying variable is crossed, a regime shift happens. Such a shift can occur in four situations (see Figure 3).

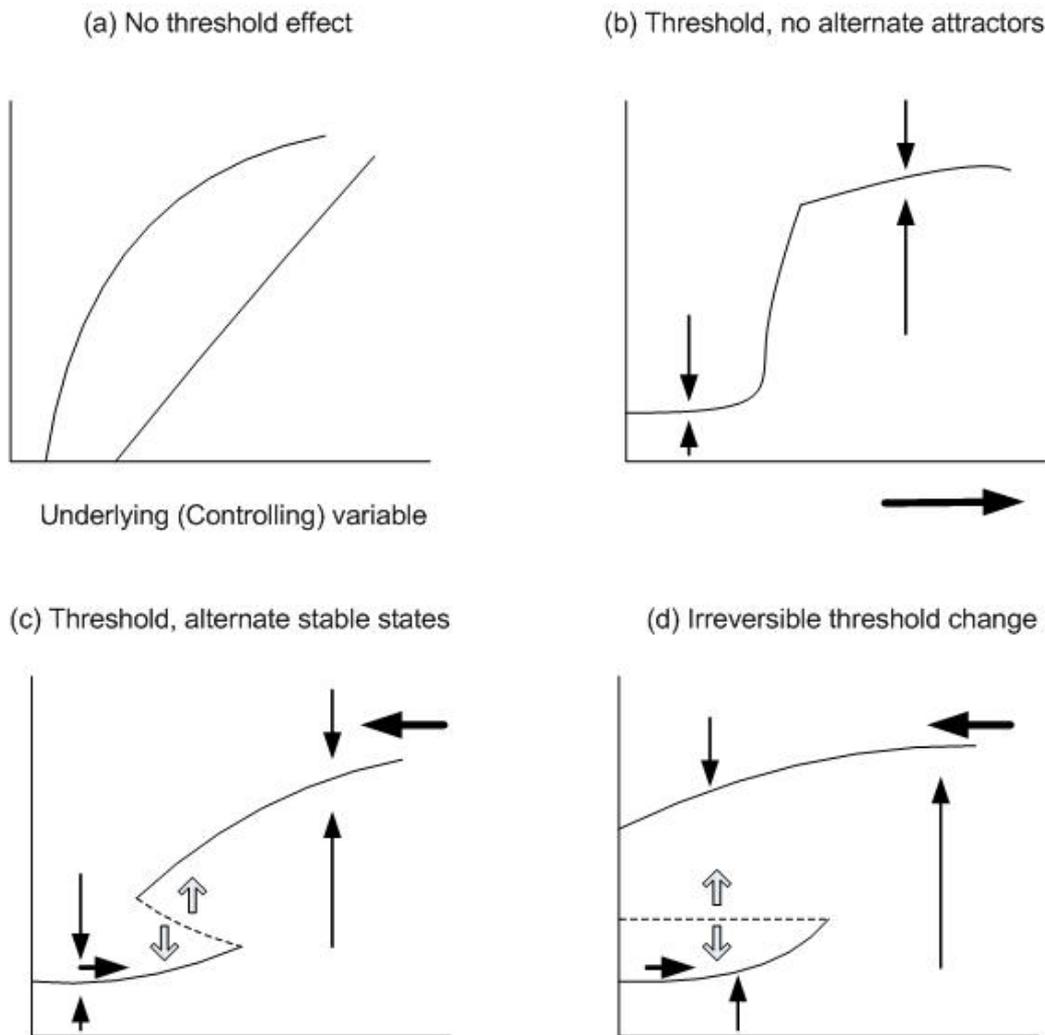


Figure 3 Relationships between possible equilibrium state of a system and underlying variable

Note: The x-axis denotes the state of the underlying (critical) variable/s and the y-axis represents the state of the system, with the units of measurement depending on the state of the respective variables. The lateral arrows in (c) and (d) represent the direction of change.

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There is no discontinuity happening in Figure 3 (a) where the state of the system changes continuously with the change in the critical variable; this situation depicts how the system state changes without the effect of thresholds. In Figure 3 (b), a dramatic change happens to the state of the system; however this is reversible as there is no completely different configuration for the system. Critical thresholds exist for the underlying variables of the system in both Figure 3 (c) and (d) and they have important effects which trigger discontinuous changes on the state of the system. Both (c) and (d) have hysteretic responses to the changes in the underlying variables under the effects of thresholds. In (c) the change is reversible while (d) is irreversible (Walker et al., 2010a & 2010b). In this case, social-ecological resilience can be explained as how much disturbance SESs can absorb. For example, a contraction below the threshold level leads to loss of jobs and decline of social networks for the dairy and fruit processing sectors; a tipping point effect exists in terms of costs and benefits from maintenance investment; tree cover affects the water table depth and also native biodiversity; and water table depth and salinized area depend on rainfall, thus on climate, water allocation, energy cost, infrastructure and tree cover.

For the management purposes, we need to recognise in which resilient regime the SESs should be, what variables determine the change of the system state, and whether there have thresholds in there, if so what thresholds need to be identified to avoid the system flipping into an undesirable regime. Some thresholds can be quantitatively identified while others are not accessible or unidentifiable, in particular for slow variables. Accordingly, research on thresholds typology is advocated as a priority topic in sustainability (Walker and Meyers 2004). This requires considering which thresholds are fixed, where they come from and how they are bundled through understanding

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ecosystem services, and which can be changed and categorising thresholds according to various uncertain drivers of resilience, e.g. known (known to exist or fairly certain), strongly suspected, and possible (with a fair degree of uncertainty) (Walker et al. 2009; Walker and Salt 2012). For example, there are two regimes in most freshwater lakes: desired – clear water, submerged vegetation and preferred fish species, and undesired – eutrophic, turbid and few fish, state. The state is dependent on variables such as vegetation and fish composition, oxygen levels in water, and phosphorus and nitrogen input from agricultural land (the main external disturbance). Water clarity is hardly affected by increased human-induced nutrient loading until its concentrations is over a critical threshold. Effective policy for preventing the regime shifts can be focusing on strategies aimed at reducing nutrient loading at source, such as regulation of fertilizer use and promotion of phosphorus-free detergents. Unknown thresholds (suspected and possible), also called potential concern thresholds (Walker and Salt 2012), are more likely presented in social and economic domains that are context dependent and require identifying ways of looking for them, especially critical ones, in similar systems. For instance, unknown thresholds in economic systems of a river basin include farm income (debt ratios), state of infrastructure and presence of high-multiplier economic sectors. The explanation is that the increased cost of water use will enhance on-farm innovation and water use efficiency, but will require increased capital investment (Walker et al. 2009). Thresholds in social systems include mainly balance among values held by individuals, which can be influenced by communication, policy or management. Thus, policy for enhancing socioeconomic resilience could be focused on these influenced aspects. For systems with no thresholds, for example cultural capital (e.g. a heritage

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building is ruined if a fire happens), policy arrangements should focus on avoiding disturbed the system.

However, how to measure thresholds for SESs still remains as a challenge for researchers. The urgent issue is not only to know what they are or which systems have thresholds but also to gauge where the system thresholds are and how to measure them. Many studies have attempted to address such questions. Among them "Planetary Boundaries" (Rockström et al., 2009) made the contribution of identifying and defining the thresholds for our planet. In it, the thresholds were defined by controlling variables (parameters), such as carbon dioxide concentration for climate change, in the Earth-system process (Rockström et al., 2009). The authors used a risk-averse approach to quantifying the planetary boundaries but considerable uncertainties remain in relation to the true position for many thresholds, such as for atmospheric aerosol loading and chemical pollution. Also, the thresholds defined in the "Planetary Boundaries" study may be conservative due to the fact that in places which are particularly vulnerable they would be much lower.

In cases when we know what the thresholds are, empirical data is useful for measuring the position of a system. However, if critical variables (typically for linked social systems) are not yet evidenced or hard to identify, what other options could be is another issue. One of the key reasons why thresholds are difficult to measure is that often they are not constant and can change along a determining variable or with scale or with changes in system feedbacks (Conway 1997; Walker 1993; Walker and Meyers, 2004). The rangelands system is such an good example – if the grass layer consists of all perennials, the threshold ratio of shrubs to grass is higher than if the grass layer embraces only annuals (cited in Walker and Meyers, 2004). To deal with unknown

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thresholds and those that have not yet been crossed as well as with those that cannot be quantified, Walker and Meyers (2004) recommend extrapolation from related systems whose thresholds have been observed. Further examples and empirical data are freely available in the regularly updating database developed by the Resilience Alliance (<http://www.resalliance.org/>).

Another options is to use a broad scale indicator as the signal for the measurements, such as microbial indicators for showing the dynamic nature of nutrient-production linkages and thresholds between water bodies (Paerl et al. 2003). For large spatial and temporal scales, approaches including surveys, experimental manipulations, paleo-ecological reconstructions and models (Groffaman et al. 2006). For some complex SESs, it is advised to develop surrogates as an effective way to measure thresholds (Carpenter et al. 2005). This requires describing the system's identity of interest in a way that the potential thresholds can be analytically described. The study by Blythe (2014) is a good example of this. It explored the social thresholds in two coastal fish communities in Mozambique by using stakeholder engagement and developed future scenarios to describe potential social responses to crossing a system threshold.

Overall, it is easier to identify thresholds that have been passed than those that may occur in the future. Yet the goal of sustainability is to avoid passing thresholds. Thus the most urgent but also challenging mission for sustainability is to identify and quantify critical social-ecological thresholds in SESs. Since some of thresholds in SESs may not be directly observable, possible approaches include scenarios (Walker et al. 2002; Folke et al. 2002), surrogates indicators combined with assessment modelling (Carpenter et al. 2005) and generic empirical indicators (Scheffer et al. 2012) are highly recommended.

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As well, to better determine them, the understanding in-depth of complex dynamics between different thresholds is needed as the cross effects and the delicate balance (Rockström et al., 2009) exist among them in our planetary system.

#### 4.3.3. *Measuring models*

The widely applied conceptual model for measuring resilience is *Panarchy* that is used to analyse the source and role of change in systems – the interplay between change and persistence, the predictable and unpredictable and between different phases (exploitation, reorganisation, conservation, and release) by means of an adaptive cycle (Gunderson and Holling 2002), including relationships between long-term environmental change and economic development (Allison and Hobbs 2004). Panarchy explains well the rules of how changes happen in nature with taking place and interacting at various scales from local to global (Allen et al., 2014). As there already exists detailed discussions and reviews of this theory (Gotts 2007; Holdschlag and Ratter, 2013; Allen et al., 2014), we examine the mathematical models which have attracted less attention.

Most of the existing models which attempt to assess resilience for sustainability are developed from an economic perspective. They tend to cover economic costs (Anderies et al. 2002), resource stock and environmental accounting with a pricing approach (Perrings 1998; Perrings and Stern 2000; Walker et al. 2010a; Mäler and Li 2010; Derissen et al. 2011; Scheufele and Bennett 2012). For instance, a Markov model was employed to analyse the dynamics of economic-environmental systems in terms of resilience by Perrings (1998) while Walker et al. (2010b) and Mäler and Li (2010) priced resilience on the basis of a probabilistic approach. We take Inclusive Wealth (IW) model as an example in this review because of its implementation for policy makers and

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closer connections to the typologies of thresholds (known and unknown) which we discussed before.

The IW model aims to evaluate inevitable trade-offs and resilience by the way of environmental accounting and by taking consideration of known or suspected thresholds (Walker et al. 2010b). According to the IW approach, inter-temporal social welfare is defined on a vector of consumption flows, i.e. goods and services. The social welfare function can be given by (1) which is assumed as a monotonically increasing and strictly concave function (cited in Walker et al., 2010b).

$$W_t = \int_t^{\infty} U(C_{\tau})e^{-\delta(\tau-t)} d\tau \quad (1)$$

where  $W_t$  represents social welfare,  $\delta$  is a positive constant which stands for the utility discount rate, to which  $W_t$  is subject, and  $U(C_{\tau})$  is the function of consumption flows (utility of goods and services).

Based on the IW model, Walker et al. (2010b) define sustainable development as non-decreasing social welfare in the long-term, namely the present value of any future utilities must be maintained over time, and short-term declines in instantaneous consumptions are allowed but need to be offset. Accordingly, they use capital stocks, time and the resource allocation mechanism to describe social welfare. Social welfare is then measurable in terms of the value of capital stocks through shadow prices of capital assets. The change in welfare over an infinitesimal period of time can be measured, as it is equivalent to the change in the capital stocks. The welfare change is given by equation (2).

$$V_T - V_0 = \sum_i (p_{iT} K_{iT} - p_{i0} K_{i0}) - \int_0^T \left( \sum_i K_{it} \frac{dp_{it}}{d\tau} \right) d\tau \quad (2)$$

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where the first part is capital gains and the second part is endogenous price changes;  $V_T$  is the value of the capital stocks at time T,  $V_0$  is the initial value of the capital stocks,  $K$  represents capital stocks. If  $K_i$  does not change between two times, there has been no change in IW. If  $V_T - V_0 \geq 0$ , then the system can be viewed as sustainable as social welfare is non-decreasing over this period.

In incorporating resilience into the assessment of sustainability, Walker et al. (2010b) quantify resilience by using the critical thresholds (distance to threshold) and measuring the shadow price, which reflects the future change in social welfare from a marginal change in current resilience (capital stocks) in terms of welfare. After introducing cumulative probability distribution and net benefit, the price of one more unit of resilience at time 0 can be estimated by equation (3).

$$q(0) = \frac{\partial E(W_0)}{\partial X_0} = \int_0^{\infty} \frac{\partial S(X_0, t)}{\partial X_0} [U_1(t) - U_2(t)] e^{-\delta t} dt \quad (3)$$

where  $E(W_0)$  is the expected intertemporal welfare, i.e. the expected present value of future utilities from the initial time 0.  $S(X_0, t)$ , called the survival function, represents the probability that the system has not flipped before time  $t$  and equals to  $1 - F(X_0, t)$ ;  $F(X_0, t)$  represents the cumulative probability of a flip up to time  $t$  and  $X_0$  is the initial resilience stocks;  $U_1(t)$  and  $U_2(t)$  is the net benefit at time  $t$  in the situation that the system has not bifurcated and the net benefit if the system has bifurcated before (or at) time  $t$ , respectively.

How can the IW model contribute to policy making? As an example, the IW model was used in Goulburn-Broken Catchment management project to assess the value of different policy options (Walker et al. 2010b). Whether the enhanced pumping policy, aiming to control water flows for regulating the water table, is feasible or socially profitable can be evaluated by the model by comparing welfare using accounting prices.

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Accordingly, the estimated values of IW are calculated to be \$46 and \$57 million in normal climate and dry climate scenarios, respectively. Accepting that the value of the enhanced pumping capacity is equal to the value of the enhanced resilience enabled by it, whether the policy is socially profitable can be evaluated by comparing if the cost of the policy to reduce the initial water table by 1 metre is less than the estimated value (i.e. \$46 and \$57 million).

Economic accounting of resilience for the assessment of sustainability is a direct way to analyse how resilience in SESs interacts with different variables. However, to implement this approach requires information about the probability of an ecosystem shift, which in many cases is unpredictable and unobservable. Despite the IW model being a good theory for evaluating projects and policy options, it relies heavily on estimates of parameters, such as capital stock and shadow prices which in many markets are hard to calculate, and expectations about the future, such as related to climate, which are unforeseeable. The estimation of parameters in the model thus needs to be analysed according to the specific situation (Walker et al. 2010b). Likewise, the existing models do not lay enough emphasis on the impacts of human activities on the resilience of SESs, while in reality these are becoming an increasingly detrimental driving force in pursuing sustainability. Any future research on resilience modelling for sustainability needs to integrate environmental and social disturbance variables to provide more meaningful insights.

#### **4.4 How to manage resilience for sustainability**

Sustainable management requires effective and efficient management strategies for social-ecological resilience (Scheffer et al. 2001). Folke et al. (2000) suggested seven general principles for building resilience for sustainability management: (1) using

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management practices based on local traditional ecological knowledge; (2) designing management systems that 'flow with nature'; (3) developing local ecological knowledge for understanding cycles of natural and unpredictable events; (4) enhancing social mechanisms; (5) promoting conditions for self-organization and intuitional learning; (6) rediscovering adaptive management and (7) developing values consistent with resilient and sustainable SESs.

From this perspective, management practices fall in three categories (Berkes et al. 2000): (1) practices found in both conventional resource management and some local societies (e.g. monitoring resource abundance and change in ecosystems; species and habitat protection); (2) practices abandoned by conventional resource management but still found in some local societies (e.g. multiple species management, resource rotation and succession management); and (3) practices related to the dynamics of SESs seldom found in conventional resource management but existing in some traditional societies (e.g. management of catchments, landscape patchiness and nurturing sources of ecosystem renewal). There are also complex social mechanisms relating to institutions, cultural internalization, and worldview behind traditional ecological knowledge practices. Institutions, either formal or informal, provide rules for individuals to organise their activities that produce outcomes affecting them and maybe others (Olsson et al. 2004). Worldview shapes cultural values, ethics, basic norms and rules within a society (Berkes et al. 2000).

The above principles are only the start in analysing SESs and sustainability, further identifications and interpretations are needed for specific studies (Berkes et al. 2000). Notwithstanding this, they clearly show that the two main components of management practices are local ecological knowledge and social mechanisms.

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People play a key role in the process of managing resilience. The first step is to identify the right people to be involved in the management practices and consideration should be given to users of resources (people from government agencies, industry groups and local stewardship groups) and people who hold the knowledge (individual, community, specialist, organizational and holistic) (Walker and Salt 2012:36). The next step is for local ecological knowledge to contribute to management practices. Views from people can help managers to specify what should be known about what is happening at different scales, their connections and what is important to the system (Walker and Salt 2012:39). Social mechanisms could be enhanced through financial interventions (investments, subsidies or taxes), building up flexible governance or institutions (multi-level and polycentric) and improving education and training to achieve active adaptive management and social-ecological resilience (Adger et al. 2005). Furthermore, resilience policies for sustainable development should: (1) strengthen the perception of humanity and nature as interdependent and stimulate building resilience in SESs; (2) create open institutions for learning and flexible collaboration as well as direct actions towards building adaptive capacity; and (3) stimulate the development of indicators and warning signals of gradual change, loss of resilience and thresholds, and develop friendly technology and economic incentives to enhance resilience, encourage learning and incorporate ecological knowledge into institutional structures (Folke et al. 2002; Adger et al. 2005).

In addition, other studies advocate increasing collective actions, i.e. coordination of efforts among groups of individuals to achieve a common goal, as a way to manage resilience for sustainability (Ostrom 1990; Tompkins and Adger 2004; Olsson et al., 2004; Fiksel 2006). For the collective action to be effective, the interests of different

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stakeholders should be carefully considered. Smaller groups that consist of diverse stakeholders with similar interests are more likely to be successful than large ones, and members of the group should have equal endowments (Ostrom 1990; Tompkins and Adger 2004). Co-management institutions are put forward as a form to achieve such collective action. Tompkins and Adger (2004) found that expanding the networks of dependence and multilevel engagement (local, regional, national and international) can contribute to building co-management institutions thereby social and ecological resilience. Olsson et al. (2004) argued that institutional and organizational landscapes should be investigated to identify what contributes to the resilience of SESs identifying important aspects of the co-management process, including legislation, leadership and trust, funds for responding to environmental change and remedial action and information flow through social networks.

Some economic means can induce change in the resilience of SESs thereby its sustainability; enhancing the resilience of SESs thus requires identifying and controlling those economic variables. For instance, price shocks to products which may affect environmental conditions can result in changes of the state of systems, and the price has different impact on change and return. A fertilizer price that induces a change of state of the lake is very different from a fertilizer price that induces a return to the original state (Perrings 2006). The ecosystem must be able to provide goods and services continuously for human development, to maintain "manageable levels of government and external debts" and to avoid "extreme sectoral imbalances which damage agricultural or industrial production" (Harris 2000:5-6). To achieve sustainability economically, a market discount rate is advocated for natural resources such as soils, and atmospheric functions should be treated as aspects of natural capital (Daly 1994).

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Particular economic implications to enhance resilience and sustainability highlighted by Perrins (2006) are to: (1) understand the ecological-economic systems dynamics as any feedback control mechanism, such as the market policy process, may be misdirected; (2) identify the existence of both ecological and economic thresholds (such as price beyond which activities have important consequences for physical conditions) and the consequences of crossing the thresholds; (3) understand the role of natural, financial and produced assets in the management of financial and ecological disturbance; and (4) pay more attention to the trade-off between productivity and resilience.

In summary, increasing co-management by engaging stakeholders, linking social networks and enhancing social mechanisms by emphasizing local and scientific ecological knowledge, facilitating social learning and establishing flexible institutions are the key measures for building resilience for sustainability in the foreseeable future. However, further research and efforts are still required to achieve such goals. There is need to explore multi-scale effects, how to evaluate environmental, social and economic trade-offs, how to monitor and evaluate strategies, how to identify and engage with stakeholders. Resilience thinking is still in its infancy while sustainability imperatives are becoming increasingly pressing for research and people to address.

## **5 Concluding remarks**

Sustainability is about a harmonious relationship between the natural and human world. It relies largely on SESs being able to withstand the increasing external uncertainties and perturbations. Managing for resilience is the best possible way to enhance the likelihood of sustainability in this uncertain future (Walker et al. 2004; Adger 2005; Berkes 2007; Folke 2006).

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The review presented provided some most needed understanding about the connection between resilience and sustainability. What we have been able to identify is:

- Resilience thinking has drawn an increasing number of researchers whose interests have started to guide interdisciplinary efforts with more focus on social and social-ecological contexts. Despite this, research on resilience and sustainability is still in its development stage with more attention required to integrating the abundant ecological evidence with socio-economic aspects and the role of human activities in shaping the planet's ecosystems.
- Despite shared objectives and resilience thinking being essential for sustainability, it is not entirely sufficient and cannot be used to totally replace sustainability as the final objective. Any studies that try to incorporate resilience into sustainability need to take a long-term perspective from an intergenerational point of view, define what the desirable state of the studied system is and ensure the system does not flip from a desirable into an undesirable state.
- The important contributions of resilience to sustainability are not only its specific views on dealing with changes and uncertainties for sustainability goals but also its growingly wide applications that are increasingly improving our understanding of sustainability. Despite this, more efforts need to be made study the uncertain and complex dynamics in particular in SESs.
- Measuring resilience for sustainability is not an easy job and still remains a challenge with the difficulties and uncertainties in identifying thresholds that have not been crossed or are non-observable. There is not enough evidence revealing critical variables that caused regime shifts of systems. This is extremely important as many of variables in SESs are tightly linked; exceeding the critical threshold of

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one may affect others thereby the balance of the whole system. The area of sustainometrics (Todorov and Marinova 2011) will continue to benefit from further research on modelling and measuring sustainability but it is unlikely that any mega single discipline would be able to deliver the knowledge required to properly understand resilience and sustainability.

- Managing resilience requires careful considerations to be given for establishing flexible institutions for social learning and co-management, including stakeholder engagement in order to improve sustainability practices and enhance local ecological knowledge about the dynamics of SESs.

In conclusion, resilience research for sustainability will need to concentrate on questions such as how to identify and manage the key drivers and elements of resilience of the SESs, what the dynamics between critical variables in SESs of different areas are, how long it will take for feedbacks from a system to cause changes to happen in others (especially hazardous changes in other systems when the thresholds of a system is crossed), how to monitor and evaluate whether the strategies are working towards building resilience, and how to identify and engage with stakeholders when building social-ecological resilience.

### **Acknowledgements**

All authors thank the Editor and three anonymous referees whose comments helped improve this survey. The second and third authors acknowledge the financial support of the Australian Research Council.

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Xu, Li, Dora Marinova, and Xiumei Guo. 2015. "Resilience thinking: a renewed system approach for sustainability science." *Sustainability Science*. 10(1): 123-138. Doi: 10.1007/s11625-014-0274-4.

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**PAPER 4: WHAT CAN WE DO BETTER FOR SUSTAINABILITY IN  
THE UNCERTAIN FUTURE?**

**Statement of Contributions of Authorship**

To whom it may concern,

I, Li Xu, contributed 95% to the paper entitled above and cited as below:

Xu, Li, and Talia Raphaely. 2015. "What can we do better for sustainability in the uncertain future?." in *Technology–Society–Sustainability: Selected Contemporary Issues, Concepts and Cases*, edited by Lech W. Zacher, Springer. (forthcoming, acceptance date 27/07/2015).

