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China's stressed waters: Societal and environmental vulnerability in China's internal and transboundary river systems

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A B S T R A C T

China is undergoing a rapid transition from rural to urban dominated economy. Economy is booming, social structures are changing, ecosystems are stressed, and sustainability is challenged. We analysed the socioeconomic and environmental vulnerability of river systems that are entirely or partly located in the continental part of China. One-third of the mankind inhabit the area covered by this study. Six stress factors (governance, economy, social issues, environment, hazards and water stress) were analysed separately and in combination as an overall vulnerability. China's most vulnerable parts were found to be situated in the lower Hai and Yellow River basins, with their high population density, low water availability and high human footprint. The other water-stressed areas in the northwest showed high vulnerability, too, and so did the water-rich coastal areas due to high population density, natural hazards and high human footprint. We went beyond existing water stress and vulnerability studies in three dimensions. First, our perspective was highly multidimensional and thus very relevant in addressing China's water challenges in a realistic and multifaceted way. Second, we combined administrative and river basin scales and used an essentially higher spatial resolution than done so far. Third, we included the transboundary dimension, which is not customary. This is highly important since one billion people China's neighbouring countries, in basins that are partly in China.

Introduction

China has been undergoing stunning economic and social development for several decades now, and the trend continues. Between 1980 and 2010, the country's Gross National Income (GNI) grew 15-fold, the poverty headcount ratio (1.25USD per day adjusted with purchasing power parity) fell from 60% to 15% and illiteracy rate from 22% to 6% (World Bank, 2014). Meanwhile, China's urban population grew by 119%, CO_2 emissions increased 2.4-fold and industrial water withdrawals 3-fold (World Bank, 2014). China being the world's most populated country with extreme population densities in large areas, this development continues to set the sustainability (in the sense of balancing environmental, social and economic development) – or harmony between nature and man, as Chinese often say – in question (Cao, Chen, & Liu, 2007; Economy, 2004; Zheng & Dai, 2013).

China has a long history of seeking harmony between humans and the nature (Cao et al., 2007, 2013; Zheng & Dai, 2013). The respect to nature in China has ancient roots and dates back at least to the Zhou Dynasty (1115–1079 BCE). At that time, the most important leadership talent for an officer was to be able to skilfully manage forests, rivers, mountains, birds, and other animals (Economy, 2004). The equally central role of water resources management in present days, too, is clearly reflected in the fact that various recent key political leaders have been water engineers. The contemporary political weight of water resources management in China continues to be extremely high. This was demonstrated in 2011 when China's most important annual policy document, the Number 1 Document, was focused on water (Gong, Yin, & Yu, 2011; Liu & Wang, 2012; Varis, 2011). Quadrupling the water conservancy investment from the past decade's level was proposed in that key policy document as the main handle to better water future (Liu & Wang, 2012).

Despite this long tradition in seeking harmony between man and nature, the country's water systems and aquatic environment are highly stressed (Economy, 2004; Gleick, 2009; Liu & Wang, 2012; Ran & Lu, 2012; Varis & Vakkilainen, 2001; Zhang, Chen,

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Chen, & Xu, 1992). Today's gigantic challenges (Bawa et al., 2010; Jiang, 2009) are due to factors such as rapid urbanization, intensification of agriculture, massive industrial development and booming energy sector development. They all contribute to growing pollution, watershed degradation and growing proneness to natural hazards (Jiang, 2009; Ran & Lu, 2012; Varis & Vakkilainen, 2001). These challenges are boosted by climate change: certain historical trends have contributed to the polarization of China's water problems: arid and water-scarce areas, particularly the North China Plain, have become even drier than before, and precipitation has increased in China's flood-prone southern part (Shen, 2010; Shen & Varis, 2001; Wang et al., 2012; Xu, Milliman, & Xu, 2010).

China is geographically a vast country with a high diversity in climate, population density, economic prosperity, ecosystems and proneness to natural hazards. Moreover, the upstream parts of several major Asian transboundary river basins (Red River, Mekong, Salween, Irrawaddy, Ganges–Brahmaputra–Meghna (GBM), Indus, Ili, Ob-Irtysh and Amur) are in China's territory, making China's water sector stresses and activities particularly relevant to its neighbours.

As the analysed river systems portray a high diversity and are extremely intricate and multifaceted systems, the data to describe their status, and the factors affecting that status, are not trivial issues. At the same time, there is an urgent need to produce information that is easily accessible to a wide range of audiences, particularly at the policy level (Asia Society, 2009; Asian Development Bank, 2007). Obtaining a systematic and analytic view on the importance of various sources of vulnerability, we argue, is of high importance.

We aim to analyse China's river basins in light of the above-outlined array of entangled change processes and to identify the related major bottlenecks to sustainable development of the country's waters. Moreover, we attempt to bring the produced information into a form which is maximally accessible and useful in policy-making. For that purpose, an approach is required which allows the analysis of the triple-bottom-line of sustainable development (social, economic and environmental aspects) and relates it to the political and governance capacity.

