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## The demanding quest for harmony: China's polarizing freshwater resilience map

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E-mail: [olli.varis@aalto.fi](mailto:olli.varis@aalto.fi)**Keywords:** adaptive capacity, China, resilience, river basins, vulnerability, water

## Abstract

China's millennial quest for harmony between nature and humanity is as important today as it has always been. Today's challenges are momentous; but at the same time, China's capacity to cope with them is strengthening rapidly. We analyse China's freshwaters using the social-ecological systems approach in a novel way. Quantitative, globally-scaled indicators for freshwater vulnerability, adaptive capacity (AC) and resilience, and their temporal evolution from 1990–2015, are analysed spatially. China's AC (governance, economy and human development) represents heterogeneity, levelling close to the global range's mean level. Coastal areas are somewhat better off than other parts. In turn, ecological vulnerability (EV) (environmental footprint, natural hazards, water scarcity) shows more pronounced contrasts across China. The human footprint and natural hazards are greatest in the east and the lowest in the west, whereas water-scarcity woes stand out in the North China Plain and Xinjiang. The North China Plain (above all the Huang basin) is particularly challenging, yet the AC there has grown fast and therefore resilience has started to grow. Nevertheless, China's capacity is now growing rapidly, allowing improvements in resilience in large parts of the country. It may provide an opportunity for changing the tide in the most challenging areas, too, but requires continuous and massive commitment. Yet China still showed a polarizing development in the years 1990–2015 in terms of spatial development in AC, EV and resilience, meaning that the diversity and heterogeneity of the country have continued to grow.

## 1. Introduction

China portrays an exceptionally long documented history of water resources management and conservancy that goes back over four millennia. Water management has had a central role in striving towards formation and stability of the state, and the relation between water and Chinese culture and civilization has been contiguous (Ball 2016).

The harmony between humans and nature is a common historical-cultural concept, that stems from the Dao philosophy (see, Ball 2016). This concept is used widely today in various contexts, including policy-making, as a synonym for sustainable development. The present situation of China's waters with regard to this interpretation for harmony is characterized by a fundamental dilemma. The country's rapid economic development, industrial transformation

and urbanization keep imposing massive pressures on waters; but at the same time, the economic, social and technological capacity to deal with societal and environmental challenges is constantly growing (Varis *et al* 2014, Cai *et al* 2016). In this highly dynamic situation, the quest for harmony between nature and man is as fundamental to China's sustainable development today as it has been in the past, and its improvement is a highly delicate and demanding task (Varis and Vakkilainen 2001, Economy 2004, Liu *et al* 2013, Jiang 2015, Zuo *et al* 2016, Satoh *et al* 2017).

We analyse how successful China has been in the recent past in this quest and relate China's freshwater challenges to the global situation. This is an extension of the study by Varis *et al* (2014) with methodological development, including temporal evolution from 1990 to 2015. We apply the social-environmental systems approach (SES) (Gallopín 1991, Berkes and

Folke 1998), which is widely used in climate change research and policy analysis, as well as in earth sciences and sustainability sciences (Adger 2006, Folke 2006, Janssen and Ostrom 2006, Hinkel 2011, Shahadu 2016), and we adopt the approach to freshwater studies.

The SES concept is appropriate to the analysis of the quest for harmony between humanity and nature, as the social system can be used to account for humanity and the ecological system for nature. We use here the concept of ecological vulnerability (EV) to indicate the status of the ecological system and adaptive capacity (AC) to indicate the social system's ability to cope with the challenges of the ecological system (Varis *et al* 2019). In the literature on earth system sciences and climate change, vulnerability is often seen as a combination of social and EV, but we assign the societal component as a part of AC. We can thereby clearly demarcate between the social and ecological systems (i.e. human and nature), which is not always clear in the social-ecological systems literature (Engle 2011, Lang *et al* 2017, Varis *et al* 2019).