Signature of Candidate:



Date: 30 October 2015

I, as a co-author, endorse that this level of contribution by the candidate indicate above is appropriate.

Talia Raphaely Signature:



Date: 2 November 2015

**This Chapter is an exact copy of the journal paper referred to above**

Published as:

Xu, Li and Talia Raphaely. 2015. "What can we do better for sustainability in an uncertain future?" in *Technology–Society–Sustainability: Selected Contemporary Issues, Concepts and Cases*, edited by Lech W. Zacher, Springer. (forthcoming).

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## WHAT CAN WE DO BETTER FOR SUSTAINABILITY IN AN UNCERTAIN FUTURE?

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### INTRODUCTION

Sustainability (or sustainable development) was introduced as a concept in the 1980s and directed people's consideration towards environmental health and human development. Although definitions abound, one of the most enduring is "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (WCED 1987). However global environmental issues - such as water scarcity, food security, peak oil, climate change and natural catastrophes including increasing instances of unexpected external and internal shocks such as earthquakes, extreme climate events, and tsunamis - have become an inevitable truth and a barrier to achieving the goal of sustainability (Barnosky et al. 2012; UNEP 2012). The realisation of social-ecological sustainability is not a simple aspiration but a huge challenge, the achievement of which is necessary for human well-being in the face of the changing world.

Since sustainability is not a "steady state" or "fixed target", achieving the goal of sustainable development requires continuous adjustments that respond to changing conditions, knowledge, and priorities (Dale et al. 2013). Integrated natural resources management needs to find optimal ways for effective actions in order to avoid social-ecological systems collapse directly resulting from external shocks triggered by nature and human-induced perturbations. Building social-ecological resilience, by improving the ability of the system to withstand such shocks without changing its original state or domain of attraction, could enhance the likelihood of successful sustainability in an uncertain future (Walker et al. 2004; Adger et al. 2005; Folke 2006; Xu et al., 2015). This chapter discusses why resilience thinking is needed to address sustainable development and how we should use this thinking to build social-ecological resilience for water resource management in an uncertain future.

### SUSTAINABILITY AND UNCERTAINTY IN WATER RESOURCE MANAGEMENT

Water resource sustainability is "the ability to use water in sufficient quantities and quality from the local to the global scale to meet the needs of humans and ecosystems for the present and the future to sustain life, and to protect humans from the damages brought about by natural and human-caused disasters that affect sustaining life" (Mays 2007, p. 4). Freshwater

Published as:

Xu, Li and Talia Raphaely. 2015. "What can we do better for sustainability in an uncertain future?" in *Technology–Society–Sustainability: Selected Contemporary Issues, Concepts and Cases*, edited by Lech W. Zacher, Springer. (forthcoming).

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is essential for survival of the living world (Wetzel 2000; Long, Teclé and Burnette 2003), and is a prerequisite for the continuity and advancement of human societies (Postel and Carpenter 1997). However, the growing severity of freshwater scarcity has become an increasing threat with freshwater systems directly impacted, damaged and depleted by human activities and anthropogenic climate change. For example, at the turn of this century, about 80% (at the time almost 5 billion people) of the world's population lived in areas where either incidental human water security or biodiversity threats exceeded the 75th percentile (Vörösmarty et al. 2010). This situation has worsened although no specific figures are available. In China, two-thirds of this country's 669 cities are facing water shortages and 80% of lakes are effected by eutrophication (Chinese Academy Science 2007; Liu and Yang 2012). Due to increasing demand, high pollution levels and the resulting decline in freshwater ecosystems (Johnson, Revenga and Echeverria 2001), limits of water availability and related considerations of water security have become major threats in the 21st century (Biswas 1991; Vörösmarty et al. 2010).

The highly uncertain future of water is caused mainly by human and climate-related impacts and changes. The complexity of social-ecological systems gives rise to a variety of projection variables on climate change. These in turn increase uncertainties regarding impacts and consequences of the interaction between the internal mechanisms of social-ecological processes and the impact of external influences (changes) on these systems. The changing impacts of climate extremes on water systems - including floods, droughts, and storms - depend not only on changes in the characteristics of climate-related variables but also on water-relevant non-climatic stressors, management characteristics, and adaptive capacity (IPCC 2012). For example, climate change has the potential to impact on river flood characteristics by changing the volume and timing of precipitation or by changing evaporation and hence accumulated soil moisture deficits. However there is considerable uncertainty in the magnitude, frequency and direction of these changes. For freshwater adaptive management, Folke (2003) advocates a shift in thinking arguing that resilience needs to be strengthened to secure and provide the possibilities for prosperous societal development. Folke reasons that active management should be undertaken to help maintain the essential role of freshwater in dynamic landscapes faced with uncertainty and shock (moving from command-and-control to complex systems thinking).

## **RESILIENCE THINKING FOR SUSTAINABILITY**

The concept of resilience for ecosystems and social-ecological systems is one of the declared focussed research areas within the sustainability discourse (Levin et al. 1998). A bibliometric analysis on resilience thinking shows it is a dominant approach within the sustainability paradigm, especially when it comes to climate change adaptation and dealing with human impacts and disturbance issues (Xu and Marinova 2013), and its value has been proven in the

Published as:

Xu, Li and Talia Raphaely. 2015. "What can we do better for sustainability in an uncertain future?" in *Technology–Society–Sustainability: Selected Contemporary Issues, Concepts and Cases*, edited by Lech W. Zacher, Springer. (forthcoming).

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past decade. To better integrate the concept of resilience into sustainable management of resources facing an uncertain future, the rest of this chapter seeks to provide a definition of resilience processes, the ways in which resilience can be incorporated into the sustainability discourse using water resource management as an example, and, finally, to outline some of the possible future directions such an approach might take.

### ***Defining resilience for water resource sustainability***

Resilience was introduced by Holling into ecological systems theory in 1973 and is generally defined by the Resilience Alliance as "the capacity of an ecosystem to tolerate disturbance without collapsing into a qualitatively different state that is controlled by a different set of processes" (Resilience Alliance 2012). Social-ecological resilience is the capacity of the system to absorb regular perturbations or uncertain disturbances from natural hazards - such as floods, typhoons, or hurricanes - by retaining their essential functions, structures, processes and feedbacks (Walker and Salt 2006; Adger et al. 2005). Applying resilience thinking to sustainability requires a definition of resilience tailored for the specific system being studied. The first question to answer is "resilience of *what* and *to what*" namely *what* system state is being considered and *to what* disturbances does resilience apply. Also important is defining resilience over *what time period*, *to whom* and *at what scale* (Carpenter et al. 2001). As sustainability encompasses three main pillars (environment, economy, and society), there is a need to consider the concept of resilience in these three contexts before defining *of what* and *to what* for water resource sustainability. Ecological (or environmental) resilience describes the ability of an ecosystem to absorb environmental disturbances as well as its capacity for renewal, reorganization, learning, adaptation and development. It includes the degree to which the system is capable of self-organization and the degree to which the system can build the ability for learning and adaptation to the external perturbations (Carpenter et al. 2001; Folke et al. 2002). Economic resilience refers to "the ability of the system to withstand either market or environmental shocks without losing the capacity to allocate resources efficiently (the functionality of the market and supporting institutions), or to deliver essential services (the functionality of the production system)" (Perrings 2006, p. 418). Social resilience emphasizes the time it takes to recover from stress and, more importantly, the access of a community to critical resources such as water (Langridge, Christian-Smith and Lohse 2006), land, finances and human skills.

Three key words can be captured from the definition of resilience above. These are *capacity*, *disturbance*, and *state*. *Capacity* is the ability of a system to absorb external shocks and mainly encompasses renewal, reorganization, learning and adaptation when coping with disturbance. *Disturbance* is the different sorts of undesirable or unpredictable changes or perturbations to a system caused by nature and human activities and includes natural shocks such as floods, storms, earthquakes and hurricanes and human-induced perturbations such as engineering constructions, timbering, land reclamation, and rangeland. *State* is the responses

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Xu, Li and Talia Raphaely. 2015. "What can we do better for sustainability in an uncertain future?" in *Technology–Society–Sustainability: Selected Contemporary Issues, Concepts and Cases*, edited by Lech W. Zacher, Springer. (forthcoming).

of a system to the disturbance. Resilience requires the system to be able to maintain a desirable state and not change to a qualitatively different state when facing with the disturbances.

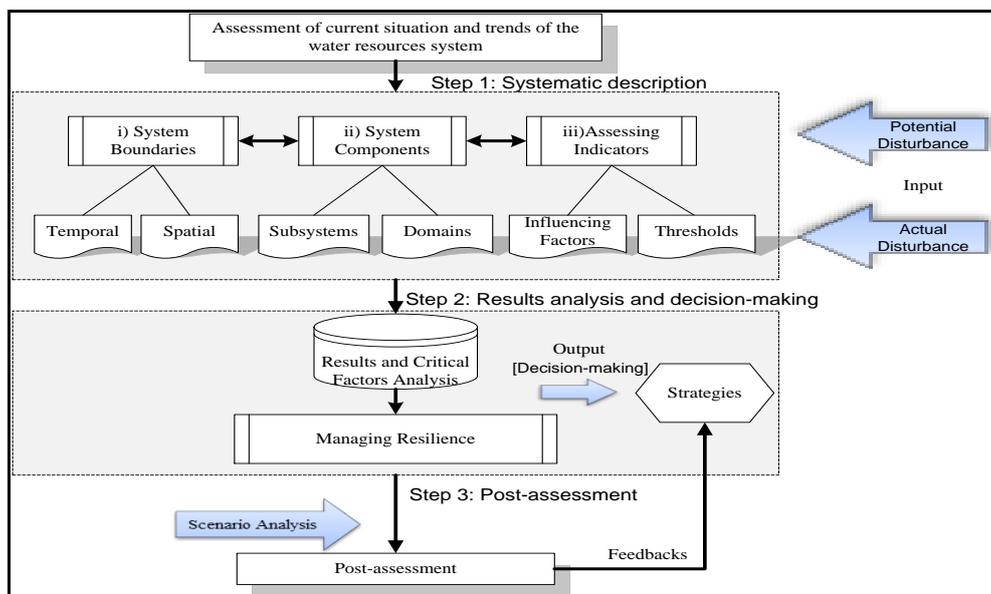
Accordingly, resilience of sustainable water resource management can be defined as

*The ability of water resources systems to withstand uncertainty and disturbance without shifting into an undesirable state by maintaining abilities of renewal, reorganization, learning and adaptation, to provide sufficient quantities of good quality water to meet the needs of humans and ecosystems for both current and future generations.*

### ***Incorporating resilience into sustainable water management***

The most important step for incorporating resilience thinking into sustainable water management is to identify and understand the current circumstances and trends of social-ecological systems. This requires identification and assessment of potential and actual disturbance and external shocks based on their impacts on the sustainability of the specific system being investigated. Once this is accomplished optimal management strategies can be explored and recommended.

The process of incorporating resilience thinking into the sustainable management of water resource systems is shown in Fig. 5.2.1 below.



**Fig. 5.2.1** Procedure of incorporating resilience thinking into the sustainable management of water resource systems

Source: Own Graphic

Published as:

Xu, Li and Talia Raphaely. 2015. "What can we do better for sustainability in an uncertain future?" in *Technology–Society–Sustainability: Selected Contemporary Issues, Concepts and Cases*, edited by Lech W. Zacher, Springer. (forthcoming).

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As Figure 1 shows, the procedure of incorporating resilience into the sustainable management of water resource systems consists of three main steps:

Step 1: *Systematic description*; in this step, three significant interacting characteristics of water resources systems are described from a systematic perspective. One of the primary tasks for resilience analysis is to define resilience over a specific time period, a specific scale and resilience for whom. The critical questions which need to be answered before achieving sustainability are *over what space and time* is sustainability to be achieved? (Bell and Morse 2008, p. 14).

- i. The description starts with defining the boundaries of the studied water resource system on a spatial and temporal scale. For example, when assessing the social-ecological sustainability of a lake, the spatial scale can be defined as the scale of the area which should be assessed in conjunction with the lake, or the areas in which users of the lakes resources live. In addition, the time scale over which the assessment is to be carried out should also be clarified during this step. The definition must be made on the basis of certain specified criteria including a definition of the concept of resilience and sustainability or the average service-life of infrastructures in the studied water system.
- ii. The second part of step 1 is to identify the various components of the system in question. This can be done through defining what subsystems are involved in the specified system and what domains are included in the assessment. In general, ecological, economic and social systems are the key domains used in terms of sustainability. Ecological systems include components relating to environmental quality and ecological health. Economic systems relate to those sectors which have a relationship with production and consumption of the specified resource. Social systems are usually communities and people that have direct interaction with the specified resource.
- iii. The third and final part of the description is to develop a set of indicators for sustainability within resilience thinking. Two sorts of disturbances need to be considered in this step: actual disturbances (disturbances that have already occurred) such as engineering constructions, and, potential disturbances (that may or are likely to occur) such as extreme floods. To do this the factors influencing sustainability within the system should be identified. That is, what kinds of factors could affect the state of the system and what are the main forces that control these factors? In addition there is also a need to identify if there are any tipping points (thresholds), especially critical ones, which determine or could create shifts in the state of system. It is known that ecological systems have tipping points within their components. Whilst the socioeconomic system tipping points, components and causes are more difficult to determine and sometimes less recognised, they are also critically important considerations to consider and include. The likelihood of system transition may gradually increase as the system approaches a tipping point whereupon a minor trigger can invoke "a self-propagating shift to a contrasting state" (Scheffer et al. 2012). Unpredictable external shocks and disturbances increase the

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possibility of these changes. Certain generic indicators may be useful for identifying the tipping points of a system and detecting if the system is close to the critical tipping point (Scheffer et al. 2012).

*Step 2: Results analysis and decision-making*; this step focuses mainly on managing social-ecological resilience around water resources systems through strategy planning and policy design. Based on the *systematic description* comprising step 1, step 2 focuses on analysing key factors affecting the state of sustainability of the system, critical thresholds that should be considered when confronting external disturbances and strategies for enhancing systems' resilience. Certain planning approaches could be useful in achieving beneficial sustainability outcomes here. For instance, Multi-objective Planning (MOP) could be one of the options encouraging systematic consideration of multiple objectives including environmental, social, regional, and economic and others (Major 1977). Specific objectives must be defined prior to applying MOP in order to optimise strategies designed for enhancing social-ecological resilience. It is important to recognize any constraints that may create obstacles in achieving the defined objectives. The constraints are identified and determined by disturbance variables, critical influencing factors and tipping points of the system as well as by the conditions of the different components within the overall system.

*Step 3: Post-assessment*; this final step evaluates if the strategies are useful for the enhancement of social-ecological resilience and sustainability of the system. This can be done by observation or simulation. While observation is an effective evaluation option it is time-consuming and costly due to the lengthy timeframes typically needed in strategy implementation and outcomes. This is particularly true of restoration plans. Consequently a simulation approach, such as a scenarios analysis or computer-based method, is highly recommended as an alternative. This post-assessment is necessary because it can assess the anticipated performance of strategies. It is also a good way to provide feedback to decision-makers for proposed strategy adjustments.

## **BUILDING UP SOCIAL-ECOLOGICAL RESILIENCE FOR WATER RESOURCES SYSTEM**

Structured scenarios and active adaptive management are two useful tools for building resilience in social-ecological systems. This includes stimulating building resilience in social-ecological systems, creating open institutions for learning and flexible collaboration and directing actions towards building adaptive capacity. Further, motivating the development of indicators and warning signals of gradual change and loss of resilience and thresholds, and encouraging learning and incorporation of ecological knowledge into institutional structures in multi-level governance (Folke et al. 2002; Adger et al. 2005) is important. Social-ecological resilience can also be built up by policy design that strengthens understanding of humanity and nature as interdependent.

Published as:

Xu, Li and Talia Raphaely. 2015. "What can we do better for sustainability in an uncertain future?" in *Technology–Society–Sustainability: Selected Contemporary Issues, Concepts and Cases*, edited by Lech W. Zacher, Springer. (forthcoming).

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Many studies have been conducted regarding building social-ecological resilience, mostly centred on initiatives enhancing collective actions through engaging stakeholders (Folke et al. 2002), co-management (Tompkins and Adger 2004), and legislation (Olsson et al. 2004). Additionally, building indigenous ecological knowledge-based systems, multi-level governance and polycentric institutions are proving to be a helpful means of facilitating institutional and social learning and multi-level governance through education and training (Adger et al. 2005; Silici et al. 2011). However, more research is required to better understand how to manage resilience for sustainability. This includes further exploration of multi-scale effects, further evaluation of environmental, social and economic trade-offs, enhanced monitoring and evaluation strategies and continuing engagement with stakeholders.

Building social-ecological resilience for water resource systems should follow seven general principles described by Folke et al. (2000):

- 1) Designing management strategies based on traditional local ecological knowledge. Local ecological knowledge may expand sources of information for ecosystem management (Becker and Ostrom 1995). Local water use knowledge, including biological knowledge and knowledge of ecological processes, may complement and enhance scientific knowledge;
- 2) Designing management systems that "flow with nature";
- 3) Developing local ecological knowledge for understanding cycles of natural and unpredictable events;
- 4) Enhancing social mechanisms;
- 5) Promoting conditions for self-organization and institutional learning;
- 6) Rediscovering adaptive management; and
- 7) Developing values consistent with resilient and sustainable social-ecological systems. Moreover, attempts to build resilience for social-ecological systems should capture and address slow variables that affect resilience rather than trying to control disturbance. This is because change can be inevitable or unobservable but still potent as is the case with climate change, nutrient stocks and soil properties (Folke et al. 2002).

This requires improved understanding of social-ecological systems dynamics and the incorporation of knowledge obtained from and by local users to gain greater insight into how systems respond to potential tipping point shocks (Berkes and Folke 1998; Carpenter et al. 2001; Folke et al. 2002.). It also requires efficient management interventions. It is however important to realise that management interventions can either build or destroy resilience depending on how the social-ecological system is able to organise itself and respond to management actions. Therefore ongoing assessment is advised to establish if strategy or intervention adjustments are appropriate.

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## **THE WAY FORWARD**

Social-ecological sustainability is essential for human wellbeing in an increasingly uncertain future. The urgent issue for natural resources management is to prevent social-ecological systems from collapsing in the face of external shocks triggered by climate change and anthropogenic perturbations. Establishing and enhancing social-ecological resilience for the sustainable management of natural resources could address this urgent challenge. However, the research on resilience and sustainability is still in the exploratory stage with more attention needed on integrating the abundant ecological evidence with socio-economic aspects and the role of human activities in shaping ecosystems. Future research around resilience and sustainability could focus on questions such as how to identify and manage the key drivers and elements of resilience within social-ecological systems, how to monitor and evaluate whether adopted resilience building strategies are working and how to identify and engage with stakeholders when building social-ecological resilience.

More specifically, it is important to identify and quantify the tipping points (thresholds) for key elements of social-ecological systems and to find the drivers which affect these elements and thereby the state of the system. Appropriate indicators may be useful for achieving this and they can detect if the system is close to the critical tipping point (Scheffer et al. 2012).

Another important issue for sustainability management into the future concerns how to build flexible institutions with the ability to adjust to changing environmental conditions. This is increasingly significant in a world of growing uncertainty and shock and requires consideration of the dynamics of affected social-ecological systems when considering the sustainable use of water and any other resource. Long-term observation of vulnerable systems needs to be established including frequent monitoring of environmental conditions. Information feedback to institutions should be monitored and assessed. Appropriate indicators (especially early warning indicators) should be developed to ensure the long-term resilience of systems under observation. Perhaps most critically for sustainability, local stakeholders need to be involved in any policy development and management program to ensure the best result for both the people and the environment.

## **ACKNOWLEDGEMENTS**

The authors would like to thank the reviewers of this article for their helpful comments which helped improve the quality of the manuscript. The authors are also thankful to the book's editors for their invitation and feedback.

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**PAPER 5: RESILIENCE-BASED SUSTAINABILITY INDICATORS  
FOR FRESHWATER LAKES WITH APPLICATION FOR DONGTING  
LAKE, CHINA**

**Statement of Contributions of Authorship**

To whom it may concern,

I, Li Xu, contributed 70% to the paper entitled above and cited as below:

Xu, Li, Dora Marinova, Pei Xin, and Xiumei Guo. 2015. "Resilience-based sustainability indicators for freshwater lakes with application for Dongting Lake, China." *Environment and Natural Resources Research*. 5(2): 165-188. doi: 10.5539/enrr.v5n2p165.

Signature of Candidate:



Date: 30 October 2015

I, as a co-author, endorse that this level of contribution by the candidate indicate above is appropriate.

Dora Marinova Signature:



Date: 2 November 2015

Pei Xin Signature:



Date: 1 November 2015

Xiumei Guo Signature:



Date: 2 November 2015

**This Chapter is an exact copy of the journal paper referred to above**

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

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Received: April 14, 2015 Accepted: April 30, 2015 Online Published: May 19, 2015

doi:10.5539/enrr.v5n2p165 URL: <http://dx.doi.org/10.5539/enrr.v5n2p165>

## 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<sup>3</sup> 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 (particularly 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.

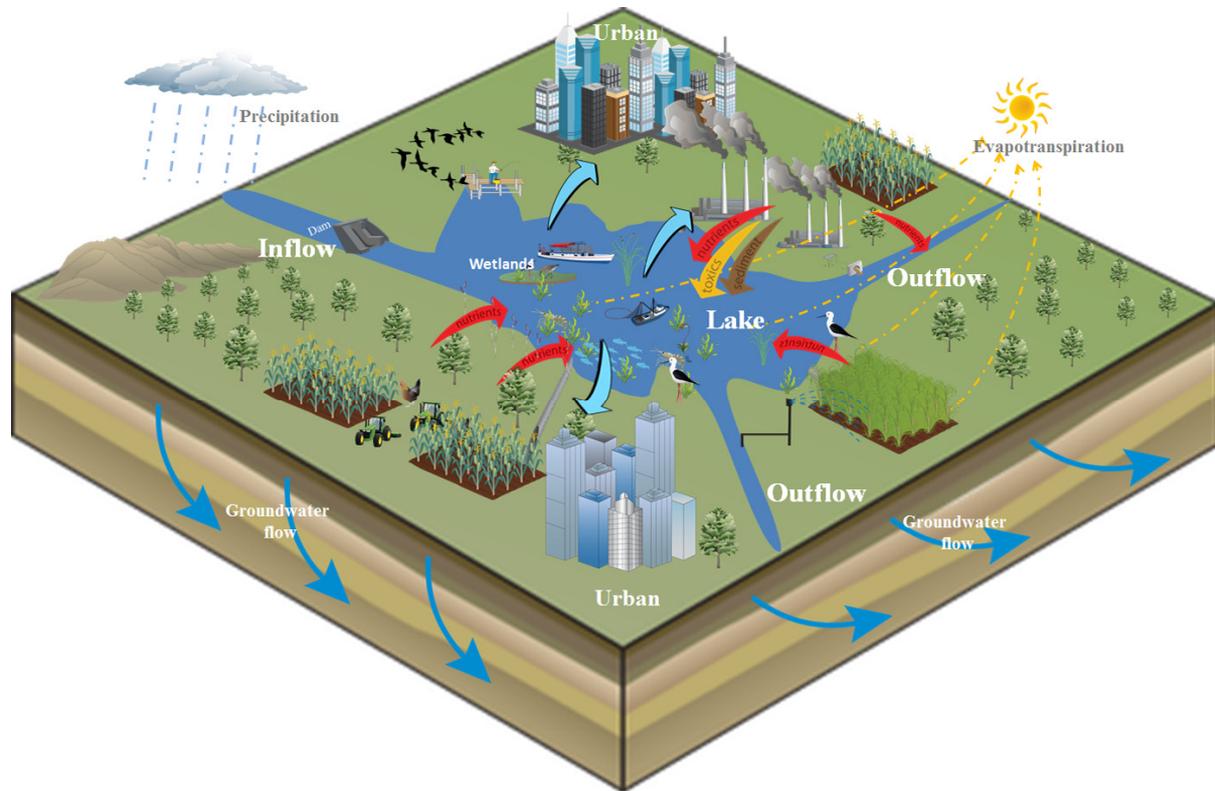


Figure 1. Dynamics of SESs of Freshwater Lakes

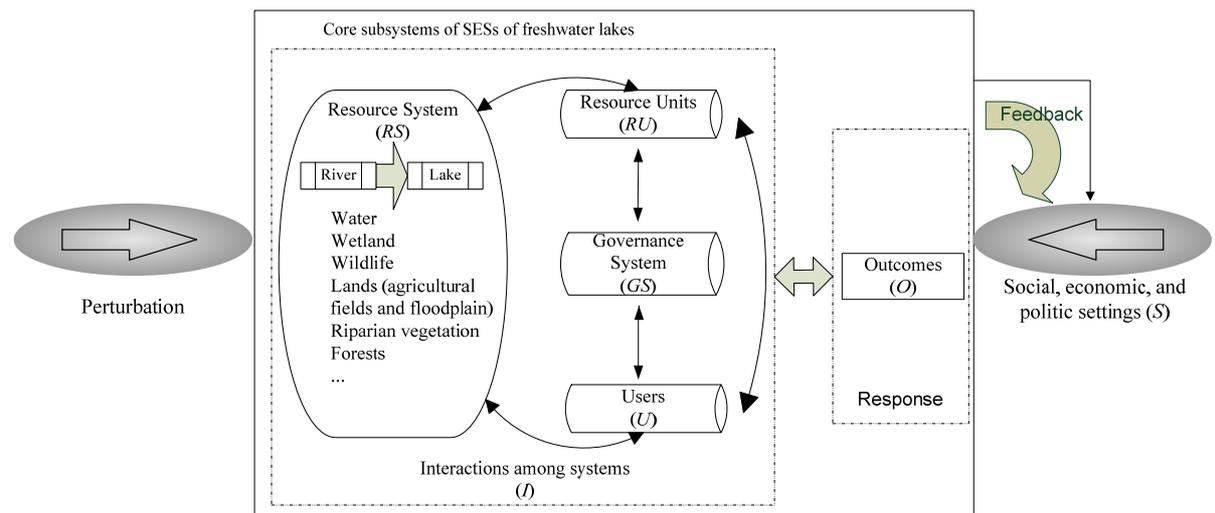


Figure 2. Core Subsystems of SESs of Freshwater Lakes

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.