We chose to approach the above-outlined complexity from the direction of vulnerability assessment. This is because Chinese water policy discourse increasingly includes the logic of adaptive management, according to which adaptation policies should focus on the reduction of vulnerabilities. We used the river basin vulnerability approach developed by Varis, Kummu, and Salmivaara (2012), which allows a joint analysis of six stress factors (or sources of vulnerability): social, economic, environmental, governance-related, natural hazards and water stress. We base our analysis largely on a river basin classification system that is used extensively by China's ministries, by other major policy actors and by many Chinese scholars working on China's river basins (see e.g. Jiang, 2009; World Bank, 2006; Xie et al., 2009). On top of that, we do not only use the river basin classification but include also jurisdictional boundaries into our analysis, since most policy-making occurs in jurisdictions and only in some special cases in river basins. These extensions, we hope, will facilitate the usefulness of our findings and our approach, besides in scholarly work, in policy-making.

Thus far, vulnerability of China's river basins has not been addressed in such a multifaceted manner although international policy agendas and recommendations call for looking at water resources challenges and policies in a comprehensive and integrated way (Biswas, 2005; Varis, 2005; WWAP, 2009). The existing vulnerability studies concentrate on specific subject areas such as river discharge (Lu, 2003), water scarcity (Huang, Cai, Zhang, & Cai, 2008; Xia, Qiu, & Li, 2012), droughts (Wang, He, Fang, & Liao, 2013; Zhang et al., 2013), groundwater (Yin et al., 2013), water management scenarios (Wu, Li, Ahmad, Chen, & Pan, 2013), urban areas (Strohschön et al., 2013) and climate change impacts on ecosystems (Ni, 2012).

Given China's highly dynamic economic and social situation, as well as massive challenges with the sustainability of water resources management, we aim at providing a comprehensive and comparable view of vulnerability of the river basins that are located entirely or partly in China, including a broad array of aspects that would allow addressing the present (and historical) quest in China towards harmonious relation between man and the nature.

Materials and methods

Delineation of China's river basins: the CARU system

We analysed China's continental territory as 21 river systems (Fig. 1 and Table 1; Fig. S1, Tables S1 and S2 in Online Supplement), of which 16 drain to oceans (we call these subsequently 'open basins') while five are endorheic (interior/closed) basins. Their total surface areas (according to Water Resources eAtlas, 2003) are 5,133,062 km^2 and 738,208 km^2, respectively.

The point of departure of the delineation of our river basin units was the conventional spatial grouping of China's river systems into so-called 'planning units'. Most planning of China's water resources occurs presently in nine units (Songhua-Liao, Hai-Luan, Yellow, Huai, Yangtze, Pearl, SE Rivers, SW Rivers, Inland Rivers; see e.g. Jiang, 2009; World Bank, 2006; Xie et al., 2009). We call those units subsequently as CPUs (Chinese Planning Units). We enhanced the resolution of this system considerably by using altogether 21 river systems, based on two datasets of river basin divisions (USGS, 2001; Water Resources eAtlas, 2003). At the same time we attempted to maintain the compatibility with the CPUs as far as possible, and, besides, included administrative borders as an additional layer in our delineation. These were done to maximize the applicability of our approach and results in Chinese policy making. As we combine administrative areas with river basins we call subsequently our novel delineation as CARU (Chinese Administrative River Basin Units).

Some of the major open river systems of China include small closed basins (Wuyur and Baicheng in Amur basin, Upper Yangtze closed basins in Yangtze Basin, and South Tibet closed basins in the GBM basin). Those basins were considered so small that they were included in the surrounding major river system. The only exception was the Ordos basin – surrounded by the Yellow River basin and sometimes seen as a part of it – that was included in the Gansu–Inner Mongolia closed basins. Both these definitions are in alignment with the CPUs.

Again, to concur with the CPUs, the following configurations were made to our CARU delineation. First, even though some parts of our Gansu–Inner Mongolia closed basins may also be seen as parts of the Yellow River basin, we maintained the boundaries used in the CPUs. Second, the Hexi corridor in Gansu is sometimes seen as a part of the Tarim basin but we maintained it in the Gansu–Inner Mongolia basins. Third, the Hai River basin's boundaries are extremely difficult to define precisely, and numerous definitions exist. We maintained the one used in the CPUs, except in the case of the Liao basin, which we excluded from the Hai system and considered it together with Northeast Coastal Rivers. This was done because we want to produce globally comparable river basin vulnerability information for the major global rivers, and, for that purpose, we chose to separate the Hai basin from the Liao basin. Both basins are extremely populated and in many ways quite different in character. Due to reasons similar to those above, we