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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%, CO2 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 skillfully 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 & Vakkiläinen, 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 5,333,062 km² and 735,208 km², 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...
excluded the coastal basins of the Leizhou Peninsula from the Pearl basin and included them to the SE River Basins.

Transboundary river basins

Over half of the river systems (11 among the 21) are transboundary (Shared with one or more neighbouring countries), while 10 are entirely in China. The total surface area and population size of the transboundary basins outside China’s territory is $8199 \times 10^3$ km$^2$, and 1044 million, respectively (Table 1). The corresponding figures for all the river systems within China are $9356 \times 10^3$ km$^2$ and 1313 million people (Table 1). Adding up the population figures, our research area thus covers the homes of over 2.35 billion people, being roughly one-third of the mankind.

In the transboundary analysis part of our study, we included all of these basins except Ob-Irtysh, Amur, and other basins that are shared with Russia or People’s Republic of Korea. This exclusion was done for two reasons. First, we have performed vulnerability analyses of the other transboundary basins in previous studies (Varis & Kummu, 2012; Varis et al., 2012), but results are not available for

Table 1

<table>
<thead>
<tr>
<th>Drainage Code</th>
<th>Basin Description</th>
<th>Area (10^3 km^2)</th>
<th>Population (millions)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>In China</td>
<td>Other countries</td>
</tr>
<tr>
<td>East China Sea, Okhotsk</td>
<td>1</td>
<td>Amur</td>
<td>895.2</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Liao &amp; NE Coastal Rivers</td>
<td>418.9</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>Hai</td>
<td>243.3</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>Yellow</td>
<td>789.8</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>Shandong Coastal Rivers</td>
<td>52.1</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>Huai</td>
<td>263.3</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>Yangtze</td>
<td>1770.5</td>
</tr>
<tr>
<td>South China Sea</td>
<td>8</td>
<td>SE River Basins</td>
<td>316.3</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>Pearl</td>
<td>447.9</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>Red River</td>
<td>84</td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>Mekong</td>
<td>168.3</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>Salween</td>
<td>139.8</td>
</tr>
<tr>
<td></td>
<td>13</td>
<td>Irrawaddy</td>
<td>21.5</td>
</tr>
<tr>
<td></td>
<td>14</td>
<td>GBM</td>
<td>316.9</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>Indus</td>
<td>86.1</td>
</tr>
<tr>
<td>Indian Ocean</td>
<td>16</td>
<td>Ob-Irtysh</td>
<td>50.4</td>
</tr>
<tr>
<td>Arctic Ocean</td>
<td>17</td>
<td>Gansu-Inner Mongolia CB</td>
<td>807.1</td>
</tr>
<tr>
<td></td>
<td>18</td>
<td>Qinghai CB</td>
<td>319.3</td>
</tr>
<tr>
<td></td>
<td>19</td>
<td>Tarim-Junggar CB</td>
<td>1411.3</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>Ili CB</td>
<td>57.7</td>
</tr>
<tr>
<td></td>
<td>21</td>
<td>Tibetan CB</td>
<td>696.5</td>
</tr>
<tr>
<td>TOTAL</td>
<td></td>
<td></td>
<td>9356.2</td>
</tr>
</tbody>
</table>

Note: SE River Basins stand for Southeast River Basins, GBM stands for Ganges–Brahmaputra–Meghna basin, and CB for closed basins.

Amur, Ob-Irtysh and other basins shared with Russia or People’s Republic of Korea. Second, the latter-mentioned basins will be a topic of a separate analysis, in which they will be set within the context of other major North Eurasian rivers.

Data

As we combine river basins with administrative units in our CARU delineation, we face a situation, in which a simultaneous operation at two geographical divisions is essential, namely, natural units of water management (i.e. river basins), and administrative units (i.e. jurisdictions). This arrangement is important in practice, since the river basin context is highly relevant in the management of water resources, whereas policy making and administration occurs typically at national, provincial, or some other jurisdictional level, which only in rare instances follow boundaries of river basins (Shen & Varis, 2000; Varis et al., 2012).

Consequently, two types of data were used: spatially gridded data were available for environment, water resources and some of the social data while for policy, governance issues, and macroeconomic aspects data were available at, or scaled to, the administrative scale of provinces (see Table 2).

We refer to the article by Varis et al. (2012) for detailed documentation of data and its selection rationale. Four modifications were made to the approach by Varis et al. (2012), regarding to the data issues, due to the limitations of sub-national data availability from China, and due to availability of more recent data.

First, provincial data was used to replace national averages for several of the components that are used to calculate the Political Instability Index (EIU, 2011). For details, see Table 2.