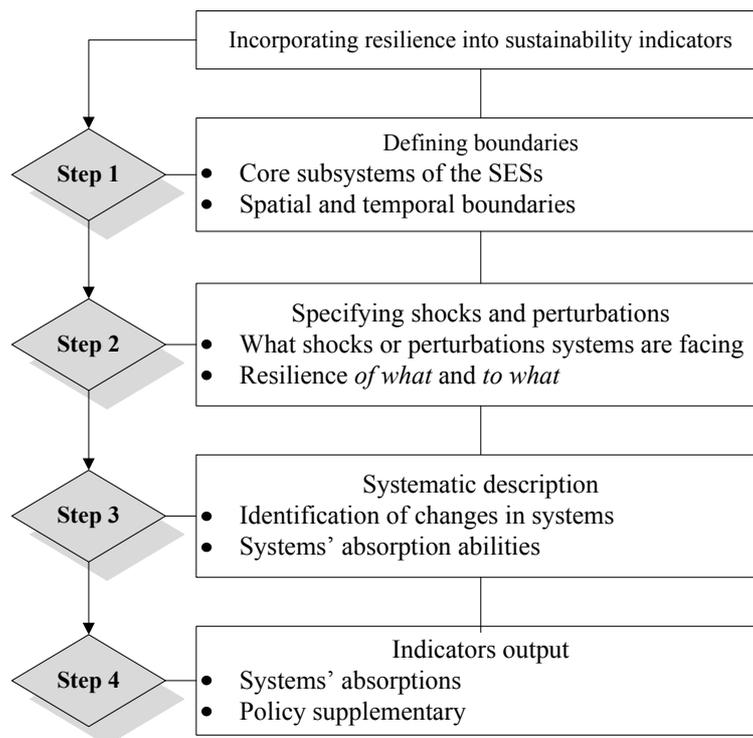


Figure 3. Flowchart for Developing the Indicators Set

- 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 Dongting 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 been 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).

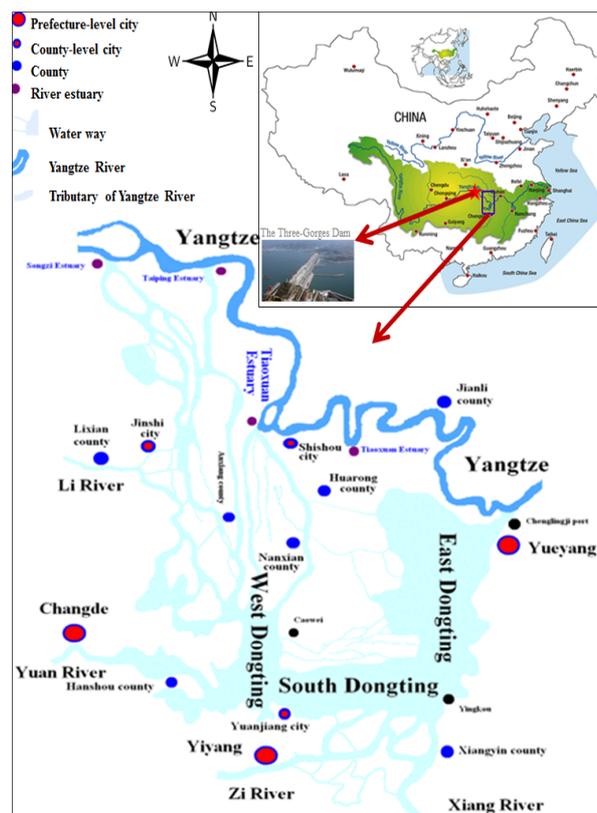


Figure 4. Location of Dongting Lake

### 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<sup>1</sup>

Core subsystems and second-level variables	Critical variables/ third-level variables	Explanations	Regional descriptions
<i>Resource Systems (RS)</i>			
<i>RS1</i> Sectors	<i>RS1.1</i> Water; <i>RS1.2</i> Wetlands; <i>RS1.3</i> Fish; <i>RS1.4</i> 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
<i>RS2</i> Size of resource system	<i>RS2.1</i> 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
<i>RS3</i> Location and clarity of system boundaries	<i>RS3.1</i> 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
<i>RS4</i> Productivity of system	<i>RS4.1</i> Stock status <i>RS4.2</i> 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
<i>RS5</i> 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
<i>RS6</i> Storage characteristics	<i>RS6.1</i> Storage in natural patterns <i>RS6.2</i> 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
<i>Resource Unit (RU)</i>			
<i>RU1</i> 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

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

	<i>GS6.2</i> 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
<i>Users (U)</i>			
<i>U1</i> Number of users		Number of users affecting decision-making process of managing resources	Large
<i>U2</i> Socioeconomic attributes	<i>U2.1</i> Education attainment <i>U2.2</i> 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
<i>U3</i> History		The duration of using resources	Long time period
<i>U4</i> 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
<i>U5</i> Leadership		Users who have skills to lead or organise actions and are followed by their group members	Not well-educated leaders
<i>U6</i> Social capital	<i>U6.1</i> Independence <i>U6.2</i> 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
<i>U7</i> 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
<i>U8</i> Importance of resource	<i>U8.1</i> Economic dependence <i>U8.2</i> 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
<i>U9</i> Technologies available	<i>U9.1</i> Ownership of technologies	Accessibility of users to technologies for their production	Moderate level

Note: <sup>1</sup> 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 living 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
<i>RS</i>					
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
<i>RU</i>					
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
<i>GS</i>					
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
<i>U</i>					
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

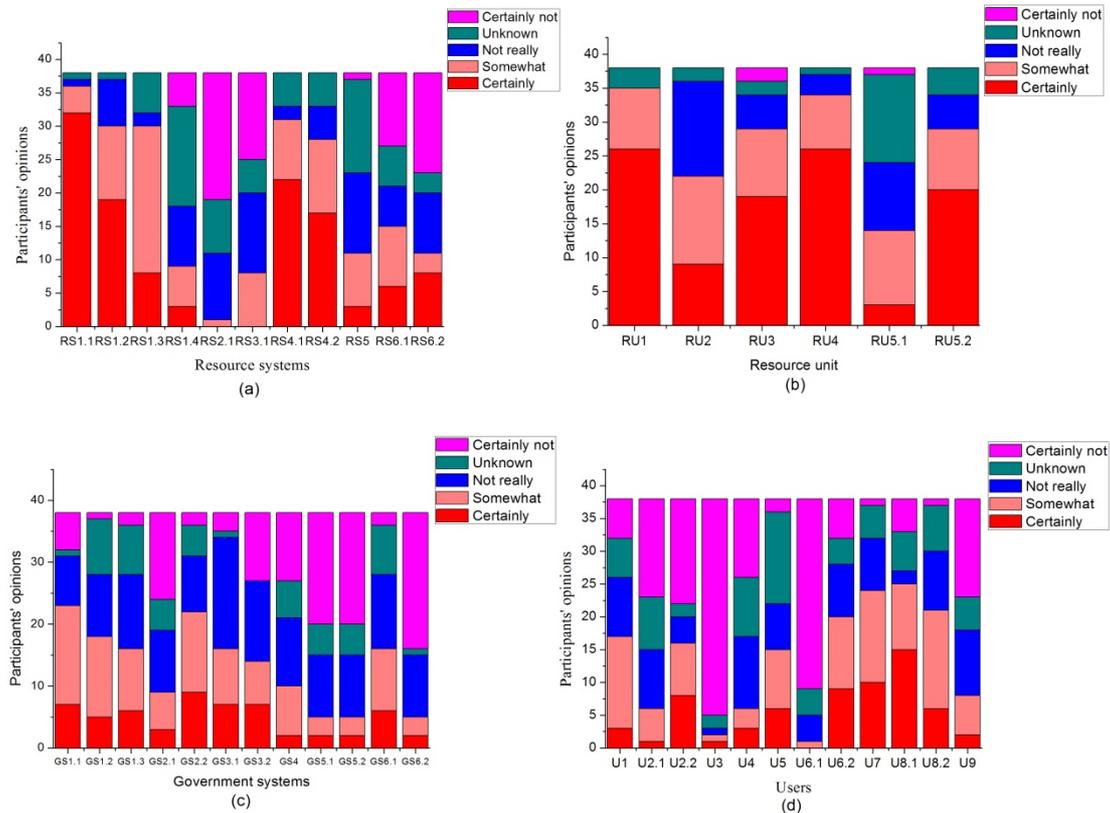


Figure 5. Identification of Changes

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, no governance 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	<ul style="list-style-type: none"> <li>Water (RS1.1)</li> <li>a. seasonal alteration to water level</li> <li>b. drying up water volume</li> </ul>	<ul style="list-style-type: none"> <li>a. Water compensation from Xiang River, Zi River, Yuan River, and Li River</li> <li>b. Supply/demand ratio in various months</li> </ul>	<ul style="list-style-type: none"> <li>a &amp; b. Water quantity adjustment proposals for the next 30 year</li> <li>c&amp;d. Availability of restoration plans for the wetlands of the lake for the next 30 years with the aim of adapting to the TGD</li> </ul>	
	<ul style="list-style-type: none"> <li>Wetlands (RS1.2)</li> <li>c. vegetation distribution (coverage)</li> <li>d. areas of emerged wetlands</li> </ul>	<ul style="list-style-type: none"> <li>c&amp;d. Permanent wetland within key vegetation (emergent macrophytes) coverage</li> <li>e&amp;f. The regeneration rate of resources with the changed hydrological conditions</li> </ul>	<ul style="list-style-type: none"> <li>e&amp;f. Availability of plans for protecting and increasing the stock of resources in the next 30 years</li> </ul>	
	<ul style="list-style-type: none"> <li>Productivity of system (RS4)</li> <li>e. Stock status (RS4.1)</li> <li>f. Biophysical factors (RS4.2)</li> </ul>			
	<ul style="list-style-type: none"> <li>Fish (RS1.3)</li> <li>g. Living space</li> <li>h. Food chain</li> </ul>	<ul style="list-style-type: none"> <li>g. NA</li> <li>h. NA</li> </ul>	<ul style="list-style-type: none"> <li>g. Fish protection and reproduce plans for the next 30 years</li> <li>h. Food chain protection plans for the next 30 years</li> </ul>	
	Nil	Nil	Nil	
	<ul style="list-style-type: none"> <li>i. Water birds (RS1.4)</li> <li>j. Predictability of system dynamics (RS5)</li> </ul>	<ul style="list-style-type: none"> <li>i. Habitat transformation</li> <li>j. Key variables in different systems</li> </ul>	<ul style="list-style-type: none"> <li>i. Long term regular observation on distribution and quantity of water birds especially during the period when water level has been changed</li> <li>j. Monitoring for key variables in the long run</li> </ul>	
	RU	<ul style="list-style-type: none"> <li>Resource unit mobility (RU1)</li> <li>a. Spatial mobility</li> <li>b. Temporal mobility</li> </ul>	<ul style="list-style-type: none"> <li>a. Liveable space of species (key plants, fish, and water birds)</li> <li>b. Food availability</li> <li>c. Community's ability to generate wealth</li> </ul>	<ul style="list-style-type: none"> <li>a &amp; b. RS a, b, c, d, e and f</li> <li>c. Financial support plans from government in the long run</li> <li>d. Technological support plans in the long run</li> </ul>
		<ul style="list-style-type: none"> <li>Economic value (RU3)</li> <li>c. Explicit economic value loss</li> <li>d. Implicit economic value loss</li> </ul>	<ul style="list-style-type: none"> <li>d. Accessibility of technology</li> <li>e. RS e&amp;f</li> <li>f. a</li> </ul>	<ul style="list-style-type: none"> <li>e. RS c&amp;d, e &amp; f</li> <li>f. RS a, b, c, d, e and f</li> </ul>
		<ul style="list-style-type: none"> <li>Number of units (RU4)</li> <li>e. Fish output and food availability for water birds</li> </ul>		
		<ul style="list-style-type: none"> <li>Spatial and temporal distribution (RU5)</li> <li>f. Homogeneous distribution of units (RU5.2)</li> </ul>		
Nil		Nil	Nil	
<ul style="list-style-type: none"> <li>g. Growth and replacement rate (RU2)</li> <li>h. Non-homogeneous distribution of units (RU5.1)</li> </ul>		<ul style="list-style-type: none"> <li>g. NA</li> <li>h. Spatial patterns of different systems</li> </ul>	<ul style="list-style-type: none"> <li>g. Long term monitor plans and experimental programs for key species of the lake</li> <li>h. Availability of monitors for resources</li> </ul>	
GS	Nil	Nil	Nil	
	<ul style="list-style-type: none"> <li>Policy area (GS1)</li> </ul>	<ul style="list-style-type: none"> <li>a &amp; b. Flexibility of existing policies (ecology, industry and</li> </ul>	<ul style="list-style-type: none"> <li>a &amp; b. The diversity and redundancy of policy responses for long term purpose</li> </ul>	

U	a. Ecology policy (GS1.1)	agriculture irrigation)	c. Policy support for NGOs in the long term (research funding support and funding for other local NGOs)
	b. Economic-ecology (GS1.2)	c. Degree of multilevel network linkages	
	• Organisation (GS2)		
	c. NGOs (GS2.2)		
	• Policy area	d. a & b	d. a & b
	d. Socio-ecology policy (GS1.3)	e. NA	e. Availability of compensations for those who would lose rights to access the resources of the lake if change happened
	• Rules in use (GS3)	f & g. The reasonability of the rules (equality)	f & g. Complementary rules for the long run purpose
	e. Property rights (GS3.1)		
	f. Collective-choice rules (GS3.2)		
	• Monitoring and sanctions (GS6)		
g. Local observation (GS6.1)			
Nil	Nil	Nil	
• Importance of resource (U8)	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	
a. Economic dependence (U8.1)			
• (b.) Number of users (U1)	b. a	b. a	
• Social capital (U6)	c. The degree of trust in social groups	c. Availability of policy that can lead those common interest groups to the right way to enhance social belief in building up resilience	
c. Common interest/shared norms (U6.2)	d. People's ability to learn knowledge	d. Strategy to help users in deeply understanding the dynamics of SES	
• (d.) Knowledge about SES (U7)	e. NA	e. Availability strategy to keep traditional culture in other ways	
• Importance of resource			
e. Cultural dependence (U8.2)			
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 $\geq 1$ , 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
	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
	RU1 RU5.2	$I_5$ : Livable space for key species in the wetlands	$P_1, P_2, P_3$
	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
	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
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
	RU2	NA	$P_9$ : Availability of long-term monitoring plans and programs for key species of the Lake for the next 30 years
	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
			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).
			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.
			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).
			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).
			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.
			Fish self-adapt by 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.
			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.
			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 to occupation transformation in 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 (*I*<sub>5</sub>) can well indicate both the status of wetlands and spatial mobility of resources units while availability of resources protection (*R*<sub>3</sub>) 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.

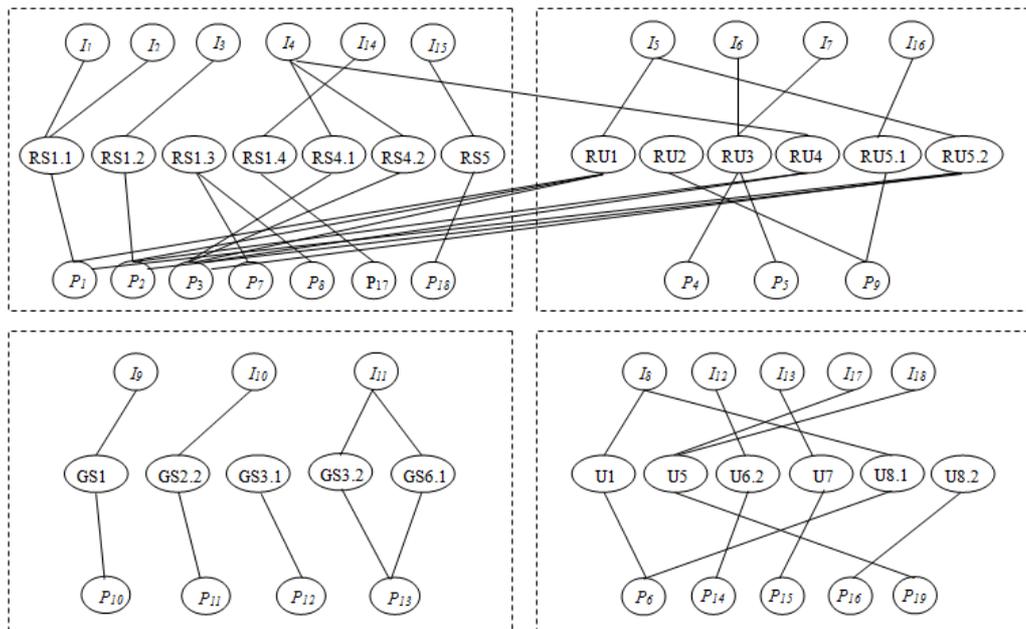


Figure 6. Relationships among Indicators and Core Subsystems of SESs

## 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.

### Acknowledgments

All authors of this paper acknowledge the crucial support of the experts from Group 5 of the National Basic Research Program of China ("973" program), including for the field surveys. We also give our sincere appreciation to all participating local stakeholders for their contribution – fishers, officers of the departments of fishery and local environmental protection, and officers in the Authority of Nature Reserve Areas of East Dongting Lake. The survey assistance of the Master's student Tianyun Xie from Hohai University is highly appreciated and acknowledged as is the help of the anonymous referees and the Journal's Editor.

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**PAPER 6: RESILIENCE OF SOCIAL-ECOLOGICAL SYSTEMS TO HUMAN PERTURBATION: ASSESSING DONGTING LAKE IN CHINA**

**Statement of Contributions of Authorship**

To whom it may concern,

I, Li Xu, contributed 75% to the paper entitled above and cited as below:

Xu, Li, Dora Marinova, and Xiumei Guo. 2015. "Resilience of social-ecological systems to human perturbation: assessing Dongting Lake in China." *Journal of Sustainable Development* 8(8): 185-200. doi: 10.5539/jsd.v8n8p182.

Signature of Candidate:



Date: 30 October 2015

I, as a co-author, endorse that this level of contribution by the candidate indicate above is appropriate.

*Dora Marinova Signature:*



Date: 2 November 2015

*Xiumei Guo Signature:*



Date: 2 November 2015

**This Chapter is an exact copy of the journal paper referred to above**

# Resilience of Social-ecological Systems to Human Perturbation: Assessing Dongting Lake in China

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Received: July 22, 2015 Accepted: August 17, 2015 Online Published: September 27, 2015

doi:10.5539/jsd.v8n8p182

URL: <http://dx.doi.org/10.5539/jsd.v8n8p182>

## Abstract

This paper conducts an assessment on the social-ecological resilience of China's Dongting Lake (and its three sections – East, West and South Dongting Lake) in relation to the perturbations of the Three Gorges Dam using a set of resilience-based indicators. Expert scoring is applied to identify the different states of the lake and their resilience levels. Based on equal weighting for all indicators and using the technique of ordering preferences according to similarity to the ideal solution, an assessment of the social-ecological resilience of Dongting Lake is generated. The results show that East Dongting has higher ability to absorb perturbations than South and West Dongting which have relatively low resilience to the changes triggered by the impoundment of the Dam. Effective adaptation measures are needed for the lake to be able to better absorb these perturbations and be sustainable in the long run.

**Keywords:** resilience indicators, social-ecological systems, sustainability, Three Gorges Dam

## 1. Introduction

Human perturbations worldwide are increasingly driving changes in freshwater ecosystems (Gleick et al., 2014). Disturbances from people and their activities have triggered numerous problems with contradictory and difficult to resolve requirements creating increasing challenges related to deteriorating environmental conditions of freshwater systems, water scarcity and safety. An example of this is climate change with its global impacts but there are also many local cases related directly to water use, such as the building of barrages, weirs and dams which change the hydrology of the region.

Accessing reliable water resources is a most important population need. The main storage of water for human use is lakes and they represent 70% of the global surface freshwater (Jorgensen, 2008). An estimated 68% of the world's liquid surface freshwater is contained in 189 large lakes (Reid & Beeton, 1992). They provide many important social and ecological services, such as water for drinking, irrigation and industry, habitat for various living species and place for dilution of pollutants. The interconnectedness and interdependent relationships between humans and nature are described through the concept of social-ecological systems (Berkes & Folke, 1998). People however often impact on the state of nature, including impairing the services of the lakes and placing many of them in peril through unsustainable exploitation for industrial development and urbanisation (Carpenter & Cottingham, 1997). Increasing demand for water, high pollution levels and the declining health of the freshwater ecosystems are continuously threatening the availability of freshwater (Biswas, 1991; Johnson Revenga, & Echeverria, 2001).

Hydropower projects, involving the construction of big dams and their use for electricity generation, agricultural irrigation and provision of drinking water, are delivering economic benefits but also changing the hydrological conditions of the areas. China is continuously supporting such water-related projects with investment increasing from ¥94.49 billion in 2007 to ¥375.76 billion in 2013 (Ministry of Water Resources of China, 2014). The ecological impacts of these large dams are drawing significant attention due to the implications they have for the state of the watersheds (Kingsford, 2000; Lajoie, Assani, Roy, & Mesfioui, 2007; Tullos, 2009; P. Wang, Lassoie, Dong, & Morreale, 2013). When the impoundment is upstream from a lake, the disturbances alter the hydrological conditions of the watershed and also have potential impact on the health of the joint social-ecological systems (SEs) (Xu, Marinova, Xin, & Guo, 2015a). The new hydrological conditions during the period of the dam's operation may cause a regime shift for the lake. Dongting Lake and Poyang Lake – the

two lakes connected to China's Yangtze River (YR), are subjected to the impacts of the Three Gorges Dam (Liu, Wu, & Zhao, 2013). In order to respond to the growing changes caused by the perturbations from the dam, understanding the lakes' resilience is becoming an urgent task.