We indicate China's EV on freshwater with the use-availability ratio, natural hazards and the environmental footprint, and AC with governance, gross domestic product (GDP) and human development. We call their differential as resilience (figure 1). We scale the results to global data, which allows us to position China's contemporary freshwater challenges and opportunities into a global perspective.

With this analysis, we aim to provide spatial mappings of China's resilience, EV and AC and their temporal development in 1990–2015. We do this on two scales, namely by river basins and provinces (including special administrative regions), and focus on the continental mainland China. Understanding China's water-related vulnerabilities and capacities to cope with them is fundamentally important in directing policy impetus toward the most efficient measures. Besides, global scaling helps in drawing international lessons and pathways to cope with freshwater issues in a broad societal and environmental context.

## 2. Materials and methods

We use open-access geospatial datasets for extracting the data and combine gridded and administrative data, both with various resolutions. All datasets are openly available in data repositories indicated in the data sources described below and in table 1. The results are aggregated into a mesh of river basins, provinces and countries in order to maximize usefulness and relevance to policy making. River basins smaller than 50 000 km<sup>2</sup> in catchment area are combined in coastal basin areas. Since this aggregation is not very accurate for the analysis of coastal small basins, we leave the Chinese islands out of the analysis, since they all are much smaller than 50 000 km<sup>2</sup>. They consist only of

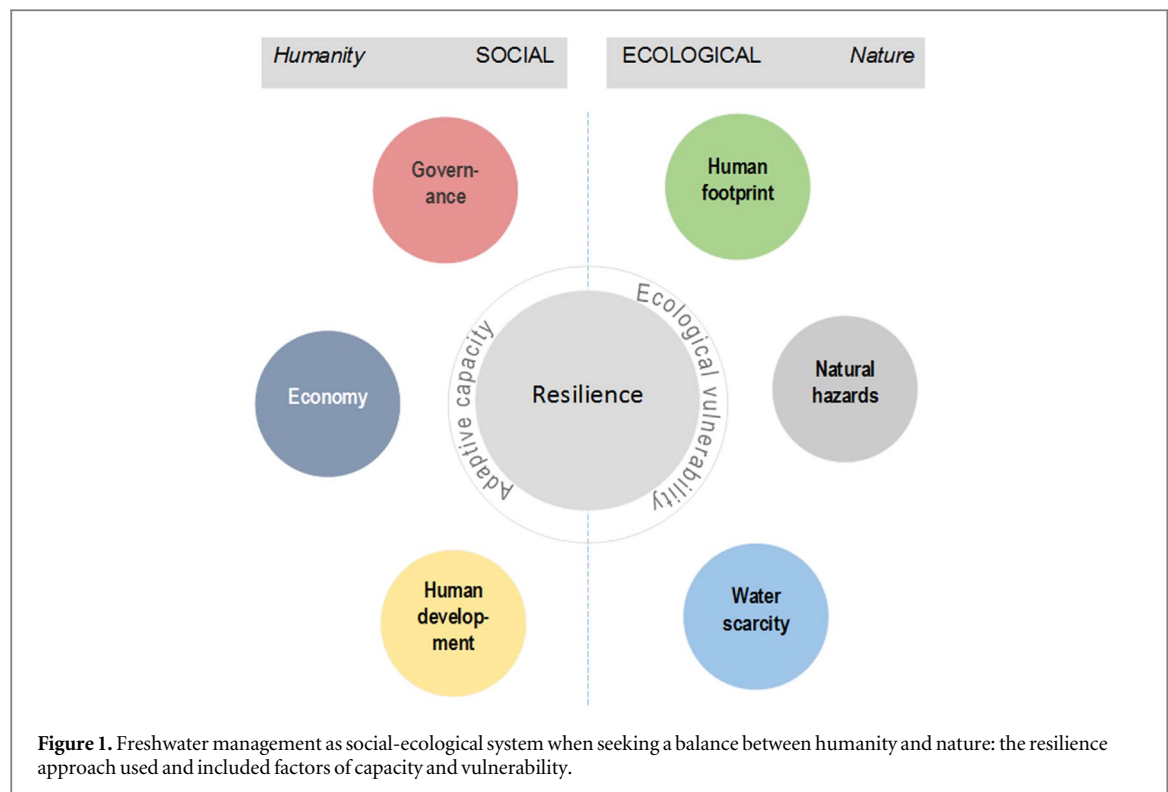
such small basins. Therefore, our analysis covers only the continental part of mainland China. The analysis is made for each year from 1990 to 2015. The details and discussion of the approach are presented in our global scale analysis of river basin resilience (Varis *et al* 2019).