Second, the Multifaceted Poverty Index (MPI; Alkire & Santos, 2010) was calculated by province from the national average by scaling the latter with the province-specific values of the three components of the MPI, namely education, health outcomes, and standard of living. The two former ones were obtained from the education and health indices of the Human Development Index (HDI) which were available for Chinese provinces by UNDP (2010). The MPI indicator used for standard of living was the access to improved water source (separately by rural and urban areas) from China Statistical Yearbook (2011).

Third, for human footprint, we used the most recent, version 2.0 data of WCS/CIESIN (2005) instead of the previous version since this was now made available.

Fourth, for water stress we used the data provided by Wada, van Beek, and Bierkens (2011, 2013) instead of the less recent GWSP Digital Water Atlas (2008) data.

These changes have a relatively small impact on the overall vulnerability maps due to fairly limited year-to-year variability in the indicator values. Anyhow, they must be taken into consideration when comparing our results to those by Varis et al. (2012).

Table 2

<table>
<thead>
<tr>
<th>Source of vulnerability (indicator)</th>
<th>Data description</th>
<th>Resolution</th>
<th>Source</th>
<th>Acronym</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data by administrative regions</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Governance (Political instability)</td>
<td>Political instability index consists of 12 indicators for Underlying vulnerability and three for Economic distress (EIU, 2011). The data were not directly available for provinces and thus, for obtaining provincial estimates, we used national averages for all other indicators except inequality, Ethnic fragmentation and Level of income per head. Those were obtained from China Statistical Yearbook (2011).</td>
<td>Country/Province</td>
<td>EIU (2011); China Statistical Yearbook (2011)</td>
<td>PSI</td>
</tr>
<tr>
<td>Social (Multidimensional Poverty Index)</td>
<td>The index (originally developed by Alkire &amp; Santos, 2010) represents the nature and intensity of poverty at the individual level in education, health outcomes, and standard of living. The MPI data were not available for provinces. Provincial values were obtained by scaling China’s national value by province-specific human development Index components of education and health (UNDP, 2010) as well as level of water services (urban and rural separately; China Statistical Yearbook, 2011).</td>
<td>Country/Province</td>
<td>Alkire and Santos (2010); UNDP (2010); China Statistical Yearbook (2011)</td>
<td>MPI</td>
</tr>
<tr>
<td>Spatially gridded data</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Environment (Human footprint)</td>
<td>Global Human Footprint Dataset from the Last of Wild v 2 project covering human population pressure, human land use, and human access</td>
<td>Grid: 30 arc seconds ( = 1 km x 1 km)</td>
<td>WCS/CIESIN (2005)</td>
<td>HF</td>
</tr>
<tr>
<td>Hazards (Multihazards)</td>
<td>Natural disaster hotspots: Global Multihazard Frequency and Distribution, classified</td>
<td>Grid: 2.5 arc min ( = 5 km x 5 km)</td>
<td>Dilley et al. (2005)</td>
<td>MH</td>
</tr>
<tr>
<td>Water stress (Water stress)</td>
<td>Net water demand divided by amount of renewable blue water resources</td>
<td>Grid: 0.5 arc degree ( = 50 km x 50 km)</td>
<td>Wada et al. (2011, 2013)</td>
<td>WS</td>
</tr>
</tbody>
</table>
River basin vulnerability index approach

We used here the river basin vulnerability (RBV) analysis approach that was developed by Varis et al. (2012) within the context of analysing the vulnerability of ten major river basins in Asia-Pacific. This was because the approach has been tailored particularly to purposes such as this one, and comparable river basin vulnerability results were already available from 16 major river basins of Asia-Pacific (Varis et al., 2012) with a population that covers well over one-quarter of the mankind. The approach, as well as the concept of vulnerability, is only briefly introduced below while details can be found from Varis et al. (2012).

The RBV method is designed to be applicable for addressing river systems when analysed as highly complex societal–environmental systems. The approach includes six sources of vulnerability which are governance, economy, social issues, environment, hazards, and water stress. They have been selected so that they cover maximally the common key dimensions of the entity where water resources management and adaptation policies are being performed. They are also aligned with the philosophy of common policy frameworks in the water sector, particularly Integrated Water Resources Management (IWRM; Rahman & Varis, 2003).

The RBV approach is able to produce results which are comparable with any other geographical area in the world. The approach thus relies maximally on already published composite indicators. This is because those indices have been thoroughly investigated in the global context, are easily available for most locations across the planet and allow the analysis of temporal evolution of the vulnerability, since they are constructed from indicators that are chiefly published on an annual basis by various organizations.