Resilience is the capacity of a system to tolerate disturbances without collapsing into another domain in which its state is qualitatively different (Walker et al., 2006). Instead of trying to control change, a resilience view of the world shifts our thinking to dealing with and adapting to it (Berkes, 2007). From a sustainability point of view, resilience does not call for finding the optimal pathway for the future but implies thinking about how to steer the SESs towards trajectories which avoid undesirable positions or states (Walker, 2014). It is therefore important to understand what the desirable states are, what changes may happen that result in undesirable states, and how to determine and cope with the uncertainties that may cause these changes.

In recent years, resilience research is experiencing a period of boom during which its coverage was extended from ecological systems (as first introduced by Holling in 1973) to SESs (Xu & Marinova, 2013; Leitch & Bohensky, 2014). This includes research focussed on aquatic systems, coral reefs, agriculture, cities and catchment management (Carpenter, Ludwig, & Brock, 1999; Nystrom, Folke, & Moberg, 2000; Cabell & Oelofse, 2012; Newman, Beatley, & Boyer, 2009; Walker, Abel, Anderies, & Ryan, 2009). Assessing resilience, especially for SESs, however still remains problematic because of the complexity and paucity of relevant data (Xu, Marinova, & Guo, 2015b).

This study is the first attempting to assess the social-ecological resilience of Dongting Lake under the impacts of the Three Gorges Dam (TGD). It aims to analyse the health of the SESs of this freshwater lake under the impact of this serious disturbance. With not all necessary data available, expert scoring is used as a proxy in this assessment. Yet, the analysis allows for a reliable picture of the lake's situation to be presented. After explaining the methodology of the study (see Section 2), an assessment of Dongting Lake is conducted (see Section 3) and the results are discussed (see Section 4). The conclusion argues the need for policy responses and further research on the resilience of freshwater lakes.

## 2. Methods and material

### 2.1 Study Site

Dongting Lake, with a drainage area of 262 800 km<sup>2</sup>, is the second largest freshwater lake in China (Feng, Hu, Chen, & Zhao, 2013). Administratively located in Hunan Province, it is conjunct to the YR in its middle stream and is a seasonal and shallow lake consisting of three parts: East Dongting (ED), South Dongting (SD) and West Dongting (WD). The water from the YR comes to the lake through three inlets – Songzi, Taiping and Ouchi, in northwest and goes out to the same river through the Chenglingji outlet in northeast. Four joint local rivers (Xiang, Zi, Yuan and Li) also supply water to the lake from the south. The annual water inflow is about 312.6 billion m<sup>3</sup>, 38% of which comes from the YR (Y. Li, 2014). In the wet season (June to September), the maximum water surface area can reach up to 2691.2 km<sup>2</sup> while it shrinks to about 500 km<sup>2</sup> in the dry season (Lai, Jiang, & Huang, 2013; Y. Li, 2014). The spatial boundary of this case study is defined as the three parts of the lake (ED, SD and WD) together with the main counties and districts in the three cities along the lake, namely Junshan district, Yueyang county and Miluo city in the ED area, Xiangyin county and Yuanjiang city in the SD area, Hanshou county, Anxiang county and Nanxian county in the WD area (see Figure 1).

### 2.2 Methods

A range of indicators was developed by Xu et al. (2015a) for resilience assessment of freshwater lakes and the specific area of Dongting Lake. These indicators (see Table 1 and 2) describe the resilience of the freshwater lakes' SESs to external perturbations, including both their self-organising capacities and policy responses (see Figure 2), as they relate to the specific components of the systems or subsystems. The Dongting Lake's subsystems cover resources – water, wetlands, fish, water birds, productivity for human use and predictability; resource units – the actual quantities, distributions, growth rates and mobility; governance systems – ecological, economic and social policies, NGOs, property rights and local observation; and human users – number of people, their knowledge, leadership, common values and economic or cultural dependence on the lake (refer also to Table 1). Each subsystem is described by second layer subsystems and variables for which specific indicators are required in order to understand the resilience of the SES of the Dongting Lake. These indicators are explained below followed by description of the expert participation and assessment criteria used for the evaluation.

#### 2.2.1 Indicators and Calculation

A detailed description of the resilience indicators together with the respective calculation methods based on data availability is presented in Table 2 and 3. When possible, a quantitative calculation is used for system capacity

indicators (see Table 2) which can be measured or for which statistical data are available. If this is not the case, surrogates are used or expert scoring is applied with “1”, “2”, “3” and “4” indicating respectively “not resilient”, “low resilience”, “medium resilience” and “high resilience”.

The indicators related to policy responses (see Table 3) are assessed based on document analysis whether they are (or not) available to use for adapting to the systems’ changes. Scores are given to each response based on the status in the policy-making process, namely “1”, “2”, “3” and “4” to indicate respectively “unavailable”, “in progress”, “being implemented” and “works effectively” representing different levels of resilience – “not resilient”, “low resilience”, “medium resilience” and “high resilience” (see Table 3). For example, if policy  $P_i$  is at the stage of being debated (in progress) either in academia or government, its score is valued at “2”.

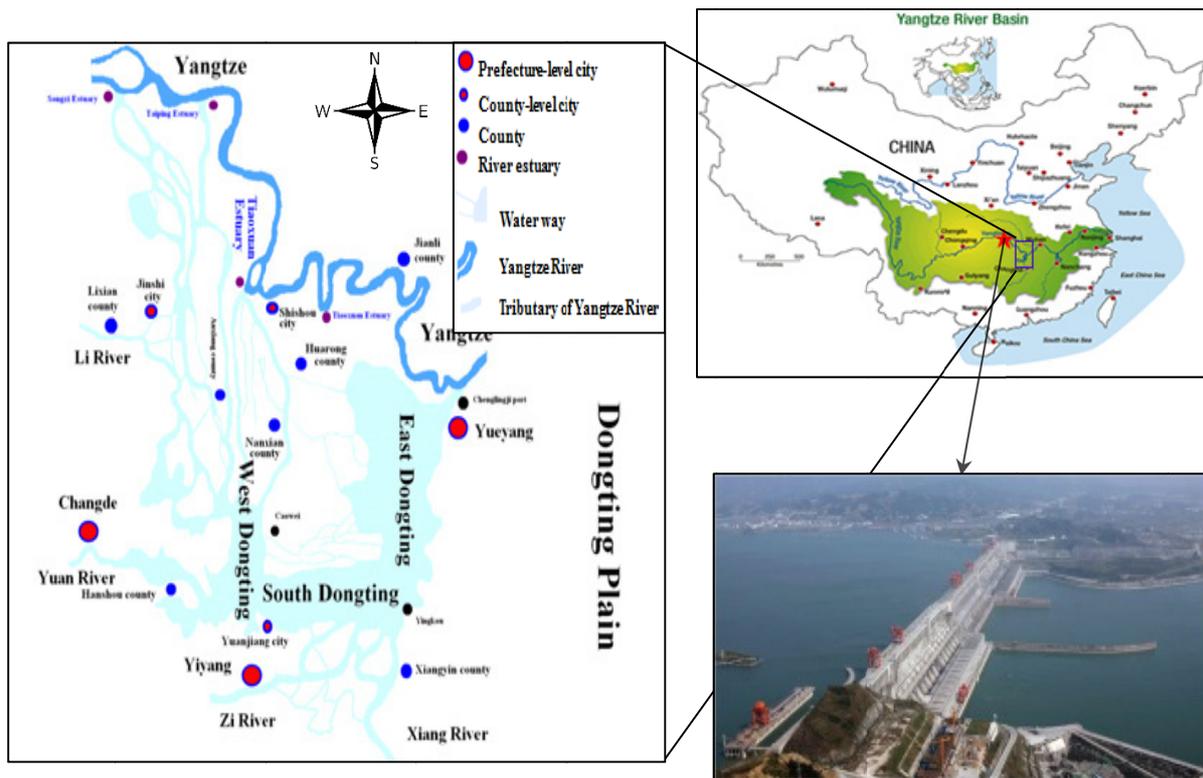


Figure 1. Location of Dongting Lake and the Three Gorges Dam

Table 1. Core subsystems and multiple variables of SESs of Dongting Lake

First layer subsystems	Second layer subsystems and variables	First layer subsystems	Second layer subsystems and variables
<b>RS</b> –Resource Systems	RS 1.1 –Water	<b>RU</b> –Resource Units	RU 1 – Resource unit mobility
	RS 1.2 – Wetlands		RU 2 – Growth and replacement rate
	RS 1.3 – Fish		RU 3 – Economic value
	RS 1.4 – Water birds		RU 4 – Quantity of units
	RS 4 – Productivity of system		RU 5.1 – Non-homogeneous distribution of units
	RS 5 – Predictability of system dynamics		RU 5.2 – Homogeneous distribution of units
<b>GS</b> – Governance Systems	GS 1.1 – Ecological policy	<b>U</b> –Users	U 1 – Number of users
	GS 1.2 – Economic-ecological policy		U 5 – Leadership
	GS 1.3 – Social-ecological policy		U 6.2 – Common interest/shared norms
	GS 2.2 – NGOs		U 7 – Knowledge of SES
	GS 3.1 – Property rights		U 8.1 – Economic dependence
	GS 3.2 – Collective-choice rules		U 8.2 – Cultural dependence
	GS 6.1 – Local observation		

Source: Compiled from Xu et al. (2015a)

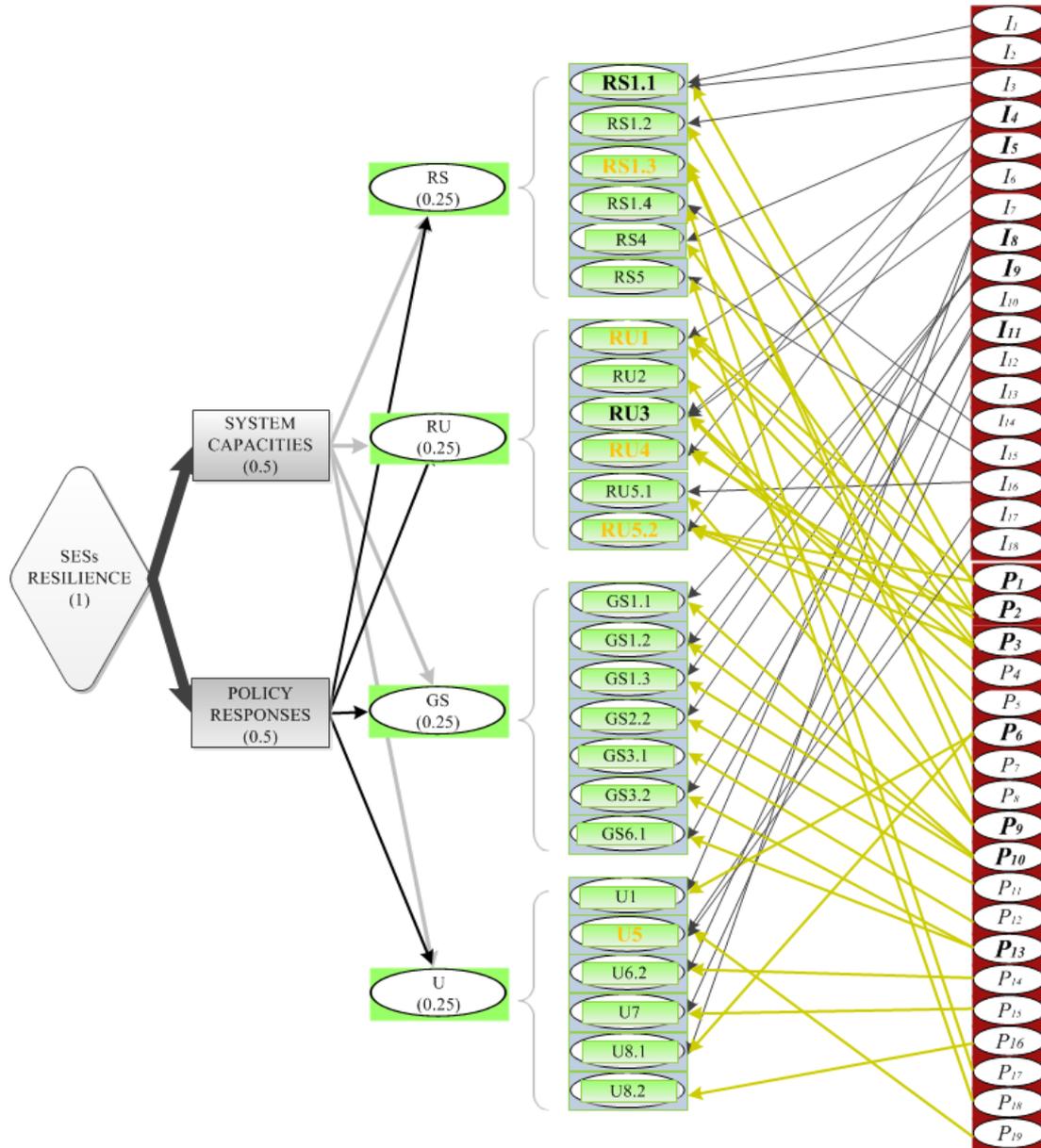


Figure 2. Hierarchical networks between SESs and indicators

Table 2. Indicators for system abilities and calculation

Indicator	Calculation/surrogate	Direction	Interpretation	Data source
Water storage ( $I_1$ )	Water level	Positive	Due to multifaceted factors, including geomorphology, water level is usually used to estimate the water storage of lakes	Li (2014)
Water supply-demand ratio ( $I_2$ )	$R_w = Q / (Dz_1 + Dz_2)$	Positive	Q is water supply of the lake; $Dz_1$ – water demands of the lake’s region; $z_1$ and $z_2$ – ecological and socioeconomic demand	Tong, Han, Lei, & Li (2014); Hunan Water Resource Bulletin
Coverage of emergent macrophytes ( $I_3$ )	Questionnaire	Positive	The core species indicating this is <i>Carex brevicuspis</i> – the main food source for waterbirds. Data are not available	Expert scoring

Regeneration rate of resources ( $I_4$ )	Questionnaire	Positive	The regeneration rate can be estimated in comparison with the rate of loss	Expert scoring
Liveable space for key species ( $I_5$ )	Questionnaire	Positive	Data about liveable space for the key species, especially fish, are fragmented	Expert scoring
Households' financial wealth ( $I_6$ )	Urban-rural poverty gap	Negative	Most people around the lake live in rural areas. The urban-rural gap (urban residents' disposable income/rural residents' annual net income per capita) can be used to estimate the households' financial ability to deal with problems. The smaller the gap is (i.e. the higher the value), the wealthier they are.	Yearbook of Hunan Province
Number of production methods (level of productivity) ( $I_7$ )	Questionnaire	Positive	The more production methods people residing in the lake areas have, the higher their resilience when resources are short	Expert scoring
Education attainment ( $I_8$ )	Dominant education level in the region	Positive	Education attainment can indicate the quality of labour skills. The higher educated people of the region are, the higher their level of resilience	Sixth Nationwide Population Census Bulletin: Hunan
Degree of public participation in policy making ( $I_9$ )	Public satisfaction	Positive	The extent to which the public is satisfied with participation in policy-making is used to estimate the degree of its participation	Interviews and expert scoring
Diversity of stakeholder networks in the region ( $I_{10}$ )	Questionnaire	Positive	Networks can include public activities and research collaborations	Expert scoring
Composition of stakeholders involved ( $I_{11}$ )	Questionnaire	Positive	Stakeholder participation should be representative and equal rules should be applied to everyone	Interviews and expert scoring
Size of local common interest groups ( $I_{12}$ )	Number of NGOs	Positive	As there are no authorised local common interest groups in the regions, NGOs are used as surrogate	Expert scoring
Population's illiteracy rate ( $I_{13}$ )	Illiteracy rate	Negative	Illiteracy rate is an important demographic variable. A lower illiteracy rate means the residents of the region have higher ability to learn knowledge	Sixth Nationwide Population Census Bulletin: Hunan
Change of habitat of water birds ( $I_{14}$ )	Questionnaire	Negative	Habitat change is an early warning signal to determine the effect of perturbation on waterbirds. The smaller the changes the less likely are they to affect the waterbirds	Expert scoring
Share of locals concerned about environmental changes ( $I_{15}$ )	Number of complaint reports to the government	Positive	Complaint reports indicate the degree of people's concern about their environmental situations	Environmental Protection Department of Hunan
Change in spatial patterns ( $I_{16}$ )	Field surveys	Negative	This indicates whether the non-homogeneous distribution of units in the SESs of the regions has changed; due to data limitation, spatial patterns assessed by experts can be used as an early warning	Expert scoring
Media coverage for social groups ( $I_{17}$ )	Online statistics	Positive	Environmental NGOs in the three regions are used as representative. Data in obtained with online search engines	News reports
Social influence power ( $I_{18}$ )	Questionnaire	Positive	Influence power of leading social groups can indicate their ability to contribute	Expert scoring

Table 3. Indicators for policy responses

Indicator	Resilience description	Resilience state	Description
Water quantity adjustment plans ( $P_1$ )	In progress	Low resilience	There are discussions about three groups of options (water transferred from YR, building of new gates and improving the regulations for TGD)
Wetlands restoration plans ( $P_2$ )	Being implemented	Medium resilience	Desilting of the lake, farmland reclamation around the lake, habitat restoration programs (started before the operation of the Dam but adaptations for its disturbance are needed)
Protection plans for the resources in the lake ( $P_3$ )	Works effectively	High resilience	Yearly events: International Festival of Birds Observation (since 2002), Love Birds Week (since 1981); spring ban for fishing; national and provincial protection regulations (12th Five-year Plan for local wetlands and natural resources protection, 2010); ban on ways of illegal fishing (such as “Mi-hun-zhen”) harmful for the sustainability of fish resources; closed, seasonal and periodical management of reserved areas
Financial support ( $P_4$ )	Being implemented	Medium resilience	Investment in irrigation infrastructures; national financial support programs approved; WWF programs for the protection of the lake (2006)
Technological support plans ( $P_5$ )	Being implemented	Medium resilience	Organic fishery program; farmland irrigation infrastructures and ecological agriculture programs
Programs to help locals with economic income ( $P_6$ )	Being implemented	Medium resilience	Development of ecological tourism, agriculture and fishery; Dongting Lake Ecological Economic Zone program (in progress)
Reproduction and protection plans for fish’s living space ( $P_7$ )	In progress	Low resilience	Representative areas of integrated utilities for agriculture, livestock and fishery around the lake; putting young fish into the lake every year (started long ago but the effects are small)
Food chain protection ( $P_8$ )	In progress	Low resilience	No specific protections for food chains in the lake, restoring habitats and water adjustment will be helpful for the integrity of food chains in the lake.
Long-term monitoring plans and experimental programs for key species ( $P_9$ )	Being implemented	Medium resilience	Several monitor stations covering ED, SD and WD areas for waterbirds, wetlands, water quality and other variables relating to the state of the lake; a database developed for WD; barriers exist – lack of professional staff and advanced instruments
Diversity of policy responses for the long-term ( $P_{10}$ )	Unavailable	Not resilient	Policies for many aspects of the lake’s health, but no policies specifically for disturbance by TGD
Diversity of policy support to local NGOs ( $P_{11}$ )	In progress	Low resilience	Limited support from the government for local environmental NGOs; the biggest barrier for the NGOs is the lack of financial support
Compensations for loss of access to the lake’s resources ( $P_{12}$ )	Being implemented	Medium resilience	Financial compensation available for fishers for income reduction during periods of ban on fishing in spring months (since 2008)
Complementary policies for enhancing collective action among stakeholders ( $P_{13}$ )	Being implemented	Medium resilience	Established collaboration with universities, institutes and governmental authorities; locals encouraged to get involved in co-management practices for the lake’s health (Beijing Forest University, Chinese Academy of Sciences, Hunan Normal University; community co-management practice in Qingshanyuan) (since 2005).
Strategies to encourage social groups ( $P_{14}$ )	In progress	Low resilience	Basic encouragement, mainly with co-organizing communities events; still insufficient financial support for wider NGOs activities.
Long-term strategies for education about the dynamics of SESs ( $P_{15}$ )	Works effectively	High resilience	Many education strategies adopted in the areas along the lake – advertising, TV programs, brochures, permanent warning signs, periodic exhibitions (videos and photographs) about environmental protection and education centres.

Strategies maintaining traditional culture ( $P_{16}$ )	Unavailable	Not resilient	Cultural dependence in the areas based on agriculture and fishery; strategies put in place to encourage ecologically sound production; no strategies to keep their traditional cultures.
Long-term observation of distribution and quantity of water birds ( $P_{17}$ )	Being implemented	Medium resilience	Several monitoring stations established covering ED, SD and WD areas; annual International Festival of Birds Observation and collaboration research groups help with observing birds.
Long-term monitoring of key variables ( $P_{18}$ )	Being implemented	Medium resilience	The established monitoring stations cover a large part of the lake and many aspects of its state; a long time required to see the effects.
Social rights regulations ( $P_{19}$ )	Unavailable	Not resilient	No governmental regulations dealing specifically with the rights of social groups and environmental NGOs in protection activities.

### 2.2.2 Expert Participation

Identifying thresholds of SESs is difficult, particularly when there is no evidence whether they or alternative regimes of the system exist. Expert assessment can help describe possible regimes and the scales of different resilience levels of the system. The experts identify the levels of resilience of the lake's SESs and also score the indicators for which data are not available.

Twenty experts familiar with the ecological and socioeconomic systems of the Dongting Lake region were involved in this study. Their opinion was collected using questionnaires consisting of 24 questions and a scoring table. The first part containing multiple-choice questions solicited knowledge about possible regimes of the SESs and thresholds; the second part was a table where experts were asked to assign scores to indicators. Half of the experts were participants in the December 2014 annual meeting of the Chinese "973" project on the interaction between the TGD and the river-connected lakes. The others were experts from the Dongting Lake Station for Wetland Ecosystem Research of the Chinese Academy of Sciences which has a specific focus on the ecological systems of the region.

### 2.2.3 States and Assessment Criteria

A threshold describes the maximum or minimum limit for a system to stay in a relatively stable state, and crossing it, even with a small change, can cause critical transitions to occur. For the purpose of assessment, a threshold not only indicates when or where the regime shifts happen but also defines the upper and lower bounds for standard criteria. From a sustainability point, it is important to keep systems in the desired configuration of states for all critical variables rather than maximise any specific supply of goods or services.

The possible regimes of freshwater lakes are identified as clean or turbid determined by the phosphate concentration in the catchment soils and lake sediments (Carpenter et al., 1999; Scheffer, Brock, & Westley, 2000; Falk et al., 2004). The regimes of the lakes' SESs are further influenced by changes in the hydrological conditions which play an important role for the state of the freshwater lakes' ecosystems in terms of water quantity. This is even more the case with the increasing impacts of climate change and big dam impoundment (Zhao, Cong, Barter, Fox, & Cao, 2012). For example, the quantity of water in a lake is essential for the living biota of the region by providing habitat and is also critical for regional security in terms of flood control and drought alleviation. Questions which require consideration are: Would hydrological changes cause regime shifts for the freshwater lakes that are different from either turbid or clean? How far is the system from unsustainable thresholds? These are discussed in relation to the situations in which the system can or cannot absorb the occurring changes (see Table 4). Thresholds are normally identified by evidence-based methods and manifested alternate regimes can be found from the literature or news reports. If this is not possible, expert assessment or proxies are used to estimate where such thresholds could be.

