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

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.

Discussion

River system vulnerability: China's geographic features

China is one of the planet's largest countries in land area, and the largest one in population. Therefore, it is not surprising that China represents a high level of spatial heterogeneity with regard to all the aspects that were included in our vulnerability analysis. This heterogeneity is important, we argue, to understand and to identify river system vulnerabilities in a systematic and pragmatic way.

Closed river basins cover one-third of China's surface area (Table 1). In contrast, large areas in the eastern and southern parts of the country produce excessive discharge to the oceans. Economic income level, population density, proneness to hazards and environmental situation all have large spatial differences inside China.

One could expect that closed basins and arid areas would be most vulnerable in terms of water resources. In China's case this appears not be true; our results indicate that the areas with highest river system vulnerability are not in dry but humid areas. The reason is partly in the spatial distribution of population; whereas around one-third of China's territory is arid, only 2.1% of the population live in closed basins (Table 1). In addition, closed basins are less prone to hazards and they have a lower human footprint than most of the humid areas. Therefore, large dry, hydrologically closed areas such as Xinjiang, Inner Mongolia and Qinghai's closed basins have not been included in most vulnerable areas in our results, despite of high water stress.

In many studies (Varis & Vakkilainen, 2001; Xia et al., 2012) China's most serious water related challenges have been addressed to the North China Plain, which has low precipitation but is still mostly humid, but has a high population density. Our study is in accordance to this. Yet, often the so-called 3H basins (Hai, Huang (Yellow) and Huai), have been used somewhat synonymously to North China Plain and attributed to be most challenged areas in terms of water resources (Berkoff, 2003; Jiang, 2009; Xia et al., 2012). Our study does not fully accord with this view. The most important reason to this disagreement is that we calculated the water stress on the basis of water use in relation to its availability, and not on basis of water withdrawals or water availability per capita as is often done (see e.g. Jiang, 2009). The two latter approaches show the 3H basins as more critical in terms of water scarcity than the former (cf. the data provided by Wada et al., 2011, 2013). Consequently, it is crucial to distinguish water use from water withdrawals in this context, as well as in more general terms when addressing water related challenges. Our approach relates water

stress to water use and not to water withdrawals since per definition part of the withdrawn water returns to the basin, whereas all water-use is away from the basin. We propose concern when selecting the metric as an indicator of water scarcity since for instance the water-availability-per-capita metric ignores the demand of water – if an area does not have much water demanding industry or agriculture, it can survive quite well with water resources that would be quite short for an area with intensive, irrigated agriculture. Instead, the water scarcity should in our view be measured through the relation of supply and demand of water as done here (for more discussion, see Falkenmark, 2013; Vörösmarty, Green, Salisbury, & Lammers, 2000; Wada et al., 2011, 2013; Wu et al., 2013).

It is interesting to note, that large areas with ample water resources, particularly in the upper-middle Yangtze basin, such as Sichuan, Chongqing and Hubei, are modestly water-stressed. This is because of their high population density. In addition, they are hazard-prone and have a high human footprint. Therefore, they classify equally or even more vulnerable than for instance Xinjiang and Inner Mongolia in our study. There is plenty of evidence in history on their vulnerability as for instance several serious floods and earthquakes have caused massive societal and property damage in these areas even in past several years. This fairly high level of vulnerability of that part of the Yangtze basin is important to note when discussing the South–North water transfer scheme which draws water mainly from the Yangtze basin towards the north, particularly to the 3H basins (Berkoff, 2003; Jiang, 2009; Xu et al. 2010).

After all, our vulnerability map shows less spatial differences in different parts of China than the studies that we refer to in the introduction would suggest, and accordingly China's vulnerability level is relatively even in most parts of the country. This is because in many areas the six components of vulnerability balance out one another; for instance in very hazard-prone coastal areas in south-east water stress is low and so is the social vulnerability.