In the approach, a geospatial mesh of administrative regions and basins was first created using the ArcGIS software (see the map in Fig. S1C). Then, using the gridded population data from LandScanTM (2007) dataset, the total population and its proportion of the total basin population were calculated for each mesh unit (see Table 2; Fig. S1D). Each indicator value was then weighted with population within each mesh unit and finally the river basin value was calculated by dividing the sum of weighted indicator values by total basin population. The spatially gridded data were aggregated directly to the basin areas (Fig. 1).

Then the data were scaled between 0 and 1 based on global distribution of each analysed vulnerability components (Table 3). We used the 5-percentile threshold of the global distribution to represent the 0 value and 95-percentile to represent the 1, in order to avoid one or few outliers to have a dramatic impact on the scaling of all other data points. The exception was Water Stress. It is calculated as the ratio of net water demand and the available renewable water resources. If this ratio exceeds 1, then the indicator receives the value 1. Finally the six components were combined to the River Basin Vulnerability Index (RBVI) as the average value over them (for more details see Varis et al., 2012).

Cluster analysis

In order to identify the areas with a similar RBV profile, we performed a k-means cluster analysis with SPSS v20. In the analysis, we grouped China’s territory into four characteristic groups in terms of vulnerability profiles. We centralized (zero mean) the data before applying the k-means clustering. Data were already standardized in the scaling (see above and Table 3) and, thus, normalization (other part of the normal standardization procedure with centralization needed before clustering) of the data were not needed.

Results

The results on the six dimensions of vulnerability included in our analysis are documented below for river systems that are entirely or partly in the continental part of China. For those not entirely within China, only the part of the system that is located in China was included in the analysis. A vulnerability profile for each basin is presented thereafter. At the end, the results of the cluster analysis are presented.

Indicator values

Governance

The western and southern parts of China as well as the coast up to Jiangsu have higher governance-related vulnerability than China’s other parts (Fig. 2A). The most vulnerable part of the country is Guizhou. The municipal cities under the central government, including Beijing, Shanghai and Tianjin, have the lowest governance-related vulnerability. The range in relation to the global variation is relatively large: from 0.15 to 0.53.

Economy

Most of the coastal China, in particular Beijing, Shanghai and Tianjin, as well as Inner Mongolia represent the lowest economic vulnerability (Fig. 2B). The economically most vulnerable provinces include Anhui in the east, Gansu, and the south-western stripe from Guizhou to Tibet Autonomous Region. The range is relatively similar to that of the Governance index.

Social issues

The range of internal variation of China in this regard is fairly small (Fig. 2C). By and large, the coastal provinces appear more advanced in this regard compared to the rest of the country, whereas Tibet Autonomous Region appears the less advantageous in this regard.

Environment

The human footprint (indicating environmental vulnerability) is lower in the west than in the east, with the exception of the lI basin with a relatively high value (Fig. 2D). In most parts of Tibet, the footprint is at the lowest, whereas the highest indicator values are for the Hai, Huai and lower Yellow River systems, as well as the Shandong Peninsula. High values exist also in certain areas along the southern coast. The internal range of China’s various parts is particularly high in this respect, as large as that of the entire world (ranging thus from 0 to 1).

Hazards

The multihazard indicator shows particularly high vulnerability for south-eastern coastal areas between the Yangtze River Delta

---

### Table 3

<table>
<thead>
<tr>
<th>Component</th>
<th>Integrated index</th>
</tr>
</thead>
<tbody>
<tr>
<td>Governance</td>
<td>PSF&lt;sup&gt;pop&lt;/sup&gt;</td>
</tr>
<tr>
<td>Economy</td>
<td>(1 - (log(GNI&lt;sub&gt;pop&lt;/sub&gt;) - log(GNI&lt;sub&gt;pop max&lt;/sub&gt;))/log(GNI&lt;sub&gt;pop min&lt;/sub&gt;))</td>
</tr>
<tr>
<td>Social</td>
<td>MPI&lt;sup&gt;pop&lt;/sup&gt;</td>
</tr>
<tr>
<td>Environment</td>
<td>HF&lt;sup&gt;e&lt;/sup&gt;</td>
</tr>
<tr>
<td>Hazards</td>
<td>MH</td>
</tr>
<tr>
<td>Water scarcity</td>
<td>min(WS, 1)</td>
</tr>
</tbody>
</table>

<sup>e</sup> — scaled value $x' = (x - x_{min})/(x_{max} - x_{min})$ where $x_{max}$ is the maximum 95% fractal of the global dataset in question, and $x_{min}$ is the minimum 5% fractal of the same set.