Table 4. Indicator scales for different levels of resilience of SESs

Indicator	Regimes/configurations		Scales of different status of resilience and descriptions			
	desirable	undesirable	non-resilient	low resilience	medium resilience	high resilience
$I_1$ Note 1	Enough for use in (1) dry and (2) wet seasons	Extreme drought	(1) $I_1 < 23m$ or $I_1 > 32m$ (2) $I_1 < 29.5m$ or $I_1 > 34m$	(1) $23m \leq I_1 < 26m$ (2) $29.5m \leq I_1 < 31m$	(1) $26m \leq I_1 < 29m$ (2) $31m \leq I_1 < 32.5m$	(1) $29m \leq I_1 \leq 32m$ (2) $32.5m \leq I_1 \leq 34m$

$I_2$	Meet average demands of SESs	A large gap exists	Basic ecological demands cannot be met	$R_w < 0.5$ , water satisfies basic ecological demands	$0.5 \leq R_w < 1$ , basic demands of SESs can be met	$R_w = 1$ , SESs' demands can be fulfilled
$I_3$ Note 2	Species do not lose their habitat	Extinction of species caused by isolation and fragmentation	Habitat cannot support most water birds	Habitat cannot support more than 50% of water birds	Habitat is fragmental but can support 50-80% of water birds	Habitat is integrated and can support more than 80% of water birds
$I_4$ Note 3	Above the rate of loss	Under the rate of loss	Loss/regeneration (ratio) is higher than 0.7	Loss/regeneration (ratio) is between 0.4 and 0.7	Loss/regeneration (ratio) is between 0.1 and 0.3	Loss/regeneration (ratio) is lower than 0.1
$I_5$	Enough living space for key species	Not enough living space for key species	Cannot be restored	Reduced and very hard to restore	Reduced but parts can be restored	Reduced but easy to restore
$I_6$ Note 4	Urban/rural gap is acceptable	Urban/rural gap can cause social crisis	The gap is larger than 3	The gap is between 2.5 and 3	The gap is between 2 and 2.4	The gap is between 1.5 and 1.9
$I_7$	Multiple technological production methods available	Very few production methods available	Production stops when resources are short	Lag in response with technology to resource availability	Alternative methods available to deal with resource shortage	Production technology easily copes with resource shortage
$I_8$	High education or training level	Low education or training level	No schooling	Junior high school or primary school	Senior high school or vocational training	Bachelor and higher degrees
$I_9$	High public participation	Very little or no participation	Less than 30% of the public satisfied with participation in governance	30-50% of the public satisfied with participation in governance	50-70% of the public satisfied with participation in governance	More than 70% of the public satisfied with participation in governance
$I_{10}$	Diverse linkages between organisations	Organisations work individually	No linkages	Very weak linkages	Some linkages exist	Regular linkages and close relationships
$I_{11}$	Equality for most stakeholders	Non-equality rules apply	Inequality	Equality rules seldom considered	Equality criterion exists but focus is on benefits for government	Equality is a criterion and is applied to all stakeholders
$I_{12}$	Many social groups	Lack of social groups	No environmental NGOs	Less NGOs than in other cities in the province	Average number of NGOs	More NGOs than in other cities in the province
$I_{13}$	Low illiteracy rate	High illiteracy rate	Higher than the national average level (4.08%)	2.71% to 4.07%	1.35% to 2.70%	0% to 1.34%
$I_{14}$	Habitat has not changed significantly	Habitat has changed dramatically	More than 35% of habitat change compared to the pre-dam period	21-35% of habitat change relative to the pre-dam period	6-20% of habitat change compared to the pre-dam period	Less than 5% habitat change compared to the pre-dam period
$I_{15}$	People very concerned about environmental changes	People not concerned about environmental changes	No complaint reports	Smaller number of complaint reports than in most cities in Hunan Province	The number of complaint reports comparable to the other cities in Hunan Province	Higher number of complaint reports than most other cities in Hunan Province
$I_{16}$	Spatial patterns of core systems are not changed	Spatial patterns of core systems are critically changed	Changed and cannot be restored/renewed	Changed in most core systems with long time to reorganise	Changed in some core systems and take short time to reorganise	Spatial patterns of core systems are not changed
$I_{17}$	The activities of social groups receive high attention	Very little information to the public about social groups	No news reports	Low media exposure compared to other cities in the province	Medium media exposure compared to other cities in the province	High media exposure compared to other cities in the province
$I_{18}$	Strong leadership	Poor leadership	Reputation of no leadership	Reputation at local level	Reputation at provincial level	Reputation at national level

## 2.2.4 Aggregation Process

The process of aggregating the indicators involves defining suitable weights and modelling. They are discussed below.

### 2.2.4.1 Indicator Weighting

The hierarchical network presented in Figure 2 is used to determine the weights of all indicators. Table 5 shows the relationships between the core system components and indicators.

The core systems are critical for the state of SESs and the interrelationships between them are complex and difficult to isolate. Also, the established indicators are specific for particular components of the core subsystems according to the certainty of occurrence triggered by TGD (Xu et al., 2015a). They are representative of the SES' responses to particular changes – that is, each indicator uniquely contributes to a different aspect of the systems' resilience. Hence, they should be treated as equally important. Equal weights are assigned to all subsystems and indicators (see Figure 2). The actual calculation of weight, including  $\omega_S$  – weights for respective subsystems (*S*),  $\omega_I$  – weights for respective indicators for systems' abilities (*I*) and  $\omega_P$  – weights for respective indicators for policies (*P*), is presented in Appendix 1 and the resulting values are listed in Table 6.

Table 5. Relationship between core subsystems and indicators

No.	Subsystem	System indicator	Policy indicator	No.	Subsystem	System indicator	Policy indicator
1	RS1.1	$I_1$	$P_1$	15	GS1.3	$I_9$	$P_{10}$
2	RS1.1	$I_2$	$P_1$	16	GS2.2	$I_{10}$	$P_{11}$
3	RS1.2	$I_3$	$P_2$	17	GS3.2	$I_{11}$	$P_{13}$
4	RS4	$I_4$	$P_3$	18	GS6.1	$I_{11}$	$P_{13}$
5	RU4	$I_4$	$P_2, P_3$	19	U6.2	$I_{12}$	$P_{14}$
6	RU1	$I_5$	$P_1, P_2, P_3$	20	U7	$I_{13}$	$P_{15}$
7	RU5.2	$I_5$	$P_1, P_2, P_3$	21	RS1.4	$I_{14}$	$P_{17}$
8	RS1.3	$I_5$	$P_7, P_8$	22	RS5	$I_{15}$	$P_{18}$
9	RU3	$I_6$	$P_4$	23	RU5.1	$I_{16}$	$P_9$
10	RU3	$I_7$	$P_5$	24	U5	$I_{17}$	$P_{19}$
11	U1	$I_8$	$P_6$	25	U5	$I_{18}$	$P_{19}$
12	U8.1	$I_8$	$P_6$	26	RU2		$P_9$
13	GS1.1	$I_9$	$P_{10}$	27	GS3.1		$P_{12}$
14	GS1.2	$I_9$	$P_{10}$	28	U8.2		$P_{16}$

Table 6. Weights of indicators for the studied SESs

<i>S</i>	$\omega_S$	<i>I</i>	$\omega_I$	<i>P</i>	$\omega_P$	<i>S</i>	$\omega_S$	<i>I</i>	$\omega_I$	<i>P</i>	$\omega_P$
RS1.1	0.071	$I_1$	0.019	$P_1$	0.058	GS2.2	0.036	$I_{14}$	0.019	$P_{14}$	0.019
RS1.2	0.036	$I_2$	0.019	$P_2$	0.048	GS3.2	0.036	$I_{15}$	0.019	$P_{15}$	0.019
RS4	0.036	$I_3$	0.019	$P_3$	0.048	GS6.1	0.036	$I_{16}$	0.019	$P_{16}$	0.019
RU4	0.036	$I_4$	0.033	$P_4$	0.019	U6.2	0.036	$I_{17}$	0.019	$P_{17}$	0.019
RU1	0.036	$I_5$	0.033	$P_5$	0.019	U7	0.036	$I_{18}$	0.019	$P_{18}$	0.019
RU5.2	0.036	$I_6$	0.019	$P_6$	0.037	RS1.4	0.036			$P_{19}$	0.037
RS1.3	0.036	$I_7$	0.019	$P_7$	0.012	RS5	0.036				
RU3	0.071	$I_8$	0.037	$P_8$	0.012	RU5.1	0.036				
U1	0.036	$I_9$	0.058	$P_9$	0.037	U5	0.071				
U8.1	0.036	$I_{10}$	0.019	$P_{10}$	0.058	RU2	0.036				
GS1.1	0.036	$I_{11}$	0.037	$P_{11}$	0.019	GS3.1	0.036				
GS1.2	0.036	$I_{12}$	0.019	$P_{12}$	0.019	U8.2	0.036				
GS1.3	0.036	$I_{13}$	0.019	$P_{13}$	0.037						

For the SESs of the studied area, 37 indicators ( $m=18$ ;  $k=19$ ) are used to assess the three areas  $u$  ( $u=1, 2, 3$ ) of the Dongting Lake region, namely ED, WD and SD. Most indicators for certain and potential changes are positive meaning that the higher their scores the higher the resilience of the system. The indicators for unknown changes however are negative meaning that they are not expected to change (see Table 1), the smaller their scores, the higher the resilience. On the other hand, all policy indicators  $P_b$  are positive and divided into three levels (“not resilient”, “low resilience”, “medium resilience” and “high resilience”).

#### 2.2.4.2 Aggregation modelling

The desirable states of SESs are the ones that are close to high resilience and away from undesirable and unsustainable regimes. This means the states of the systems should have the shortest distance from the positive state (high resilience or sustainable) and the longest distance from the negative state (low resilience or unsustainable). Such a requirement matches well the core concept of the technique for ordering preferences according to their similarity to the ideal solution (TOPSIS) (Hwang & Yoon, 1981) used in multi-criteria decision analysis modelling. The approach is based on the idea that the optimal resolution should have the shortest distance from the ideal solution and the farthest from the negative solution. It has proven useful in complex environmental assessments when compensating for data limitation through fuzzy linguistic descriptions (Chen, 2000).

The weighted TOPSIS method applied in this study allows for the lake areas to be ranked according to preference based on the value of the relative closeness ( $C^*$ ) to the ideal solutions for the indicators (refer to Append 2 for further details). Using the value of  $C^*$  the ranking is in a descending order starting from the best performance.

### 3. Results

#### 3.1 Indicator Scoring

Quantitative values were obtained for the indicators which could be measured or for which statistical information was available. In addition, the experts were asked to assign scores to the remaining indicators. The obtained results are presented in Table 7 where 1 represents “not resilient”, 2 – “low resilience”, 3 – “medium resilience” and 4 – “high resilience”).

Table 7. Values of indicators

Indicator	U			Indicator	U		
	ED	SD	WD		ED	SD	WD
$I_1$	24.94	29.5	30.02	$P_1$	2	2	2
$I_2$	0.95	0.84	0.81	$P_2$	3	3	3
$I_3$	4	3	3	$P_3$	4	4	4
$I_4$	3	3	3	$P_4$	3	3	3
$I_5$	4	3	3	$P_5$	3	3	3
$I_6$	2.5	2.41	2.63	$P_6$	3	3	3
$I_7$	3	2	2	$P_7$	2	2	2
$I_8$	2	2	2	$P_8$	2	2	2
$I_9$	2	2	2	$P_9$	3	3	3
$I_{10}$	4	3	3	$P_{10}$	1	1	1
$I_{11}$	3	3	3	$P_{11}$	2	2	2
$I_{12}$	3	3	3	$P_{12}$	3	3	3
$I_{13}$	1.76	2.32	3.20	$P_{13}$	3	3	3
$I_{14}$	4	3	3	$P_{14}$	2	2	2
$I_{15}$	3	3	4	$P_{15}$	4	4	4
$I_{16}$	3	4	4	$P_{16}$	1	1	1
$I_{17}$	4	2	3	$P_{17}$	3	3	3
$I_{18}$	4	2	3	$P_{18}$	3	3	3
				$P_{19}$	1	1	1

The average monthly water level in Chenglingji was 24.94 m between 2003 and 2008 which was a 0.43 m decrease compared to 25.37 m in 1981-2002 prior to the operation of the dam (Y. Li, 2014 pp198). Water shortage is more serious for SD and WD. During 2003–2008, the average water level in the Nanzui and Xiaohuzui monitoring stations in SD and WD was 30.02 m and 29.5 m respectively (X. Wang, Xiao, Zhu, & Shi, 2012) a reduction by 0.93 m and 1.01 m respectively compared to the period before the operation of the dam (Tong, Han, Lei, & Li, 2014).

Water demands of the SESs in the Dongting Lake region include ecological, agricultural, industrial and domestic requirements. According to Tong et al. (2014), the 2006 total average water demands in WD, SD and ED were respectively 1.22, 1.34 and 1.38 billion m<sup>3</sup> with increasing trends. The supplies for these three regions are 0.99, 1.13 and 1.32 billion m<sup>3</sup> and the basic ecological water demand of Dongting Lake is estimated at 0.27 billion m<sup>3</sup> (Tong et al., 2014). With priority given to ecological demands, there are gaps in meeting the needs for socioeconomic development in all areas of the lake. The supply-demand ratios are 0.81 for WD, 0.84 for SD and 0.95 for ED with water shortages being common. Without effective adaptation, the gap will continue to increase especially for SD and WD.

Since the operation of the TGD and lower water level caused by the impoundment of the dam, key resources of the lake such as waterbirds, fish and *Carex brevicuspis* are all decreasing due to declining liveable spaces. More specifically, the impoundment of the TGD leads to the earlier appearance of emergent macrophytes causing large parts of the lands and *Carex brevicuspis* to become dry and withered at the time of arrival of the migratory waterbirds. Such an early dry-up results in shortage of food sources for the waterbirds of the lake. From the 300-400 thousands waterbirds who used to live in the lake decades ago, about 130 thousands were seen between 2003 and 2004, less than 100 thousands between 2005 and 2006 (cited in Tong et al., 2014), and about 110 thousands between 2008 and 2009 (Xie, Zhang, & Jiang, 2014). Due to fragmented data, expert scoring was used for the assessment of  $I_5$ . The majority of the participating experts, namely 12 out of 20, agreed that the liveable space for key resources (fish, vegetation distribution and waterbirds) of the lake has reduced because of the TGD disturbance. Although parts of the disturbed spaces in the ED areas recover with further adaptations, the situation is worse in SD and WD because of more severe water shortage.

According to 2003-2008 statistical data, the average urban-rural gaps ( $I_6$ ) were 2.50, 2.41, and 2.63 for ED, SD, and WD respectively (S. Li, N. Li, & L. Li, 2014). The experts' average scores for  $I_7$  are 3, 2 and 2 meaning medium resilience for ED and low resilience for SD and WD. Despite the values for both agriculture and fishery increasing in the three areas between 2003 and 2008, the production methods are still at a low level with technology lacking in the region (S. Li et al., 2014).

With regards to  $I_8$ , the number of people in Yueyang City with junior high and primary school qualifications, senior high school and vocational training qualifications, and bachelor degrees were respectively 3.4, 1.3 and 0.4 million persons (Regional bulletins of the sixth nationwide population census, 2011). In Yiyang and Changde cities, these numbers were 3, 0.7 and 0.1 and 3.9, 1 and 0.4 million persons (Regional bulletins of the sixth nationwide population census, 2011). The education attainment of the three areas is similar and at a low level, which is also in accord with the experts' scoring.

During the field survey, the stakeholders were asked whether they were satisfied with the involvement of local people in government decision-making ( $I_9$ ). Only 5 out of 20 stated that they were satisfied with public participation strategies in the ED area. Some regulations have been put in place to enhance public participation at a provincial level; for example, the Regulations for Governance Procedures of Hunan Province give residents, representatives of enterprises and other organisations rights to participate in and propose rules of governance (Hunan Government, 2008). Their implementation however is ineffective. Most local stakeholders stated that the participating people did not represent them, did not know that the government called for local resident participation or who attended these events. Some fishers claimed that participation opportunities are not equal to everyone: doors open easier for licenced fishers but semi-fishers (who do not have licence but also have rights to fish in the lake in specific months of the year) have very few ways to get involved. The public is not satisfied with participation because of poor feedback from government. This was also confirmed by the analysis of information and documents related to public participation in the Dongting Lake areas which showed very narrow ways for participating in decision making. A similar situation exists for the SD and WD areas as their upper governance departments are affiliated with Hunan Province. The experts confirmed this problem: 17 (out of 20) are of the opinion that the degree of public participation is very low in the three regions and gave low scores. Experts scored the equality of stakeholders involved ( $I_{11}$ ) higher as the government uses this criterion in selecting stakeholders but mainly for its own benefits.

The average expert scores for the linkages of social networks are respectively 4, 3 and 3 for ED, SD and WD. Special events periodically held in the lake areas confirm this. For example, the Dongting Lake International Bird Watching Festival is held in ED in December of each year, Love Birds Week events are organised in SD and WD, research collaboration exists between the Dongting Lake Reserve Authorities, universities, institutes and the World Wildlife Fund for Nature (WWF).

The number of environmental NGOs is used as a surrogate for the size of social groups ( $I_{12}$ ). Experts gave a higher score for Yueyang city (located in the ED area) than that for Yiyang and Changde cities (in SD and WD). The All-China Environment Federation database (2014) shows that the total number of registered environmental NGOs in Hunan Province is 126, of which Changsha, the capital of the province, accounts for 68%. Except Changsha (which is outside the study area, with a total number at 14 the three cities of Dongting Lake have more registered NGOs than most other cities: Yueyang City has 6 (the third highest number in Hunan Province after Changsha and Hengyang both with 7), Changde – 5 and Yiyang – 3.

Both habitat loss and fragmentation increase the probability of species (such as birds and fish) leaving their habitat and entering another hostile place where their overall mortality rate increases. Habitat loss which is more significant than habitat fragmentation can also result in reduction in reproduction (Fahrig, 2002). According to Yang (2013), the habitat of Dongting Lake has begun to fragment since 1987 and this has accelerated especially since 2003. The total number of patches of the lake has increased from 16350 in 1998 to 19564 in 2008. However, the average area coverage of the patches has decreased from about 1.58 km<sup>2</sup> in 1998 to 1.32 km<sup>2</sup> in 2008. A key place for most species is ED which provides habitat for 80.92% of the total waterbirds of the lake while SD and WD account respectively for 2.68% and 3.45% (Xie et al., 2014). Since the operation of the dam, the habitat areas for critical waterbirds (such as cranes) have dramatically decreased, particularly in ED. The experts scored changes in habitat higher for ED than in SD and WD (4, 3 and 3 respectively).

The number of complaint reports ( $I_{15}$ ) data was obtained from the 2013-2014 Environmental Protection Department of Hunan. We counted the online complaints made on the website of the Department and compared the data with all cities in the province. In Hunan Province, Changde is the third highest city according to frequency of complaints (with an average rank of 17.5 for 2013 and 2014) made through the Department's online system. Yueyang and Yiyang cities were in the middle of the ranked 14 and 13.5 respectively. The three areas consequently scored 4 (WD), 3(ED) and 3(SD).

According to the experts, the spatial patterns of the core systems in three areas have somewhat changed due to alteration in the hydrological conditions. These changes are much severer in SD and WD which have lower water supplies compared to the period prior to the operation of the dam. Thus, experts scored 3, 4 and 4 for ED, SD and WD respectively.

China's online search engine Baidu was used to analyse media exposure of environmental NGOs in Hunan Province. Yueyang is the second highest ranked city with number of times its NGOs reported in the mass media being 74, which is far more often than the others –Zhuzhou with 19. Changde with 10 and Yiyang with 3. With respect to the power of the leading local social groups ( $I_{18}$ ), the experts from Hunan Province saw the environmental NGOs in Yueyang as the most well-known not only in the region but also at the national level. The leader (Zaibao Zhu) of the biggest NGO in Yueyang has a high reputation and he has been involved in environmental protection activities in the past 35 years despite health drawbacks (he was diagnosed with gastric cancer 20 years ago). The respective scores experts are 4 for ED, 2 for SD and 3 for WD.

Most policies apply to the whole lake with very little differences between the three areas. Hence they received the same scores (see Table 3 and 7).

### 3.2 Social-ecological Resilience of Dongting Lake Region

With the relative distance valued between 0 and 1, five levels were introduced to describe the level of social-ecological resilience of the Dongting Lake areas (see Table 8). Table 9 presents the results for the resilience of the SESs of Dongting Lake based on the established weights and values of the indicators (in Tables 6 and 7) and aggregation model (in Appendix 2). The social-ecological resilience of ED is the highest among the three areas with a relative closeness of less than 0.1 to the ideal high level; SD and WD have relatively low resilience in the face of the perturbation of TGD. Although the estimated social-ecological resilience for SD and WD is at the same level, WD is better than SD being 0.1 closer to the positive ideal solution (see Table 9).

Table 8. Assessment criteria for resilience of SESs

Integrated level	Standard score	Interpretation
High	$0.8 < C_u^* \leq 1$	The system is sustainable. Changes can be absorbed over a long time period.
Relatively high	$0.6 < C_u^* \leq 0.8$	Most changes can be absorbed but specific long-term policies or strategies are needed to adapt to the changes.
Medium	$0.4 < C_u^* \leq 0.6$	About half of the changes can be absorbed. More specific adaptations are needed to enhance the systems' abilities.
Relatively low	$0.2 < C_u^* \leq 0.4$	Most changes cannot be absorbed and many specific policies are needed to enhance the systems' abilities.
Low	$0 \leq C_u^* \leq 0.2$	The system is unsustainable. More efficient and specific strategies are required to enhance the systems' abilities to absorb perturbations.

Table 9. Social-ecological resilience of Dongting Lake

	$S^+$	$S^-$	$C^*$	Level of resilience
<b>ED</b>	0.036	0.106	0.744	Relatively high
<b>SD</b>	0.099	0.040	0.285	Relatively low
<b>WD</b>	0.085	0.051	0.375	Relatively low

Note:  $S^+$  – desirable state of high resilience;  $S^-$  – undesirable state of non-resilience.

#### 4. Discussion

Since its impoundment, not only has the TGD impacted Dongting Lake's ecological systems, it has also affected its socioeconomic systems. Overall, ED has stronger abilities to absorb most changes but specific long-term policies and strategies are needed for better adaptation. The diversity of stakeholder networks ( $I_{10}$ ) in the region is assessed to be at a high level in the ED area, including regular activities collaboratively organised by NGOs and local government such as the Love Birds Week event. However, the policy support to local NGOs ( $P_{11}$ ) is basic and a variety of measures are needed to enhance the social networks' power in long-term adaptation. By comparison, SD and WD are more vulnerable in responding to perturbations from the TGD with many aspects needed strengthening. For example, production methods in both areas are simple and technological support is needed to improve the locals' production level ( $I_7$ ). Also, social groups and their leadership should be encouraged and seen as more important for the purposes of environmental protection and adaptation. The study revealed a large number of universities-based environmental NGOs; however, their media coverage is small. This might indicate that their contribution to environmental protection activities is also small with the biggest barrier being insufficient funding support. More financial support for NGOs could enable them to make a real difference.

The reasons for ED having a higher resilience than the other two areas can be explained along three aspects. First of all, the topographical differences in the three areas make ED more ecologically resilient to the reduced water level. The landform of the bottom of ED is lower than in SD and WD, which gives the "U" shape topography of Dongting Lake – the water slopes from northwest to southeast. Thus, the water coverage area in ED is the largest (about 1327.8 km<sup>2</sup>) among the three (920 km<sup>2</sup> for SD and 443.4 km<sup>2</sup> for WD) (S. Li et al., 2014 pp.87-88). All water going into the lake discharges into the YR through the outlet at Chenglingji (ED). When the water supply from the YR to the lake through the inlets (Songzi, Taiping, and Ouchi) dries up, water scarcity becomes more serious for SD and WD.

Secondly, economic growth in ED is faster than SD and WD which makes this area more adaptive to external disturbances, especially its socioeconomic systems. The output values for primary, secondary and tertiary industries in Yueyang City (ED) in 2010 were 0.22, 0.83 and 0.49 billion Yuan. In Yiyang City (SD) the respective values were 0.16, 0.29 and 0.26 billion Yuan while in Changde City (WD) they were 0.28, 0.69 and 0.53 billion Yuan (Yearbook of Hunan Province, 2011). The good economic situation of Yueyang City gives the ED area higher abilities to adapt to changes. This is in line with Rose and Liao (2005) and Alessa et al. (2008)

who claim that wealthier communities have higher resilience in absorbing disturbances and changes. Hence, the current development plan for a Dongting Lake Ecological Economic Zone may be able to contribute for improving the livelihoods of the communities around the lake. Development emphasises should also be given to SD and WD in a way that strengthens their traditional economic activities, such as increasing agricultural productivity through innovative technology support, and supports innovative industries that are less resources-based, eco-friendly and economically efficient, such as eco-tourism and biomedical industries (which can potentially use wastes from the catchment).