Major transboundary basins

China shares several major continental-scale river basins with its neighbours (He, Tang, & He, 2000). In this study, we analysed

their vulnerabilities for the part that is located inside China's territory. In previous studies, nine of the total 11 transboundary basins have been analysed with the RBVI method as a geographic entity (Varis & Kummu, 2012; Varis et al., 2012). The comparison of river systems inside China's boundaries and the 9 transboundary basins (Fig. 6) shows that, whereas the level and range of vulnerability of those basins that are in China is remarkable, there are several large basins which appear to be essentially more vulnerable than any basin in China. Those include, above all, Indus and GBM. These two basins have a total population of around 900 million people (Table 1; see also Varis et al., 2012). Therefore, when expressing the very justified concern of the status and vulnerability of China's water systems, one should indeed relate those challenges to the ones existing in some of the surrounding river basins – some of which China also shares as an upstream country.

In more general terms, transboundary basins are crucial when talking about China's waters, albeit they are too often ignored in analyses such as those mentioned in the above sections. Notable institutional and legislative challenges exist in transboundary co-operation on shared river basins of China and its neighbours, yet the situation is highly dynamic for the time being and potentially developing towards the wider acceptance of international principles and law (Wouters & Chen, 2013). Although the size of the population and vulnerability level of the Chinese sections of those transboundary basins tend not to be quite high, China influences and modifies profoundly many of these basins, causing impacts to the downstream countries (Pearce, 2012; Ran & Lu, 2012). Massive hydropower construction in Lancang–Mekong (Keskinen, Kummu, Käkönen, & Varis, 2012; Molle, Foran, & Käkönen, 2009) can be used as one example and the emerging pressures of various economic activities upstream the Brahmaputra (Grumbine & Pandit, 2013; Rahaman & Varis, 2009) and Salween (Magee, 2011) river basins as other examples. Despite of these major impacts on China's neighbours, and disregarding of perennial recommendations by various policy documents (e.g., Jiang et al., 2009; World Bank, 2006;

Xie et al., 2009), China's water policy remains thin in transboundary waters (Liu & Wang, 2012). Consequently, when addressing China's water related challenges, we argue that the inclusion of transboundary waters should be done far more rigorously than done in most of the contemporary cases.

Vulnerability analysis approach

We produced vulnerability maps of the six aspects of vulnerability and their combined overall vulnerability. No such mapping and analysis have been available for China before. Besides having a finer resolution for river systems, we overlaid the basins with administrative borders in our CARU river system delineation. This aspect is typically missing from water resources studies of China, although it is highly relevant to policy making and policy analysis since most policies are implemented through jurisdictions. Equally novel in the context of China's water resources studies is our combination of social, economic, governance, hazards and environmental indicator data with water availability data.

Therefore, the current analysis provides a new level of spatial resolution and systematization of challenges and pressures to China's river systems when compared to the existing studies (e.g. Bawa et al., 2010; Economy, 2004; Gleick, 2009; Huang et al., 2008; Jiang, 2009; Lu, 2003; Ni, 2012; Varis & Vakkilainen, 2001; Wang et al., 2012; Xia et al., 2012; Zhang et al., 1992). This is the case with basins that are entirely in China as well as with those shared with China's neighbours. In our division, the basin borders are defined precisely as spatial data, and this obviously helps in performing comparable studies on China's river basins in the future. Besides, our analysis reveals quite clearly that water related vulnerability is a far more complicated issue than the mere water stress. In most of the analyses that we have referred in this paper, water stress has not been looked together with coping capacity of the society to tackle with water challenges, nor with other stress factors to the environment. We maintain that this should be done more often than done today.

The vulnerability analysis approach by Varis et al. (2012) that we used here has been developed for the analysis of large-scale river basins in which much of the administrative-unit based data is at a fairly coarse scale – often only at national level. When applying such an approach in a sub-national scale, as was done here, there is a certain challenge to find corresponding data for local jurisdictions such as China's provinces and autonomous regions. Therefore, complicated indices such as PSI and MPI are easy to use by country, but certain challenges emerge when used in a sub-national context. It remains somewhat obscure whether the indicators used are able to capture the internal variability in China.

Another source of inaccuracy to the analysis stems from the fact that the data stem from several different years. This type of data, as it comes from various auxiliary datasets, is not available for each year. This is unfortunate, yet we do not believe, that year-to-year changes or fluctuations in these data are large enough to cause any notable inaccuracy to this analysis, since annual changes are incremental in nature and remain relatively small with regard to all aspects studied.

Accordingly, certain reservations are justified, particularly when comparing vulnerabilities related to governance and social issue within and outside China. However, we do not believe that this is a major shortcoming of the approach.