$pop$ — population weighted basin average value.
and the China-Vietnam border (Fig. 2E). The lowest values are recorded on the large inland stripe from Tibet (excluding the GBM system) towards Inner Mongolia. As in the case with environmental vulnerability, the range is as large as that of the entire world.

Water stress

A stripe of high water stress crosses China in the northwest–east direction (Fig. 2F). It is most pronounced in large parts of North-Central China, and in. Besides, the Xinjiang province together with lowest parts of the Hai, Yellow, and Huai systems large areas in Central China, are highly water-stressed. In the case of water stress, China’s internal range is as big as the global range (0–1).

The overall vulnerability

The overall vulnerability, i.e. RBVI, is highest in central and low parts of the Yellow river system and in southeastern part of the Hai river system (Fig. 3). The very high population density combined with low water availability and high human footprint yield a particularly challenging combination. This is despite lower economic vulnerability than in China’s most other parts. Quite interestingly, large parts of the rest of China show relatively even vulnerability level, although the combination of vulnerability sources differs quite remarkably (compare to Fig. 2 for the six sources).

Fig. 2. The scaled indicator values mapped for China’s river basin systems. A: Governance (Political Instability Index); B: Economy (Gross National Income per capita adjusted with Purchasing Power Parity); C: Social issues (Multidimensional Poverty Index); D: Environment (Human Footprint); E: Hazards (Multihazard Index); and F: Water stress. Note: the same hue for different colours means similar index value. There are 10 steps for each tone of a colour, i.e. 0–0.1; 0.1–0.2; etc., as indicated in the legends. The larger the value, the larger is the vulnerability. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
As an exception, most parts of Tibet and Qinghai (particularly Tibetan closed basins and the upper parts of the Yangtze basin) show the lowest vulnerability. Here a combination of low population density, low human footprint and low hazard level are the most important factors. The economic affluence level and social development that are lower than in most other parts of the country does not change the situation.

Vulnerability profiles

We grouped the river systems into open and closed ones. We further grouped the open systems with regard to the sea they drain to. The river systems were thus classified into four groups (Fig. 4A): those draining (1) to the East China Sea, (2) to the South China Sea, (3) to the Indian and Arctic Oceans, and (4) to closed basins.

The systems draining to the East China Sea have all a fairly high overall vulnerability: Yellow has the highest and Amur the lowest. The systems draining to the South China Sea are also highly vulnerable. The systems draining to the Indian and Arctic Oceans represent low vulnerability levels, with an exception of Irrawaddy. The closed basins show a very heterogeneous group of vulnerability with Tibetan CBs scoring reasonably low.

The open river systems show an interesting geographic vulnerability pattern (Fig. 4B). Starting from the north, from the Amur, there is a growing vulnerability tendency towards the Huai, and then gradually decreasing tendency all the way to Indus. Both the environment- and hazards-related vulnerabilities grow towards the Huai, and thereafter, the direction is opposite. There are few exceptional river systems that score markedly higher than their surrounding systems. Those are the Hai, Yellow, Red and Irrawaddy systems. This anomaly is explained by water scarcity in all other cases besides the Irrawaddy, in which environmental vulnerability is exceptionally high.

Clustering the administrative-basin mesh

The total number of investigated river systems being fairly high (21), we clustered them into five groups in order to obtain a condensed view of the areas with similar vulnerability characteristics (Fig. 5).

Group a consists of the west, excluding the Ili system (see Fig. 2F). Here, the overall vulnerability is relatively low. Comparing to the population density map (Fig. S1D) is revealing; the population density within this cluster is quite low in comparison to the area to the east and south-east of this cluster. We name this group as the Western Cluster.

Group b includes the water-stressed areas in north-central China including Inner Mongolia. This group covers quite well the northern part of the arid area of China, which is outside the monsoon influence. Their overall vulnerability is highest in water stress and environment. We name this as the Dry Cluster.

Group c includes most of the central and southern parts of China (excluding the coastal stripe, the northeast, and the Ili basin). Here, environment and economy are important sources of vulnerability. We call this as the Humid Inland Cluster.

Group d consists of most of the Yellow and Huai river systems. For those, water stress and environment appear particularly important vulnerability sources. The area is highly crowded and short of water. We name this as the North China Plain Cluster.

Group e covers most of the coastal area of China. Its challenge is very high vulnerability due to environment and hazards. We call this as the Coastal Cluster.

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 to 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

![Fig. 3. The overall vulnerability (RBVI) of China.](https://example.com/fig3.png)
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; Vorosmarty, 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 cooperation 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, Käkänen, & Varis, 2012; Molle, Foran, & Käkänen, 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;
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 socioeconomic 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.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.apgeog.2014.05.012.

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