Thirdly, the ED's social and natural capitals improve its resilience abilities. Labour capital in Yueyang City is of higher quality with the proportion of people in the labour force who have at least college qualification being 11.9% compared to 8.8% in Yiyang and 11.1% in Changde. Geographically, ED has the largest area with 1900 km<sup>2</sup> followed by SD with 1600 km<sup>2</sup> and WD with only 350 km<sup>2</sup>. A larger area means more resources. The total habitat coverage in ED is 400 km<sup>2</sup> while it is 300 km<sup>2</sup> in SD and 150 km<sup>2</sup> in WD. Between 2008 and 2009, there were respectively 88239, 2918 and 3762 waterbirds living in ED, SD and WD, accounting for 80.92%, 2.68% and 3.45% of total waterbirds of the lake (S. Li et al., 2014; Xie et al., 2014). To enhance the resilience of SD and WD, policy priority has to be given to restoration and protection strategies, including resource protection plans and reproduction plans for the fish. Increasing the quality of the labour force is also essential for enhancing the social resilience in the SD and WD regions, not only relying on school education but also offering professional training to residents and workers by local government officers.

Nevertheless, the three regions also face some common issues. First, the water exchange between the lake and joint rivers is generally unbalanced. Water inflows to the lake overweigh its outflows. The average monthly water level in Chenglingji between 2003 and 2008 shows low water levels and shortage in the lake from December to March (wet season). Water levels during these months were all lower than 23 m with the lowest at 21 m in January while in the wet season the water levels used to be nearly 29 m. The TGD actually expended the duration of drought in the lake regions and reduced its resilience in dry seasons. Policy responses to such change are still being debated. Water adjustment options need to be finalised as soon as possible for effective adaptation to the declining water levels.

Second, the low educational attainment of the people in the lake region contributes to low resilience. Further attempts need to be made to improve the education and professional training of local residents to increase their ability to learn new knowledge and skills for effective adaptation to environmental changes. Third, public participation in policy making has to be extended and made more effective as well as representative of all stakeholders. Although governmental regulation exist at provincial level (Hunan Government, 2008), public participation is not always conducted properly with all stakeholders identified. Fourth, there is still a dearth of diversity in strategies and policies to respond specifically to the disturbance of the TGD. For example, the support for local environmental NGOs should be financial at a sufficient level for effective operation as well as through giving them appropriate rights. There is more potential for NGOs to contribute for effective regional adaptation.

## 5. Conclusion

The TGD has delivered significant socioeconomic benefits to the Dongting Lake region. However, its negative impacts on the river-lake interactions through alterations in the hydrological conditions and ecological systems should not be ignored. The assessment on the link between the dam and joint lakes should not only focus separately on ecological or socioeconomic systems but on the combined SESs due to the high dependency of the communities on the lake and the impact they have on it. The resilience of the SESs of the lake areas can indicate the changes triggered by the dam to the socioeconomic systems and the responses and abilities of SESs to absorb these changes.

This study conducted an integrated assessment on the social-ecological resilience of Dongting Lake. The assessment was based on a set of social-ecological resilience indicators developed by Xu et al. (2015a) which were applied to three parts of the lake – east (ED), west (WD) and south (SD). Its results demonstrate that ED has the highest resilience with the most ability to absorb current and future perturbations caused by TGD to its social-ecological system. The existing policy responses however are basic with more diverse strategies needed to improve the resilience of the lake's communities and the power of social groups. With the social-ecological resilience of SD and WD at a relatively low level, more strategies are required to enhance the systems' absorption abilities (including improvement in productions technologies, education and professional training for local people, and public participation in policy makings) as well as to diversify the policy responses including

support for local social groups and NGOs and planning for the protection of the lake's food chains. Effective adaptation measures can improve the lake's resilience and support its long-term sustainability.

### Acknowledgments

The first author would like to acknowledge the financial support of CUSPA (Curtin University) for the field surveys of this study. All authors express their appreciation of the participation of experts from the Department of Fisheries of Dongting Lake, Dongting Lake Station for Wetland Ecosystem Research of the Chinese Academy of Sciences, Hohai University and Nanjing Institute of Geography and Limnology of the Chinese Academy of Sciences and Nanjing Technology University.

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## Notes

Note 1. Water storage affects the state of the lake with three different regimes for its SESs, i.e. abundant water (enough water for all uses), seasonal low water (users receive water under a specific scheme) and extreme drought (water is available only for priority schemes) (Ostrom, 1990). It is important in resilience management not to maximise the supply of any resources but to maintain them in a desirable configuration (Walker et al., 2002). Dongting is a seasonally influenced lake. There is abundant water in wet seasons and shortages during dry seasons. In this sense, the desirable state of water storage advocated in this study is “enough for uses”. Chenglingji hydrometric station is located in ED. When the water level is 33.5 m at the station (1.5 m higher than the warning water level), flood occurs in the lake region with about 16.76 billion m<sup>3</sup> of water storage (Deng et al., 2014). On the other hand, according to the reports, the lowest average water level of the lake was 23 m (Chenglingji station) in the past decades, below which serious impacts occur including suspension of shipping and fishing (Xinhua Net, 2009). Nanzui and Xiaohezui hydrometric stations are located at the joint point between SD and WD. When the water level monitored in Nanzui and Xiaohezui is about 29.5 m serious drought happens to SD and WD. The floods warning level is 34 m. Thus, the lower threshold for water level is defined as 23 m at which the water storage is about 1.33 billion m<sup>3</sup> (Xinhua Net, 2009) for ED and 29.5 m for SD and WD (Wetlands China, 2011). The resilience scale for the lake water storage can be divided into three – between 23 m

and 32 m for ED, 29.5 m for SD and 34 m for WD.

Note 2. According to the experts, the coverage of emergent macrophytes has to be at least 40-60% to support the livelihood of water birds in the lake. We set 50% and 80% as the thresholds for the low and high levels of resilience of the indicator  $I_3$ .

Note 3. For key resources, the experts suggest that the ratio between regeneration rate and rate of loss should be at least 0.9 to ensure the biodiversity of the lake, i.e. a rate of loss of less than 0.1. The medium level of resilience for key resources ranges between 0.1 and 0.4 and between 0.4 and 0.7 for low resilience. When the rate of loss is more than 0.4 it is very hard to maintain or recover biodiversity.

Note 4. As thresholds for the urban-rural gaps (Kuijs & Wang, 2006), we use 3 to 2.5, 2.5 to 2, and 2 to 1.5, where the systems' resilience is low, medium, and high, respectively. A smaller gap means that the people from rural areas (the lakeshore areas in our case are classified as the rural areas) have relative high ability to generate income when there is loss of economic values due to changes in natural resources.

### Appendix 1. Calculation of Weights

With the set of indicators for the systems' abilities defined as  $I_a = \{I_1, I_2, \dots, I_m\}$ , where  $m=18$  and the set of all policy indicators defined as  $P_b = \{P_1, P_2, \dots, P_k\}$ , where  $k=19$ , the combined indicators set is presented as:

$$C = \{(I_1, P_1), (I_2, P_2), \dots, (I_m, P_k)\}, (m=1, 2, \dots, 18; k=1, 2, \dots, 19)$$

where  $(I_m, P_k)$  refers to the corresponding combination of  $I$  and  $P$  indicators for the given subsystem. For instance, there are: one indicator for the systems' absorption ability (i.e.  $I_4$  – regeneration rate of resources) and two policy indicators (i.e.  $P_2$  – wetlands restoration plans and  $P_3$  – protection plans for the resources in the lake) for the subsystem RU4 (quantity of units). Then the combined indicators set for RU4 is  $[I_4, (P_2, P_3)]$ .  $(I_{n_a}, P_{n_b})$ .

More than one indicator and policy option however are used for some subsystems making these repeated indicators and subsystems (in bold on Figure 2) relatively more important for the resilience of the SESs – in bold black for the systems' self-organising abilities and in bold yellow for the policy adaptation options. The relationships between all system abilities and policies generate 28 different combinations (see Table 5).

If a subsystem is described as  $S_n$  and the weight assigned to it is  $\omega_{S_n}$ , then  $\omega_{S_n} = \frac{t_{S_n}}{n}$  ( $\omega_{S_n} \geq 0$ ,  $\sum_n \omega_{S_n} = 1$ ),

where  $t_{S_n}$  is the number of times  $S_n$  appears in Table 5 and  $n$  is the number of combinations, namely 28. For example, RS1.1 appears twice, its weight is then 1/14 while the weight of RS1.2 is 1/28 as it appears once. The equal weights for the combined set  $C$  are given by:

$$\omega_C = \frac{\omega_S}{N_I + N_P}, \quad \omega_C \geq 0, \quad \sum_n \omega_C = 1$$

where  $N_I$  and  $N_P$  denote the number of systems' ability and policy indicators for  $S$ , which appear in Table 5. For example, the combined indicators set for RS1.1 is  $[(I_1, I_2), P_1]$  (see Table 5). As  $P_1$  appears twice, it is a relatively important indicator,  $N_I$  and  $N_P$  are both 2 in this case (i.e.  $N_I + N_P = 4$ ). The weight for  $I_1$  and  $I_2$  is then 0.0179, i.e.  $(1/14)/4$ . As  $C$  is composed of  $I_m$  and  $P_k$ , its weights need to be equally distributed. The weights for  $I_m$  and  $P_k$  are given as:

$$\omega_I = \omega_C \{I_m\}; \quad \omega_P = \omega_C \{P_k\},$$

$$\omega_I, \omega_P \geq 0, \quad \sum_{I=1}^m \sum_{P=1}^k \omega_I \omega_P = 1$$

In the above example, the weights of  $I_1$  and  $I_2$  are distributed to 0.0179 while  $P_1$  is 0.0357 for the case of RS1.1. However,  $P_1$  appears as the response not only for RS1.1 but also for RU1 and RU5.2. Its weight thus will be added from the distributed weights from RU1 and RU5.2, reflecting its relative importance in the whole system. The weights for all indicators are listed in Table 5.

### Appendix 2. Aggregation Modelling

The following steps are used to develop the weighted TOPSIS method applied in this study to assess the

resilience of the SESs of the lake:

- a. Defining the initial indicator set or decision matrix of the SESs:

$$X=(x_{uC})_{u \times j} = \begin{bmatrix} x_{11} & \dots & x_{1j} \\ \vdots & \vdots & \vdots \\ x_{u1} & \dots & x_{uj} \end{bmatrix}$$

where  $x_{uC}$  is the value of the combined indicators set  $C$  for the assessed unit  $u$ . In this case, the assessed units are three with corresponding  $j=37$  indicators, i.e. the evaluation matrix  $X=(x_{uC})_{3 \times 37}$ .

- b. Establishing the normalisation matrix

As shown in Table 2, the systems' indicators can have two directions: positive (+) and negative (-), and different dimensions. Therefore all indicators need to be normalised into a common dimension. The normalised matrix is given by:

$$Y = \begin{bmatrix} y_{11} & \dots & y_{1j} \\ \vdots & \vdots & \vdots \\ y_{u1} & \dots & y_{uj} \end{bmatrix}, u=1, 2, 3; j=1, 2, \dots, 37 \quad (3)$$

$$\text{where } y_{uj} = x_{uj} / \sqrt{\sum_{u=1}^3 x_{uj}^2}, 0 \leq y_{uj} \leq 1$$

- c. Determining negative and positive ideal solutions

The positive ideal solution is the desirable state while negative ideal solution is the undesirable state of the system. They can be defined as  $F^+$  and  $F^-$  respectively and represented as:

$$F^+ = (y_1^+, y_2^+, \dots, y_j^+) = \left\{ \left( \max_u y_{uj} \mid j \in J \right), \left( \min_u y_{uj} \mid j \in J' \right) \right\} \quad (4a)$$

$$F^- = (y_1^-, y_2^-, \dots, y_j^-) = \left\{ \left( \min_u y_{uj} \mid j \in J \right), \left( \max_u y_{uj} \mid j \in J' \right) \right\} \quad (4b)$$

where  $u=1, 2, 3; j=1, 2, \dots, 37, J$  is associated with the positive and  $J'$  with the negative indicator set.

- d. Assigning weight vectors for indicators and calculating the distance of each indicator from the ideal solutions

To distinguish the relative importance of the indicators, the established weights (Table 6) are added to calculate the distance of each indicator from the ideal solutions ( $S_u$ ) by the equations:

$$S_u^+ = \sqrt{\sum_{j=1}^{37} \omega_j (y_{uj} - y_j^+)^2}; S_u^- = \sqrt{\sum_{j=1}^{37} \omega_j (y_{uj} - y_j^-)^2}, u=1,2,3; j=1,2,\dots,37 \quad (5)$$

- e. Determining the relative closeness ( $C^*$ ) to the ideal solutions for the indicators

The relative closeness describes the performance of the different lake areas. The larger the value of  $C^*$ , the better the performance of the area. The relative closeness of the  $u$ th unit can be calculated by:

$$C_u^* = S_u^- / (S_u^+ + S_u^-), 0 \leq C_u^* \leq 1, u=1,2,3 \quad (6)$$

- f. Ranking the performance of the lake areas

In the final step, the lake areas can be ranked according to preference using the value of  $C^*$  in a descending order starting from the best performance.

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**PAPER 7: MANAGING SOCIAL NETWORKS FOR COMMUNITY  
RESILIENCE FROM THE PERSPECTIVE OF BONDING  
RELATIONSHIPS**

**Statement of Contributions of Authorship**

To whom it may concern,

I, Li Xu, contributed 70% to the paper entitled above and cited as below:

Xu, Li, Xiumei Guo, Margaret Gollagher, and Dora Marinova. 2016. "Managing social networks for community resilience from the perspective of bonding relationships." in *Sustainability Issues in South Asia and Pacific*, edited by Marinova, Dora, and Xiumei Guo. Edward Elgar (forthcoming, acceptance date 30/09/2015).

Signature of Candidate:



Date: 30 October 2015

I, as a co-author, endorse that this level of contribution by the candidate indicate above is appropriate.

*Xiumei Guo Signature:*



Date: 2 November 2015

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Date: 2 November 2015

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Date: 2 November 2015

**This Chapter is an exact copy of the journal paper referred to above**

Published as:

Xu, Li, Xiumei Guo, Margaret Gollagher and Dora Marinova. 2016. "Managing social networks for community resilience from the perspective of bonding relationships." in *Sustainability Issues in South Asia and Pacific*, edited by Marinova, Dora, and Xiumei Guo. Edward Elgar (forthcoming).

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## **Managing social networks for community resilience from the perspective of bonding relationships**

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### **Abstract**

Highly resilient communities have an intrinsic capacity for adaptive self-management to response to sustainability challenges associated with natural resource management. This can occur when groups of citizens and stakeholders self-organise into social networks in order to undertake adaptive learning processes and/or to act to address particular issues. Indeed, social networks are critical determinants of a community's resilience and are influenced by bonding relationships among different people and social groups. This paper examines ways to enhance the bonding relationships within social networks that underpin community resilience and therefore sustainability. The analysis focuses on the following aspects of social networks that permeate resilient, sustainability-responsive communities: (1) well connected social networks exhibit high levels of social trust, strong leadership, extensive social memory, and knowledge of social-ecological dynamics; (2) their capacity for self-organisation is facilitated by social trust and strong leadership; (3) in particular, networks of strong leadership are important for community resilience; (4) social networks are connected by different kinds of bonding relationships (family, social, and regional bonds) through different leadership networks at different levels.

**Keywords:** Adaptive management; leadership; social trust; social networks; social-ecological systems; resilience, sustainability

Published as:

Xu, Li, Xiumei Guo, Margaret Gollagher and Dora Marinova. 2016. "Managing social networks for community resilience from the perspective of bonding relationships." in *Sustainability Issues in South Asia and Pacific*, edited by Marinova, Dora, and Xiumei Guo. Edward Elgar (forthcoming).

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## **1. Introduction**

Natural resource management must often contend with ongoing and unpredictable environmental changes, characterised by a high level of uncertainty. For example, climate change coupled with various unanticipated environmental shocks such as extreme floods, droughts and storms. Sustainability requires natural resource management to be more adaptive. Some argue that resilient communities have the potential to utilise these changes and uncertainty as an opportunity to become more sustainable (Levin, 1999; Folke et al., 2005). Consequently, sustainability science for adaptive management is shifting its focus from how to control those changes and uncertainties to how to effectively adapt to them, i.e. towards a resilience thinking (Xu et al., 2015).

Collaborative action between community members or groups is important for successful adaptive natural resource management as it enhances communities' resilience and adaptive capacity to future changes (Adger, 2003). Effective collaboration relies strongly on the optimisation of existing social relationships within a community, through formal and/or informal linkages between community members and/or stakeholders (Lauber et al., 2008). These relationships create social networks which facilitate communities' access to resources to adapt to changes. For example, community members can enhance their capacity to self-organise through exchanging or even co-creating new knowledge and seeking opportunities to learn with one another. This is thought to be a crucial characteristic of strong social networks (Borgatti and Foster, 2003). To build up community resilience and achieve effective adaptive natural resource management, social networks analysis can be a suitable method (Borgatti and Foster, 2003; Olsson and Folke, 2006; Lauber et al., 2008; Bodin and Crona, 2009; Poortinga, 2012).

Although attempts have been taken to analyse how social networks can increase

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communities' adaptive capacities and facilitate collaborations (Newman and Dale, 2005; Bodin et al., 2006; Ramirez-Sanchez and Pinkerton, 2009), there is still much more to learn about the context dependent nature of social networks that are able to contribute to the resilience of combined social and ecological systems, i.e. social-ecological systems (Janssen et al., 2006). More conceptual and empirical studies thus will contribute to the generalisation of how and in which way social networks can be useful for the effective adaptive management in the face of changes.

Relatively dense social links (the actors in the networks are closed tied together) can better strengthen the whole social networks and group resilience than the loose ones (Newman and Dale, 2005; Bordin et al., 2006; Ramirez-Sanchez and Pinkerton, 2009). However, if the networks are too dense it may give rise to the opposite effect which may weaken the group resilience (Bodin and Crona, 2009). Increasing the diversity of network linkages rather than the unordered connections can be more rational. This is also the purpose of this paper.

Social bonding (sometimes as human bonding) is the process of development of relationship between people and groups. It takes place between family members, friends, and social groups. The basics of social bonding include "attachment to families, commitment to social norms and institutions (school, employment), involvement in activities, and the belief that these things are important" (Hirschi, 1969, p.16). It is one of the vital aspects of social capital (Poortinga, 2012), which contributes to diversifying linkages between stakeholders and making the networks denser. Social bonding significantly strengthens social networks and therefore community resilience. Hence, this paper attempts to explore ways for the improvement of social networks by focusing on social bonding relationships, namely how to build up ordered and diverse social networks by using social bonding relations to enhance community resilience.

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Section 2 of this paper discusses community resilience and social networks as well as their relationship. Then, Section 3 emphasises the important roles of social bonding in enhancing social networks for community resilience. In Section 4, several ways are explored for the improvement of social networks by taking advantage of social bonding at different levels. The paper is concluded in Section 5.

## **2. Community resilience and social networks**

### **2.1. Community resilience**

Community resilience is the community's capacity to adapt to changes. Resilient communities are capable of absorbing environmental surprises and can learn from disturbance as well as create opportunities for innovation and the renewal of the system for reacting to disturbances (Levin, 1999; Folke 2006; Berkes and Ross, 2013). To establish a resilient community, a combination of social groups needs to work together towards communal objectives, which requires "existence, development and engagement of community resources by community members to thrive in an environment characterized by change, uncertainty, unpredictability and surprise" (Magis 2010 pp. 401). This is highly dependent on effective learning and adapting strategies (Marschke and Berkes, 2006). In order to ensure the contribution of social groups to community resilience, good social networks among groups and government agencies are essential.

### **2.2. Social networks and their contribution to community resilience**

Communities learn to live with changes and shocks by their self-organising ability (i.e. indigenous knowledge) retrieved from their responses to those changes (Berkes and Ross, 2013). The ability to self-organise thus can be enhanced by improving their knowledge in dynamics of environments and social-ecological systems in the face of unpredictability and surprises (Adger et al., 2005) as well as the ability to actively develop community resources including economic, cultural, and social resources

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(Walker et al., 2004). This intrinsic ability could also be strengthened and shared via connections within the community and among different communities at larger scales. Social networks are useful for this purpose and they help to build up general resilience and some parts of the specific resilience in social-ecological systems (Hahn et al., 2008; Berkes and Ross, 2012). An ideal social network is one in which members are tightly knitted and share information, knowledge and interests. In this way, information flow can be assured and effective collaborations may occur.

Social-ecological systems are formed by the interactions between society and nature (the using and being used relations). Good social links enable different groups of citizens and stakeholders with interests at different scales from local to global to mobilise to facilitate self-organising and learning processes in social-ecological systems (Scheffer et al., 2003). The stakeholders include members of local communities, government agencies, and social groups from different places. Within the network, communities, especially the ones being close to the resources, are dependent on the resources for their well-being. Government agencies are responsible for managing resources for human use and natural resource management. Social groups as pivotal intermediates or bridging organisations can play a role in connecting communities to government agencies and exchanging information and knowledge flows in the whole network (Figure 5.1).

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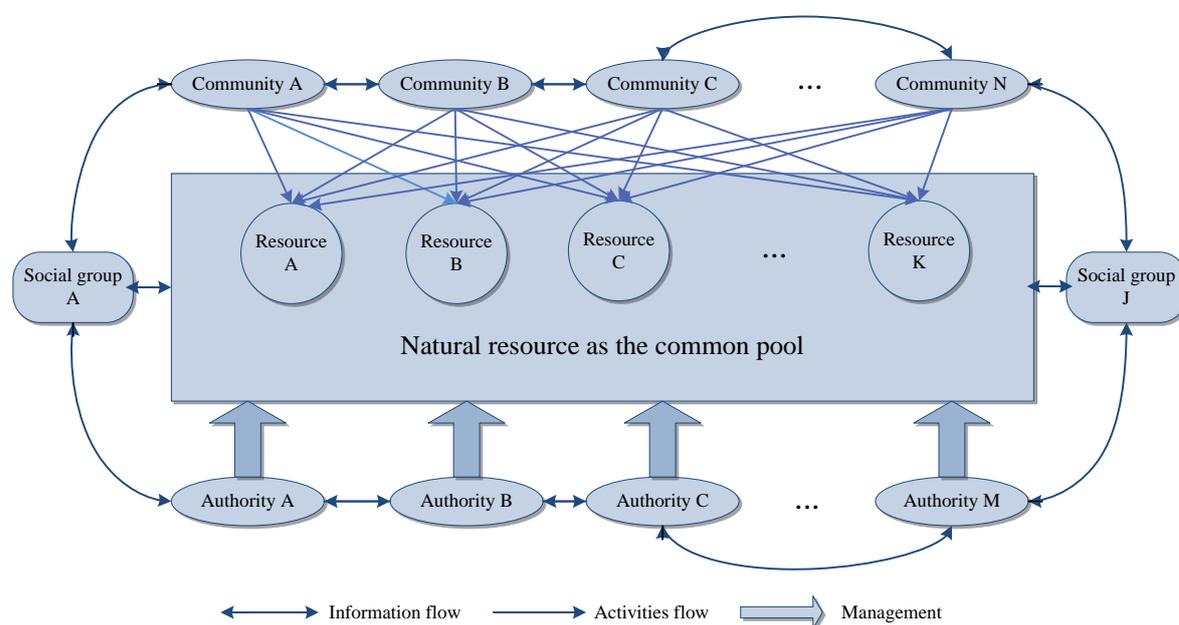


Figure 1 Network in social-ecological systems

To obtain good connections, social networks must have strong social trust, leadership, social memory and knowledge about social-ecological dynamics thereafter the improvement of community resilience (Folke et al., 2005). All of these components have reciprocal relations and contribute to different extents to communities' learning and adaptations abilities in the face of uncertainties and change. For example, social-ecological dynamics can be obtained through observation on how natural systems changes or environmental disasters affect communities and how they respond to different types of impacts (Xu et al., 2013). The following sections give more discussions about those key components and their functions in social networks, namely social trust, leadership, social memory and knowledge.

### 2.2.1. Social trust

Trust is the foundation of collaboration and maintenance of social networks. Social trust is helpful for community resilience through affecting the degree to which group members are willing to share information with others and enhancing systems' adaptive capacity to changes (Ramirez-Sanchez and Pinkerton, 2009). Strong social

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trust in social networks enables people to work collaboratively because it is easier to influence someone who are trusting in the networks. The more people trust each other in the networks the more likely they work collaboratively. Following such rule, social institutions can be formed (Cook, 2003).