Future research directions

We have excluded several important factors that could be addressed in more refined studies. These include China's islands, water quality (Xie et al., 2009), groundwater (Jiang, 2009; Qiu, 2011; Xie et al., 2009), impact of hydraulic constructions such as dams and water transfers (Ran & Lu, 2012; Yan et al., 2012), climate change (Shen & Varis, 2001; Wang et al., 2012; Xu et al., 2010), climatic variations and variability (Xie et al., 2009; Xu et al., 2010) and particularities of urban areas (Bao & Fang, 2011; Finlayson et al., 2012; Shen, 2009; Wang, 2011). These aspects were excluded from our study, due to the already large dimension of our analysis. We encourage inclusion of those aspects in future analyses. For instance, in the case of the North China Plain – an area which was classified as the most vulnerable part of China according to our method – inclusion of groundwater, water quality and other concerns mentioned above would be highly valuable (cf. Xia et al. 2012; Xie et al., 2009).

The methodology employed allows a straightforward extension of the analysis to cover other geographic areas to obtain comparable results. An extension up to a global analysis is a feasible option.

Conclusions

In this article, we have documented an analysis of the socio-economic and environmental vulnerability of China's river systems. China's water resources challenges have frequently been emphasized as one of the bottlenecks of the future development possibilities of the country (Bawa et al., 2010; Gleick, 2009; Gong et al., 2011; Jiang, 2009; Liu & Wang, 2012; Ran & Lu, 2012; Yu, 2011). We share this major concern. However, it is worth recognizing that the vulnerability level in many of the river systems in China's neighbouring areas (e.g., Indus, GBM, Hari Rud, Helmand and Amu Darya) is clearly higher than in any river system inside China.

It is also well-known that, given the vast geographical size, China represents notable spatial heterogeneity. The range of heterogeneity with regard to environmental aspects (water stress, hazards, human footprint) equalled that of the entire globe, while societal heterogeneity was substantially smaller in China compared to the global context.

We found the highest overall vulnerability, calculated as the combination of the six classes of vulnerability, in central and low parts of the Yellow river system and in southeastern part of the Hai river system. This area covers only roughly one-third of the most water-stressed parts of China; an area where water stress meets with high environmental stress and relatively high hazard level. Also coping capacity in terms of social and economic development level is fairly low in that area. Despite of good water availability, most coastal areas also appeared highly vulnerable due to high population density and human footprint. Tibet and Qinghai showed lowest vulnerability, largely due to low hazard level and low stress to water and environment. Quite interestingly, large parts of the rest of China show relatively even vulnerability level, although the combination of vulnerability sources is highly varied across the country.

Our study went beyond the existing water sector challenge studies of China in three dimensions:

1. *Broader perspective*. Broadening the perspective towards more multidisciplinarity – particularly to societal direction as called for by Liu and Wang (2012) – is highly important when searching for ways to develop river basin management into a more sustainable direction or towards a higher level of harmony as often articulated by Chinese. These two articulations may not be very far from one another, and the aspects included in our analysis aim at being relevant to both articulations.
2. *Enhanced spatial resolution*. A systematic, multidisciplinary analysis of China's water challenges combining jurisdictional and river basin aspects has been missing thus far. Our study provided such an analysis and produced a novel delineation of China's river system units (the CARU system). The CARU has been designed to be compatible with the existing Chinese river

basin planning units (CPUs) while providing essentially higher spatial resolution together with inclusion of administrative boundaries besides river basin boundaries.

3. *Beyond China*. Around one-third of humans live in the river basins that are entirely or partly in China, and almost half of them outside China's borders. Therefore, it is extremely important to better include the transboundary aspect to China's river basin policies, as emphasized by e.g. World Bank (2006), Xie et al. (2009) and Jiang et al. (2009). Our analysis covers this entire geographic area, and enables the joint consideration of China's internal and transboundary river systems.

We argue that all these three aspects are important in understanding and addressing China's water problems, particularly within the agenda of sustainable development (in the sense of balancing environmental, social and economic interests). We sincerely hope that our analysis will be a useful step in advancing China's – and more generally Asian – river basin development and management towards higher level of balance and harmony between man and the nature. This would be very important due to the highly demanding economic, environmental and social challenges that this swiftly changing and developing part of the planet is currently facing.