### 2.2.2. *Social memory*

Social memory is one part of the cultural capital embedded in human societies (Bekers and Folke, 1992). It can be used as the experience learned from past changes to inform responses to new circumstances and to design policy adaptations to potential future changes. It is involved experiential knowledge that community members have gained from "learning-by-doing". This form of knowledge is co-created and shared by members of social networks, and can improve people's understanding and therefore management of social-ecological dynamics.

### 2.2.3. *Knowledge combination*

It should be noted that the knowledge being discussed in this context is the people's knowledge about social-ecological system dynamics, i.e. changes and responses that occur. The successful combination of knowledge relies on the level to which the knowledge can be shared within networks. Although the declined resources may reduce people's willingness to share their knowledge due to the competitive behaviours, it is not always the case (Ramirez-Sanchez and Pinkerton, 2009). In fact, the information about environmental changes possessed by individuals can be easily encouraged to share if changes are related to the abundant of resources. Resources are not abundant would mean that the certain environmental changes have affected the resources that people can access and policy adaptations are needed. At this time, the information can be widely shared through informal and formal networks. This kind of sharing information helps natural resource managers to find ways to adapt to changes. For instant, managers can determine when and to what extent intervenes are needed to

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keep the resources abundant when the similar changes happen.

#### 2.2.4. *leadership*

Good leadership can result in successful collaborations in networks. The group leaders are important in managing existing knowledge within the networks and developing learning mechanisms. In this way, information flows in the networks and self-organising processes become possible across actors at different levels. Leadership also contributes to community resilience by mobilising social memory at various degrees especially at the organisational level (Folke et al., 2005) such as government agencies and local social groups. Thus, the main tasks of group leaders are to collect knowledge and memory of the networks and enhance the information flow across both spatial and temporal scales.

### **3. Social bonding in networks**

Social networks are differentiated by patterns of relations with respect to promoting knowledge transfer, information sharing, and agreement building (Bodin and Crona, 2009). Social bonding influences the extent of community members' willingness to share information and affects the structure of social networks. Such bonding is presented as trust between kinship, friendship, and acquaintance relations in the community (Ramirez-Sanchez and Pinkerton, 2009). For example, fishers share their knowledge and information about where and when fish is abundant within their family group and with close friends or people who have bonded interests. Herein we define bonding relationships as the implicit interpersonal and social relations occurring among different families, social groups and government agencies, in which they are tied together by endogenously and exogenously cohesive linkages. Bonding relationships thus can be divided into (1) family bonds, which happen between family members and relatives (kinship); (2) social bonds which develop and are supported by interactive process between friends and within neighbourhood; and (3) regional bonds

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which link different communities through social groups and government agencies across regions (from local to regional levels, from regional to national levels, and from national to international levels).

Well combined bonding relationships in the networks can build up strong social trust and leadership, foster social memory, and integrate knowledge of social-ecological systems dynamics. In this paper, we specifically discuss the social trust and leadership as the improvement of them can largely contribute to the enhancement of the other two.

### **3.1. Social trust in networks**

Trust is the prerequisite of linkages between people or organisations. Weak trust networks at family levels can be presented as in Figure 2 (left). Although members (nodes) from different families are linked by family bonds (edges) which are formed by kinships, the information is insufficiently shared in the networks. The trust is much stronger between families which have closer relations, i.e. closer kinships. In the case of family networks with weak trust, the information is transmitted one by one through the networks rather than shared as a group. This can usually lead to misunderstandings in information and inefficient communications. In contrast, family networks with strong trust ensure the information being shared in various ways all over the networks. In such networks, group members actively share information with each other (Figure 2 right).

Social bonds happen via interactions (for example working, gathering, and other social events) among family members and their friends, neighbours, and members from other social groups with whom they have connections at larger regional levels. The edges in figure 2 linking different family groups are such social bonds and show the bonding relationships at regional level. Weak trust also leads to loose social networks at a broader level. Knowledge sharing occurs more easily between those

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people who have closer relationships such as among friends and colleagues. The dense networks would be possible when strong social trust is built.

Regional bonds appear between different regions across the nation. Social bonds which bring different families together are tied by broader bridging groups through regional bonds. These bonds include both formal and informal patterns. Formal patterns can result from the authority of governments or government agencies whereas informal patterns are formed by either interpersonal actions or social groups. Successful social networks at a national level are reliant on effective collaborations among various communities from different regions. In this case, social trust may play weaker roles while common interests could assume a more important position.

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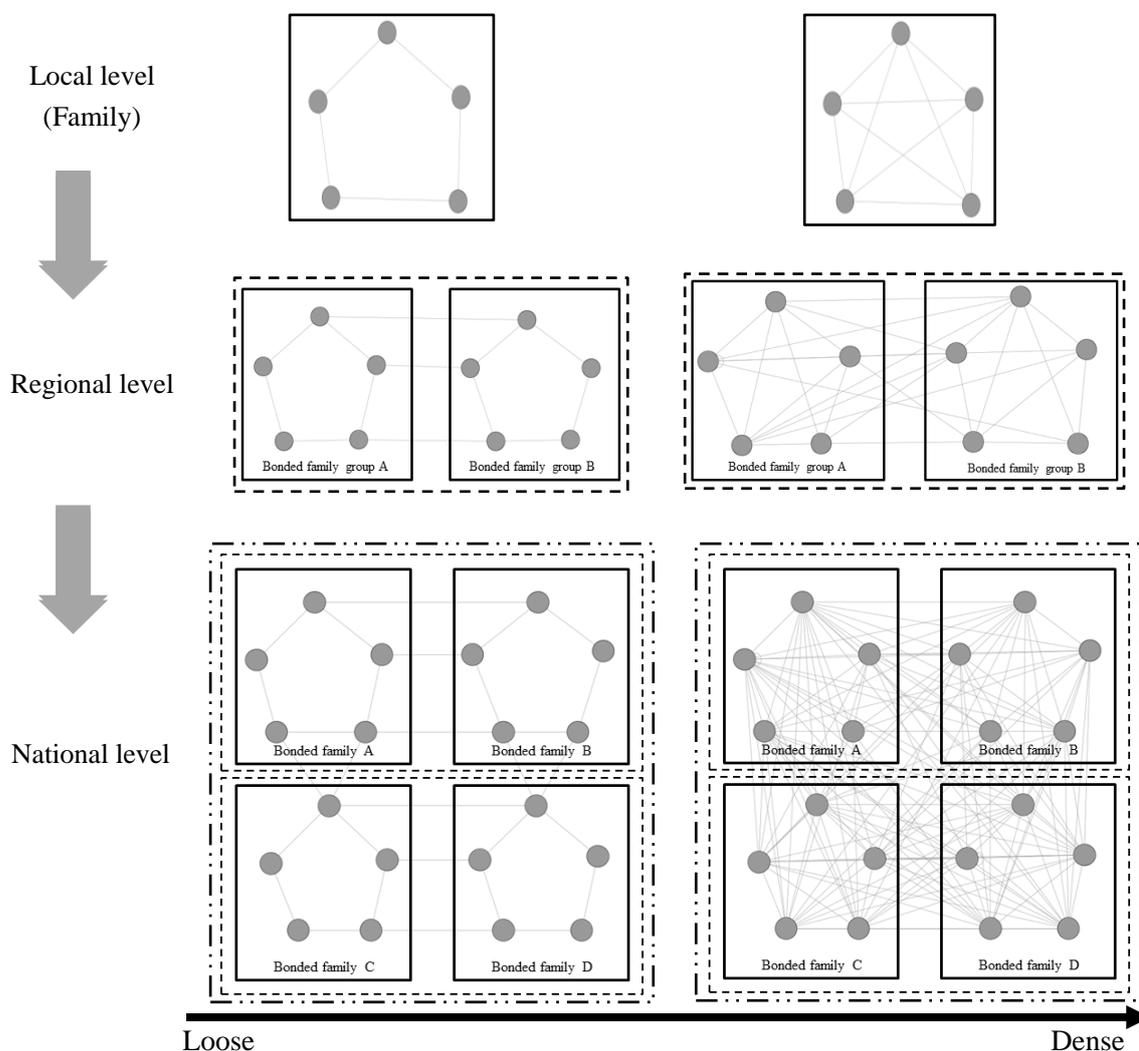


Figure 2 Loose and dense networks within weak and strong trust

Strong trust in networks can create better connections and dense networks. However, this pattern does not always improve community resilience. As Bodin and Crona (2009) argue, although studies have shown that the higher density of networks can increase the possibility of collective actions, the opposite effect could also be brought by extremely high density. For example, if the network is too dense, the exchanged information through it would be messy and incorrect because it lacks of well organised. This may lead to more misinterpretation of problems. We argue that the leadership of networks can be useful to resolve this issue since strong leaders can help

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to avoid the unordered information flows that can be caused by extreme density and can better connect different members and groups of the networks. This is discussed in the next section.

### **3.2. Leadership in networks**

Good leadership can contribute greatly to the integration and management of the knowledge of various individuals throughout social networks, so as to increase collective actions and community resilience. Without well-built-in leadership in social networks, the information flow between different social groups can be weak. Leadership can be a useful bridging power to connect social groups and their members within networks. This is especially critical for networks at larger scales. Figure 3 below displays the social networks within leadership at different levels. The red nodes are the leadership networks in the whole network which can also be regarded as bridging ties. They are information holders and transmitters of the networks consisting of leaders from different families and communities.

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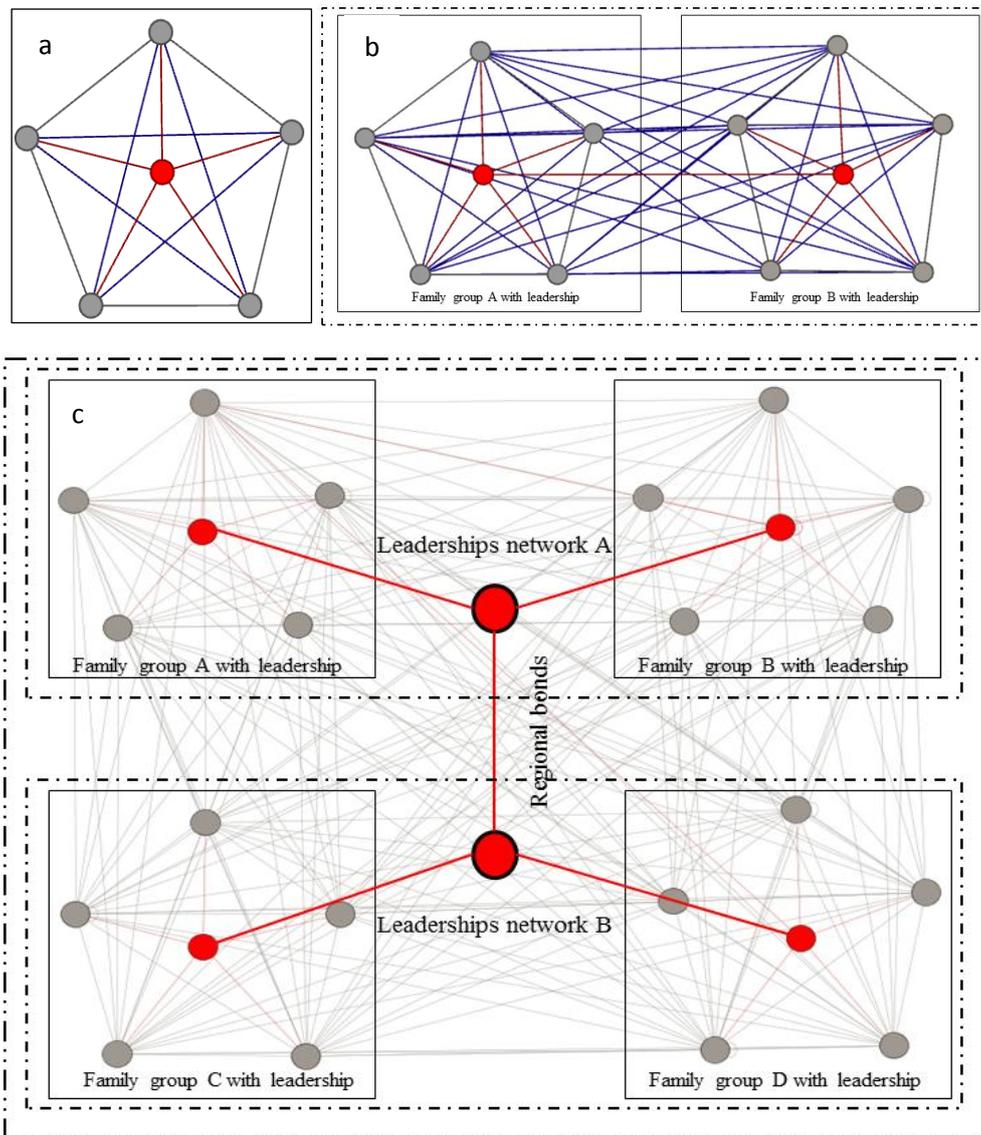


Figure 3 Social networks with leaderships at different levels

Compared with Figure 2, social networks within leadership (Figure 3) present better organised structures in terms of information flows. This is because the information is better organised in the networks via core flow lines rather than in an unordered pattern than that in networks without leadership. In these networks, information and knowledge from different social groups and family members are organised and managed by leaders from different levels. Although the cohesive bonding relationships still give rise to interpersonal communications among members of different families and groups in a dense network (shown as blue lines in Figure 3), the

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information from leadership networks is more important and useful. Natural resource managers should pay more attention to information generated by the leadership networks.

At family (local) level (Figure 3a), the leader can be determined by those people who have higher prestige in the family or can be voted by family members. The leaders from different families of different kinships constitute a leadership network at local level representing the interests of different families. The basis of this leadership network is the cohesive trust in the kinships. The leadership networks at regional level (Figure 3b) are established by social bonds through social activities. Leaders get information from their social networks and formal connections organised by governments with other leaders from different communities. Since the connections are built among leaders of different communities, the broader leadership networks will be established as the bridging subgroups. The leadership networks at national level (across regions, Figure 3c) are highly dependent on regional bonds such as governance and political power, and the leaders. They should be composed of those people who are from social groups within different stakeholders and people who have strong authorities such as in administrative areas, academic and professional experts.

#### **4. Enhancing social networks at different levels**

Enhancing the social networks at a large scale relies on transformational changes at local or smaller levels. This is because gradual local transformational changes can result in feedback impacts on improving resilience of the whole system (Walker et al., 2009) and help the whole region become more resilient (Berkes and Ross, 2012). Therefore, we discuss ways of improving social networks for community resilience in a bottom-up manner, namely from the local scale to the national scale.

Community resilience can be improved by strengthening community bonds in social networks ranging from local level to municipal levels, to regional and national levels,

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and even to international levels. The reasons for this are twofold. First, community bonds underpin social trust and collective action. They are one of the three types of social capital (with bridging and linking capital) that have close ties which create consistency within groups and help to build up community resilience (Magis, 2010). Moreover, social networks can build resilience but must be expanded to larger scales by bridging links. Links which only embrace local people or groups may reduce the community's resilience (Newman and Dale, 2005). This is due to the fact that local networks may be isolated from useful information and knowledge of other regions. Without broader links and sharing of knowledge, local community could not be able to withstand changes or shocks which might have not happened in one region but in others.

This paper focuses on enhancing social bonding via emphasising social trust and leadership in order to strengthen social networks. We believe that the strong social trust and leadership can boost the combination of knowledge and information sharing and managing social memory throughout the whole network, and consequently improve community resilience.

#### **4.1. Networks at the local level**

Bonding relationships at the local level are typically informal and are tied by family bonds and social bonds. We define social networks at local level as those constituted by family networks (group), and/or those belonging to different interest groups in the same geographical area (such as a county or city). A family network is composed of all family members (including relatives) within the same area. In such networks, family members are linked by cohesive kinships (i.e. family bonds), and each family network is assumed to be highly relied on the same resource. The leadership network is made up of each leader from different family networks. For example, given family network A as a group of fishers, the members in the network are from different

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families within the same kinship, and all the members of the network are fishers. Family network B is a group of farmers, the members of the network are from families within the same kinship and doing farming. Then, the leadership network at the local scale is constituted by the leaders selected from different family networks.

#### *4.1.1. Linking different families to foster trust*

Studies have found that bonding has positive effect on fostering social trust especially among those unconnected groups by exchanging information and knowledge (see the review of Bodin and Crona, 2009). At the local level, family bonds are easily connected because of the kinship among them. However, this is not always the case with social bonds. One of the ways to tackle this is to identify and establish leadership networks (subgroups) which consist of various leaders from different family groups (family bonds linked groups) to better exchange knowledge with other family groups. Researchers such as Schneider (2003) and Hoppe and Reinelt (2010) refer to these subgroups as bridging ties or peer leadership networks. Interaction within these leadership networks contributes to the diversity of knowledge developed in different subgroups and gives confidence to those actors attempting to solve conflicts and co-manage with natural resources managers. The linkages created by leaders at the local level can enhance the capacity of actors in the social network to self-organise by fostering trust but also increase their knowledge to adapt to changes through exchanging information.

#### *4.1.2. Determining leaders to make the linkages*

The leader(s) of each family (including kinship, i.e. relatives' families) is/are the person(s) who possesses a favourable position (prestige) in their family networks and (or) formal authority. King (2000) has shown that this kind of person(s) has/have a great influence in decision-making processes. To identify the leadership of a family, there is a need to compare the common characteristics including age, education,

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occupation, and income or earning among the family members. Also, field surveys are highly recommended as a combined method to identify the right leaders for the studied area in order to establish the leadership networks which can get involved as different stakeholders as possible into the co-management processes.

#### *4.1.3. Facilitating leadership network for collaboration*

Social networks at a local level are closely related to the self-organising ability of families. The leaders of local social networks have to collect information about ecological changes of the area and their families' responses to those changes. This information is then can be reported to the leadership networks and brings knowledge into management processes by exchanging with other leadership networks from different communities. Leadership networks can avoid the disagreement among different stakeholders. This is because the leaders of the networks represent different groups of stakeholders and possess collected information from them. Leadership networks are also helpful for the well-ordinated collective action because of the strong internally connected family bonds. Collaboration between leaders of different networks will foster natural resources management and enhance community resilience.

First of all, sharing resources can facilitate collaboration among groups (Magis, 2010). Such resources could not only include the knowledge and information about changes but also the management rights or power of local leaders for their better leadership in the networks. The devolution of management rights to local stakeholders or local groups in the fishing association in Sweden for example, has been approved as an effective manner to increase local control over the resources (Olsson and Folk, 2001). The intermediates that can be used to share knowledge, and successful experiences in particular, with the public include personal interactions, local media, and reports. These are effective ways for maintaining social memory of adapting to changes. The

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case of Ecomuseum Kristianstads Vattenrike project of Sweden is a good example of this (Hahn et al., 2006).

On the other hand, funding and technological resources have to be distributed to local leadership groups to enable them to function well. The increased investments are able to boost the productivity of current resources and generate new resources, i.e. community capital which not only includes economic but also social, cultural, spiritual, and political resources (Maigs, 2010). Hence, local resilience could be improved by funding support to local nongovernmental organisations and other social groups.

## **4.2. Networks at the regional level**

Although individual and household activities contribute to community resilience at local levels, their work alone is not sufficient to build up community resilience throughout the entire social system (Berkes et al., 2003). Broader collaborative actions have to be enhanced in order to deal with changes. Effective collective actions should be conducted among different groups within diverse stakeholders across different communities, i.e. at a regional level and a national level.

### *4.2.1. Linking different communities*

Collective actions at the regional level differ from the ones at local level. They require the participation of government agencies and other social groups. As well, regional bonds play more critical roles than that of family and social bonds at this level. Social bonds link people via their friendship, neighbourhood, and acquaintances from different communities. However information sharing obtained through social bonds is uncertain and depends on the extent to which they are close and trust each other. If the trust is weak between two people, they may be less likely to share information. In this case, the leadership networks may be more useful to improve the information sharing because of the leader impacts they have within their communities. Leaders of different

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communities collected information from different groups and then share it via leadership networks. Yet, the connections between leadership networks have to be supported and facilitated by bridging organisations (subgroups such as NGOs and government agencies).

#### *4.2.2. Using subgroups as the bridge to build the linkages*

Social bonds can be regarded as the information carriers while the mission of bridging linkages is to keep the information flow throughout the networks. Missing any of them may lead to the loose social networks resulting in the low adaptive capacity of communities. As discussed above, subgroups could be good sources of such bridges and should be constituted by the core people of leadership networks from each community. The subgroups have to embrace as various stakeholders as possible to make sure the legitimacy and must be implicated in the management processes. In order words, the most relevant representatives of various subgroups should be invited in the participatory processes.

More specifically, subgroups composed of core people of different leadership networks can be established and supported by *ac hoc* projects and funding. The core people can be selected by comparing personal backgrounds and the voting process within the leadership groups. The government agency must be considered as a participant in the selection procedure to insure the authority of the selected core people. After this, political participation (Poortinga, 2012) is advised to get such subgroups into the governance system. For example, the members of the leadership subgroups should be empowered with rights to participate in making environmental laws and regulations. The information and knowledge from different communities can be gathered during the processes. These bridging subgroups have been approved, in the case of Ecomuseum Kristianstads Vattenrike of Sweden (Hahn et al., 2006), to be

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an effective way to create trust, knowledge, learning, conflict resolution among actors across different levels and to develop a trajectory of social-ecological resilience.

In addition, establishing multilayered participation between government agencies and leadership networks is a vital stage to bridge the linkages. Leadership networks are representative of different groups of stakeholders while government agencies can play roles in linking them together across levels. The multilevel interactions can be facilitated by nongovernmental organizations and other groups in networks, which in turn results in social learning and resilience building for communities (Robinson and Berkes, 2011). The linkages among organisations and institutions within the same level and across different levels have been approved to be important in strengthening social networks and social-ecological resilience (Gunderson et al., 2006).

### **4.3. Networks at the national level**

Networks at national level appear as the connections and collaborative actions among various social groups across different regions. Family bonds are the fundamentals of social networks at a national level whilst social bonds and regional bonds are boosters of linking those networks as a whole, by which the power of social networks can be spread to larger scales. Regional bonds are critical to link social networks at national level and are relied in large part on formal patterns such as institutions and governance linkages.

#### *4.3.1. Linking different regions*

Regional bonds can be established by linking different hierarchical levels of authorities and communities from different areas in terms of social capital connections. This has been approved to be essential for successful natural resource governance by King (2000). The effective way in doing so is to bridge the linkages among regional leadership networks and government agencies as well as nongovernmental organisations.

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#### *4.3.2. Facilitating linkages among different regions*

Duplications and overlapping of authority and policy inconsistencies are typical barriers that hamper the connections across regions. For example, the management of wetlands in Dongting Lake region of China involves multiple government agencies including not only Department of Agriculture but also forestry, fishery, and environmental protection. The overlapping and duplications of authority lead to the ambiguity of management responsibilities and conflicts especially when benefits concerned issues occur (Xie et al., 2014). The issues of duplications and overlapping of authority and policy inconsistencies are the common perceptions of inefficiencies that may jeopardise community resilience (Folk et al., 2005). Thus, the management of social networks at the national level has to solve these two issues.

The recommended way of coping with this is to share management power and responsibilities among communities, government agencies and nongovernmental organisations. The sharing power and responsibilities should be organised by leadership networks from different vertical levels (Carlsson and Berkes, 2005; Folke et al., 2005), i.e. leadership networks composed of leaders from different families, communities, and regions. Establishing institutional linkages among those different subgroups is effective in doing so (Robinson and Berkes, 2011). For instance, government agencies and nongovernmental organisations explain social-ecological dynamics to members of local and regional networks whilst the upward feedback is given to the agencies within data information from local observations. This sort of interactive connection (comanagement) between communities and government causes the effective adaptive management and increase local knowledge about social-ecological dynamics as well.

## **5. Conclusion**

Changing environment in nowadays and variations of the future have shifted

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sustainability science to a new arena that can improve the adaptive capacity not only of natural ecological systems but also of social-ecological systems. In adapting to the environmental changes for their means of living, communities have to increase their resilience in order to absorb those changes and withstand unanticipated shocks. In a social-ecological domain, self-organisation is a critical capacity for communities to live through the changes and shocks. Such self-organisation is reliant on effective learning mechanisms and smooth information flows about the social-ecological system concerned. Social networks can facilitate the development and flow of knowledge and information throughout a community, and social bonding is useful capital to build up effective social networks which can improve the learning mechanisms of social-ecological systems and boost community resilience.

As two of the important elements, social trust and leadership of networks are advantageous for improving systems' self-organisation by maintaining the information flows and affecting collaborations of the whole network. This paper focuses on the roles of social trust and leadership in social networks and how to use bonding relationships to analyse social networks at different levels. It is believed that trust is the precondition of linkages between people or organisations, and bonding relations are the fundamental of establishing social trust in the network. Strong trust can produce a relative dense social network. However, only within clear and strong leadership can such dense social networks effectively work for community resilience. The built-in leadership subgroups at different levels can smooth information and knowledge exchange throughout the whole networks.

For the community resilience, managing social networks must be focused on strengthening community bonds and linkages among various actors across different levels. Family bonds are the bases of the trust between families within a same kinship and different families of a community can be tied together by social bonds such as friendship, neighbourhood, and acquaintance at local level. The information flows in

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local social networks should be organised by leadership networks which consist of leaders from each family. Managers have responsibilities to facilitate the work of leadership networks and its efficiency in manners such as sharing power, funding and technological supports. Regional bonds are the more important properties for social networks at regional and national levels. Such bridges which are constituted by the core people of leadership networks from each community (area) can be the main sources to bridge the linkages at regional level. The emphasis of enhancing social networks at national level should concentrate on dealing with duplications and overlapping of authority and policy inconsistencies. The recommended way is to share management power and responsibilities among communities, government agencies and nongovernmental organisations.

To conclude, this study has discussed how social networks can contribute to the community resilience. Simulation and empirical studies, as next steps, would be helpful for the deeper understandings in dynamics of social networks in the processes of constructing community resilience. To do so, computer-based techniques such as multi-agent modelling, Monte Carlo simulation, and dynamic analysis may be useful while participatory approach which involves different stakeholders is highly recommended.

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Bibliography

## **APPENDICES**

## Appendix A

### 长江三峡对洞庭湖生态环境影响及湖泊响应

尊敬的专家：

非常感谢您能从百忙之中抽出时间接受我们的咨询，您的意见将对本研究产生极为重要的作用。本表主要分为两大部分：第一部分为选择填空题，第二部分为专家打分题。

**【背景】**洞庭湖作为中国第二大淡水湖，在长江中下游地区不仅具有调蓄洪水和生物多样性保护的作用，而且是湖南省沿湖区域 19 个县市的社会经济发展的重要保障。然而，随着人类扰动的日趋频繁，洞庭湖生态环境持续恶化。人类活动对湖泊健康的影响及湖泊自身可持续发展能力的探讨已成为学界争论的热点。其中，长江三峡的修建和运行给洞庭湖带来的生态环境以及社会经济影响成为争论的焦点之一。为此，本研究就三峡运行给洞庭湖生态环境系统带来的变化以及系统对变化的自我吸纳能力和承受能力，咨询各位专家如下：

➤ 请将您擅长的研究领域或所从事的职业从以下选项中钩出：

- 1 水文学 2 环境科学 3 环境工程 4 湖沼学 4 生态学  
5 经济学 6 社会学 7 行政管理人员 8 环境监测人员

#### 一. 单项选择及填空题

1. 您是否同意以下观点：

1A. 从可持续发展角度出发，理想的淡水湖泊环境状态一方面应该是湖泊的水量能够长期保持供需平衡，另一方面则是湖泊水质清澈。

- a. 同意 → **请继续回答 1B**  
b. 不同意 → **请继续回答 2A**

1B. 淡水湖泊水量的供需平衡和水质水平的关键因子是湖泊水位及水量和水中营养物质含量。

- a. 同意 → **请继续回答 1C**  
b. 不同意 → **请继续回答 2B**

1C. 从可持续发展角度出发，理想的淡水湖泊生态状态一方面应该是生态系统完整，另一方面则是物种多样性。

- a. 同意 → **请继续回答 1D**  
b. 不同意 → **请继续回答 2C**

1D. 淡水湖泊的生态完整性和物种多样性的关键因子是湿地和植被的完整性和健康状况，以及当地物种的维系。

- a. 同意 → **请转到问题二**  
b. 不同意 → **请继续回答 2D**

2. 您对以下问题的观点:

2A. 从可持续发展的角度, 您认为淡水湖泊理想的环境状态应该是:

\_\_\_\_\_ →请继续回答 2B

2B. 您认为决定这种环境状态的关键因子主要是: \_\_\_\_\_ →请继续回答 1C

2C. 从可持续发展的角度, 您认为淡水湖泊理想的生态状态应该是:

\_\_\_\_\_ →请继续回答 2D

2D. 您认为决定这种生态状态的关键因子主要是: \_\_\_\_\_ →请转到问题二

## 二. 指标打分题

文献研究表明, 三峡的建设和运行给洞庭湖水文条件和湖区生态环境带来了诸多的干扰。针对系统具有的吸纳干扰和变化的能力, 请您从指标可测性、指标反映系统吸纳相应干扰的相关性、指标之间的独立性的角度, 给以下指标赋予相应的分值。各分值所代表的意义请参照表 1 及表 2:

表 1 指标可测性、独立性分值分配

项目 \ 分值	0	1
可测性	数据不可得或无法测量	数据可得或可通过计算获得
独立性	非独立指标 (与其它指标重复)	独立指标

表 2 指标可测性、独立性分值分配

项目 \ 分值	1	2	3	4	5
相关性	不相关	弱相关	相关	很相关	绝对相关

### 1. 三峡给洞庭湖带来的环境变化及湖泊系统的响应 (吸纳)

变动 (干扰)	指 标			
	系统的响应 (吸纳能力)	相关性	可测性	独立性
水位、水量的季节性变动	5 河补水、分水能力 (以湖泊水量受扰动的 5-11 月为主) (A <sub>1</sub> )			
湖口进出水量变化	湖口地区水量供需平衡率 (以受扰动月份环境需水为主) (A <sub>2</sub> )			
洪水和旱灾发生频率及强度变化	泛滥平原面积 (floodplain) 及其与湖口地区人类活动区域的距离 (农业、养殖业生产及生活活动) (A <sub>3</sub> )			
湖口地区泥沙淤积及营养物 (氮、磷) 负荷	湖口地区湖水对来自长江泥沙和营养物质的承载能力与稀释能力			

Appendices

(loading)	(A <sub>4</sub> )			
<p>1) 如果您不赞同以上所给的变动或您认为还存在其它的变动, 请将您的观点填入以下对应的表格;                  2) 如果您对以上指标的相关性给出 1 分或 2 分, 那么请将您认为可能的更相关的指标填入以下对应的表格;                  3) 请将以上 相互重复的指标填入以下对应的表格 (例如: 如果指标 A<sub>1</sub> 的独立性得分为 0, 您认为 A<sub>1</sub> 与 A<sub>2</sub> 重复, 那么可将 A<sub>1</sub>, A<sub>2</sub> 直接填入下面对应独立性的空白栏)。</p>				
变动 (干扰)	指 标			
	系统的响应 (吸纳能力)	相关性	可测性	独立性

Appendices

2. 三峡给洞庭湖生态系统带来的变化及湖泊系统的响应（吸纳）

变动（干扰）	指标			
	系统的响应（ <u>吸纳能力</u> ）	相关性	可测性	独立性
湖区水鸟及其他主要物种栖息地变化	永久性湿地覆盖面积(B <sub>1</sub> )			
关键物种（含和濒危、和受保护物种）存量（数量和种类）	候鸟食物的可获取性（不同季节苦草涵盖率、单位面积覆盖率）(B <sub>2</sub> )			
地方植被分布和覆盖率（水生植物）	水量供需平衡率（以受扰动月份植被生态需水为主）(B <sub>3</sub> )			
湖口地区泥沙磷含量	湖口地区泥沙自我稀释能力(当上层低营养泥沙覆盖下层高营养泥沙时，泥沙发生内部营养迁，另外浮游植物的种群生物量也可起到增加自我稀释能力的作用)(B <sub>4</sub> )			
地方鱼种与湖口地区长江鱼种（数量及种类）	湖口地区浮游植物的种群生物量以及原有食物链的完整性(B <sub>5</sub> )			
<p>1) 如果您不赞同以上所给的变动或您认为还存在其它的变动，请将您的观点填入以下对应的表格；</p> <p>2) 如果您对以上指标的相关性给出 1 分或 2 分，那么请将您认为可能的更相关的指标填入以下对应的表格；</p> <p>3) 请将以上 相互重复的指标填入以下对应的表格（例如：如果指标 B<sub>1</sub> 的独立性得分为 0，您认为 B<sub>1</sub> 与 B<sub>2</sub> 重复，那么可将 B<sub>1</sub>，B<sub>2</sub> 直接填入下面对应独立性的空白栏）。</p>				
变动（干扰）	指标			
	系统的响应（ <u>吸纳能力</u> ）	相关性	可测性	独立性

您的签名：\_\_\_\_\_

## Appendix B

### 长江三峡对洞庭湖生态环境影响及湖泊响应

尊敬的专家：

您好！

非常感谢您能在百忙之中抽出时间参与我这次问卷调查。本调查仅用于本人的博士研究课题，论文主题为淡水湖泊社会-生态系统恢复力及其可持续发展研究。本次调查以及后期研究不会涉及您的个人信息。问卷主要分为两个部分：选择填空和评分。以下为调查背景的简要说明：

中国湖泊受来自气候变化和人类干扰的双重影响，其可持续能力的研究已变得十分紧迫。在诸多影响中，上游水电站的建设和运行的影响是除气候变化外另一个备受争议的热点问题。以长江三峡为例，自三峡大坝调蓄运行以来，长江中下游通江湖泊（洞庭湖和鄱阳湖）的社会生态系统受到了不同程度的影响。为此，本次调研针对三峡大坝对洞庭湖的影响，从湖泊社会-生态联合系统的响应出发，对其系统的可恢复能力进行评价。

#### 一、选择填空

1. 从水量平衡的角度看，您认为洞庭湖可能存在几个不同的状态（**多选**）：

A. 富足； B. 洪涝； C. 短缺或干旱； D. 其他（\_\_\_\_\_）

2. 根据您的经验，以上不同状态下湖泊的蓄水量和城陵矶水位大概为多少？

**注：**有关报道及研究显示，当城陵矶水位为 21.6 米时洞庭湖蓄水量约 8 亿立方米，湖泊出现大旱；当城陵矶水位为 33.5 米时，洞庭湖蓄水量约 167.6 亿立方米，此时湖区面临洪涝威胁。

状态	城陵矶水位（米）	蓄水量（亿立方米）
富足		
洪涝		
短缺或干旱		
其他		

3. 在水量持续减少的情况下，您认为目前洞庭湖的状态是：

- A. 季节性影响明显，无论是生态还是社会，湖泊水量长年无法满足需求  
 B. 季节性影响明显，但湖泊生态环境需水量长年基本可以满足，区域用水有短缺现象  
 C. 季节性影响明显，但区域用水量基本能够满足  
 D. 季节性影响明显，但湖泊水量基本能够满足未来 30 年区域用水的需求

4. 假设只考虑主要支流的补给，您认为洞庭湖四河的来水是否能够补给流失长江的水？

A. 全年基本能够补给； B. 能够补给，但是季节性影响明显； C. 不足以补给； D. 其他（\_\_\_\_\_）

5. 若不足以补给，您认为**最主要**的原因是？

- A. 气候变化导致流域降雨减少水分蒸发增加      B. 三峡调蓄使得湖泊下泄水量逐年增加  
 C. 流域工业和灌溉等人为因素增加了流域用水量      D. 其他（\_\_\_\_\_）

6. 您认为洞庭湖生物栖息地目前的状态为：

- A. 栖息地锐减、破碎或消失，最多能够满足 50% 候鸟的基本生计  
 B. 栖息地不完整，但仍能够满足 50-80% 候鸟的基本生计

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- C. 栖息地基本完整，能够满足 80%以上的候鸟生计  
 D. 其他(\_\_\_\_\_)
7. 要维持洞庭湖候鸟的生计，您认为浅水植被（苔草为主）的覆盖率**最少**为：(\_\_\_\_)%。
8. 根据您的了解，洞庭湖候鸟栖息地的分布和面积在三峡开始运行之后是否发生了明显的变化？
- A. 很明显（数量和分布的变化程度在 50%以上）  
 B. 有一定的变化（数量和分布的变化程度在 20-50%之间）  
 C. 无明显变化（数量和分布的变化程度小于 20%）  
 D. 其他(\_\_\_\_\_)
9. 从生态环境以及社会经济的服务功能来看，您认为洞庭湖**相对重要**的资源有哪些（如鱼、特有植被、其他生物等）？
- \_\_\_\_\_

10. 您认为以上资源在三峡调蓄影响下的再生能力如何？
- A. 强 B. 中等 C. 弱 D. 其他(\_\_\_\_\_)
11. 以下三种不同的状态，您认为以上资源的再生率与消亡率之比应该为多少或介于什么范围？

状态	再生率/消亡率 (%)
生物多样性无法保证	
生物多样性基本能够保证	
生物多样性能够保证	

12. 洞庭湖的关键物种主要是鱼、植被、候鸟。
- A. 同意 B. 不同意 C. 其他(\_\_\_\_\_)
13. 与三峡运行前的时期相比，这些关键物种的生存空间状态为：
- A. 逐年减少，且不可恢复； B. 逐年减少，或许可以恢复或部分可以恢复  
 C. 逐年减少，绝大多数可以恢复但难度较大 D. 逐年减少，但较易恢复 E.其他(\_\_\_\_\_)
14. 从**分布特征和数量**看，您认为洞庭湖的核心系统（包括水资源、湿地、生物）的空间模式的变化状态为：
- A. 水资源系统在时间上的变化**未**明显的导致其他资源发生空间上的变化  
 B. 水资源系统在时间上的变化已导致**部分**关联系统发生空间上的变化，但这些变化未超过系统的自我恢复能力  
 C. 水资源系统在时间上的变化已导致**部分**关联系统发生空间上的变化，并且在这些变化的影响下，系统已不能自我恢复  
 D. 水资源系统在时间上的变化不会导致其他资源系统发生空间上的变化
15. 您认为洞庭湖地区公众参与环境决策制定的有效性现状为：
- A. 高 B. 中 C. 低 D. 无参与
16. 据您所知，洞庭湖区域的民间环保组织、当地政府、相关研究机构、当地群众代表、以及其他旨在保护洞庭湖的组织之间是否存在定期或不定期的联系？
- A. 这些组织之间有定期联系，且联系紧密  
 B. 这些组织之间不定期或者偶尔的联系，但并非所有组织彼此都存在联系  
 C. 这些组织之间很少有联系，有些甚至不会相互联系  
 D. 其他(\_\_\_\_\_)

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17.当地政府在制定关于湖区资源开发利用的规章和原则时，是否全面的考虑了不同利益相关者之间的公平性？

- A. 考虑，基本都会顾及不同利益者对于湖泊资源获取的公平性
- B. 考虑，但由于利益和其他原因较少的考虑到普通群众的利益
- C. 不考虑，主要考虑当地政府为此所获得的利益
- D. 其他\_(-----)

18. 现行的开发利用和保护政策措施是否是考虑各方利益后制定的？

- A. 是；
- B. 不是；
- C. 很难说

### 二、评分

请根据您的经验和研究，为目前湖泊应对外部环境变化的可恢复能力评分。

#### 1（能力低或变化强度弱）—9（能力强或变化强度高）

专长：（                      ） 单位：（                      ）

<b>湖区社会生态系统的恢复能力（或变化强度）</b>			
<b>参考性指标描述</b>	<b>东湖</b>	<b>南湖</b>	<b>西湖</b>
湖泊水量平衡 (湖泊的存水能力)			
湖水供需比率 (湖水供给是否满足需求)			
浅水植被覆盖率 (核心植被如，苔草)			
核心资源的再生率 (鱼、苔草、候鸟等)			
栖息地分布变化			
系统关键要素的可识别性及人们对环境变化的关注程度			
可供关键物种生存的空间 (空间大物种适应能力强)			
家庭可支配收入 (收入越多越能适应)			
生产模式的多样性 (多样性越多收入依赖性越低)			
不同系统的空间分布模式变化 (供万只候鸟集聚栖息的湿地有 37 块，是否有变化？)			
公众参与政策制定的程度 (便捷性、参与方式的多样性)			
组织之间相互联系的紧密性 (密切的联系有助信息的共享)			
是否有相关政策出台			
合作渠道的畅通程度和合作者之间利益的分配公平			
是否迫使居民主动观察湖泊环境的变化并告知有关管理部门			
居民教育或职业技能培训的水平			
共同利益群体的规模 (人数和覆盖面)			
地区的文盲率 (文盲率低居民认知能力强)			
媒体对民间群体的曝光率			
民间群体内部成员的受教育程度			

## Appendix C

## 长江三峡对洞庭湖生态环境影响及湖泊响应

尊敬的专家：

您好！

非常感谢您能在百忙之中抽出时间参与我这次问卷调查。本调查仅用于本人的博士研究课题，论文主题为淡水湖泊社会-生态系统恢复力及其可持续发展研究。本次调查以及后期研究不会涉及您的个人信息。问卷主要分为两个部分：选择填空和评分。以下为调查背景的简要说明：

中国湖泊受来自气候变化和人类干扰的双重影响，其可持续能力的研究已变得十分紧迫。在诸多影响中，上游水电站的建设和运行的影响是除气候变化外另一个备受争议的热点问题。以长江三峡为例，自三峡大坝调蓄运行以来，长江中下游通江湖泊（洞庭湖和鄱阳湖）的社会生态系统受到了不同程度的影响。为此，本次调研针对三峡大坝对洞庭湖的影响，从湖泊社会-生态联合系统的响应出发，对其系统的可恢复能力进行评价。

1. 您是否同意“人们越关注周边环境的变化，他们对因为某种环境变化所可能带来的次生变化的预见能力越敏锐。”的说法？

A. 同意            B. 不同意

2. 若同意，假设主动关注环境变化的人数比例可以代表该地区总体的环境认知水平，那么您认为对于以下不同的环境认知水平，关注环境变化的人数比例应该分别为多少合理？

A. 高( )%            B. 中( )%            C. 低( )%

3. 若不同意，您认为什么最能够反映出人们预测由于环境变化带来的连锁反应的能力？

4. 若将公众参与环境决策制定的有效性分为高（积极参与）、中（部分参与）、低（极少参与），那么根据参与频率（即公众参与制定的项目占总项目数的比例），您认为各个等级对应的比例应该介于：

A. 高( )%

B. 中( )%

C. 低( )%

5. 由于水量的逐年减少，渔业产量连年减少导致大量渔民蒙受损失，收入缩水。为保障生活，不少渔民不得不另谋其他经济来源。而是否能够通过其他渠道获得收入，很大程度上取决于渔民自身的受教育水平。通常认为，接收过高中教育或中专职业技能培训及以上的人更易获取其他的经济来源。那么，若将洞庭湖渔民寻求其他经济来源的总体能力分为高、中、低三个水平。您认为：相应的受教育水平的人数比例应该介于多少之间？举例：若您认为 50%-60%的渔民具有高中以上文化水平代表湖区渔民寻求经济来源的总体能力为中，则 50-60 填入 B。

A. 高( )%； B. 中( )%； C. 低( )%

6. 若将居民对社会和生态系统的认知和学习能力分为强、一般、差三个水平，您认为相应的文盲率应该为多少或者介于多少之间？

A. 学习能力强( )%； B. 学习能力一般( )%； C. 学习能力差( )%

## 二、评分

请根据您的经验和研究，为以下指标评分。

### 1（能力低或变化强度弱）—9（能力强或变化强度强）

专长：（                      ） 单位：（                      ）

我国社会系统的恢复能力（或变化强度）				
参考性指标描述	东部地区	西部地区	南部地区	北部地区
系统关键要素的可识别性及人们对环境变化的关注程度				
家庭可支配收入 （收入越多越能适应）				
农、渔民生产模式的多样性 （多样性越多收入依赖性越低）				
公众参与政策制定的程度 （便捷性、参与方式的多样性）				
组织之间相互联系的紧密性 （密切的联系有助信息的共享）				
合作渠道的畅通程度和合作者之间利益的分配公平				
是否迫使居民主动观察环境的变化并告知有关管理部门				
居民教育或职业技能培训的水平				
共同利益群体的规模 （人数和覆盖面）				
地区的文盲率 （文盲率低居民认知能力强）				
媒体对民间群体的曝光率				
民间群体内部成员的受教育程度				

## Appendix D

**From:** Lech Zacher <lzacher@kozminski.edu.pl>

**Sent:** Monday, 27 July 2015 6:23 AM

**To:** Dora Marinova

**Subject:** chapter acceptance

This is to confirm that the chapter “Nano-biotechnology for water sustainability: bibliometric analysis” by Li Xu and Dora Marinova has been accepted for inclusion in the book *Technology–Society–Sustainability: Selected Contemporary Issues, Concepts and Cases*, edited by Lech W. Zacher to be published by Springer

Prof. Lech W. Zacher, Ph. D.

Director

Center for Impact Assessment Studies and Forecasting

Kozminski University

Jagiellonska 59, 03-301 Warsaw, Poland

## Appendix E

**From:** Lech Zacher <lzacher@kozminski.edu.pl>

**Sent:** Monday, 27 July 2015 6:23 AM

**To:** Li Xu

**Subject:** chapter acceptance

This is to confirm that the chapter “What can we do better for sustainability in the uncertain future?” by Li Xu and Talia Raphaely has been accepted for inclusion in the book *Technology–Society–Sustainability: Selected Contemporary Issues, Concepts and Cases*, edited by Lech W. Zacher to be published by Springer

Prof. Lech W. Zacher, Ph. D.

Director

Center for Impact Assessment Studies and Forecasting

Kozminski University

Jagiellonska 59, 03-301 Warsaw, Poland

## Appendix F

TO WHOM IT MAY CONCERN

The chapter entitled “Managing social networks for community resilience from the perspective of bonding relationships” has been accepted for inclusion in *Sustainability Issues in South Asia and the Pacific*, edited by Dora Marinova and Xiumei Guo to be published by Edward Elgar, Cheltenham, UK.

Signature:

A handwritten signature in blue ink, appearing to be 'D. Marinova', with a stylized flourish at the end.

Dora Marinova

30 September 2015

**Memorandum**

<b>To</b>	Li Xu, Curtin University Sustainability Policy (CUSP) Institute
<b>From</b>	Miss Linda Teasdale, Manager, Research Ethics
<b>Subject</b>	Protocol Approval <b>RD-12-12</b>
<b>Date</b>	9 May 2012
<b>Copy</b>	Professor Dora Marinova, Curtin University Sustainability Policy (CUSP) Institute

Office of Research and Development

Human Research Ethics Committee

Telephone 9266 2784

Facsimile 9266 3793

Email [hrec@curtin.edu.au](mailto:hrec@curtin.edu.au)

Thank you for your "Form C Application for Approval of Research with Low Risk (Ethical Requirements)" for the project titled "*Sustainability of Chinese Freshwater Lakes: the case of Poyang Lake*". On behalf of the Human Research Ethics Committee I am authorised to inform you that the project is approved.

Approval of this project is for a period of twelve months **30-04-12** to **01-05-13**.

The approval number for your project is **RD-12-12**. *Please quote this number in any future correspondence.* If at any time during the twelve months changes/amendments occur, or if a serious or unexpected adverse event occurs, please advise me immediately.



Miss Linda Teasdale  
Manager, Research Ethics  
Office of Research and Development

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Please Note: The following standard statement must be included in the information sheet to participants:  
*This study has been approved by the Curtin University Human Research Ethics Committee (Approval Number RD-12-12). If needed, verification of approval can be obtained either by writing to the Curtin University Human Research Ethics Committee, c/- Office of Research and Development, Curtin University, GPO Box U1987, Perth, 6845 or by telephoning 9266 2784 or [hrec@curtin.edu.au](mailto:hrec@curtin.edu.au)*

## **Statement for the ethic approval**

This is to state that Poyang Lake was the provisional case study mentioned in the ethics approval. The case study was subsequently finalised to be Dongting Lake.

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