Assessing all the indicators over the whole study period (1990–2015) allows us to map trends in the indices. We use the Mann-Kendall test to estimate direction and statistical significance of the trend. To support the interpretation of the temporal trend analysis, we apply the k-means clustering to divide the study area to units with common patterns in a trend. For clustering, we use the trends in EV, AC and resilience.

For AC, we use the following indicators: national-level governance (WGI 2018), subnational level economy and human development (both from Kummur *et al* 2018a, Kummur *et al* 2018b). The approach is derived from the political economy concept of List (1851). This concept, in comparison to the often used classical economic model (which focuses on economic output), includes also the capabilities of human individuals as well as institutions, law, and their implementation (Rössner 2018). The selected three indicators—like those that we use to indicate EV—are those used widely in both governance and scientific contexts globally, they are openly available, continuously updated, and historical time series are available for several decades.

For EV, the three factors are (see figure 1): the human footprint (Venter *et al* 2016), natural hazards (the multihazard index by Dilley *et al* 2005), and water scarcity (the squared sum of water stress and water shortage from Kummur *et al* 2016). All this data are gridded. This selection is derived from the Natural Capital and Ecosystem Health literature. This literature is ample and highly diverse, with one typical approach is to analyse the volume of the natural capital stock (and/or ecosystems) together with their degradation status, given a certain management context (see e.g. Costanza and Daly 1992). As we use river basins as the basic geographic unit for our analysis, we use water scarcity as an indicator for the natural capital. Degradation of ecosystems is indicated by human footprint, and the management context is included as the variability of the resource (natural hazards). The latter is not included in the water scarcity nor the human footprint indices, yet it is instrumental in any management of a river basin, and therefore we include it in our EV parameterization.

We use the Equal Weight Composite Index (e.g. Ding *et al* 2018) for the construction of the indices for EV, AC and resilience. Thus, both the EV and AC are calculated as the arithmetic mean of their three factors. Resilience is calculated by subtracting EV from AC. The Equal Weight Composite method is widely used in areas such as finance and economy (e.g. stock exchange indices) and development (e.g. many basic indices of multilateral organizations, such as the



**Table 1.** Introduced indicators and their input datasets with their spatial resolution.

Resilience (AC—EV)	Input indicator	Source	Spatial resolution
Adaptive capacity (AC)	Government effectiveness	WGI 2018	National
	Gross domestic production (GDP) per capita PPP (USD)	Kummu <i>et al</i> 2018a, 2018b	5 arc min
Ecological vulnerability (EC)	Human development index (HDI)	Kummu <i>et al</i> 2018a, 2018b	5 arc min
	Human footprint	Venter <i>et al</i> 2016	1 km <sup>2</sup>
	Natural hazards	Dilley <i>et al</i> 2005	2.5 arc min
	Water scarcity	Kummu <i>et al</i> 2016, Wada <i>et al</i> 2016	30 arc min

World Bank, United Nations, and Organization of Economic Co-operation and Development). It is a maximally transparent and parsimonious approach for constructing indices from factors that are also used separately in a policy context (Ding *et al* 2018).

Each indicator is normalised between 0 and 1. We used global scale observations for normalising to ensure that our results are comparable to any other geographical area. Further, instead of using max and min values for normalising, we used 95th percentile and 5th percentile of the observed values. This ensures that potential outliers do not become overly weighted in the normalising process. The negative values after normalising are set to 0 and values larger than 1 to 1.

### 3. Results

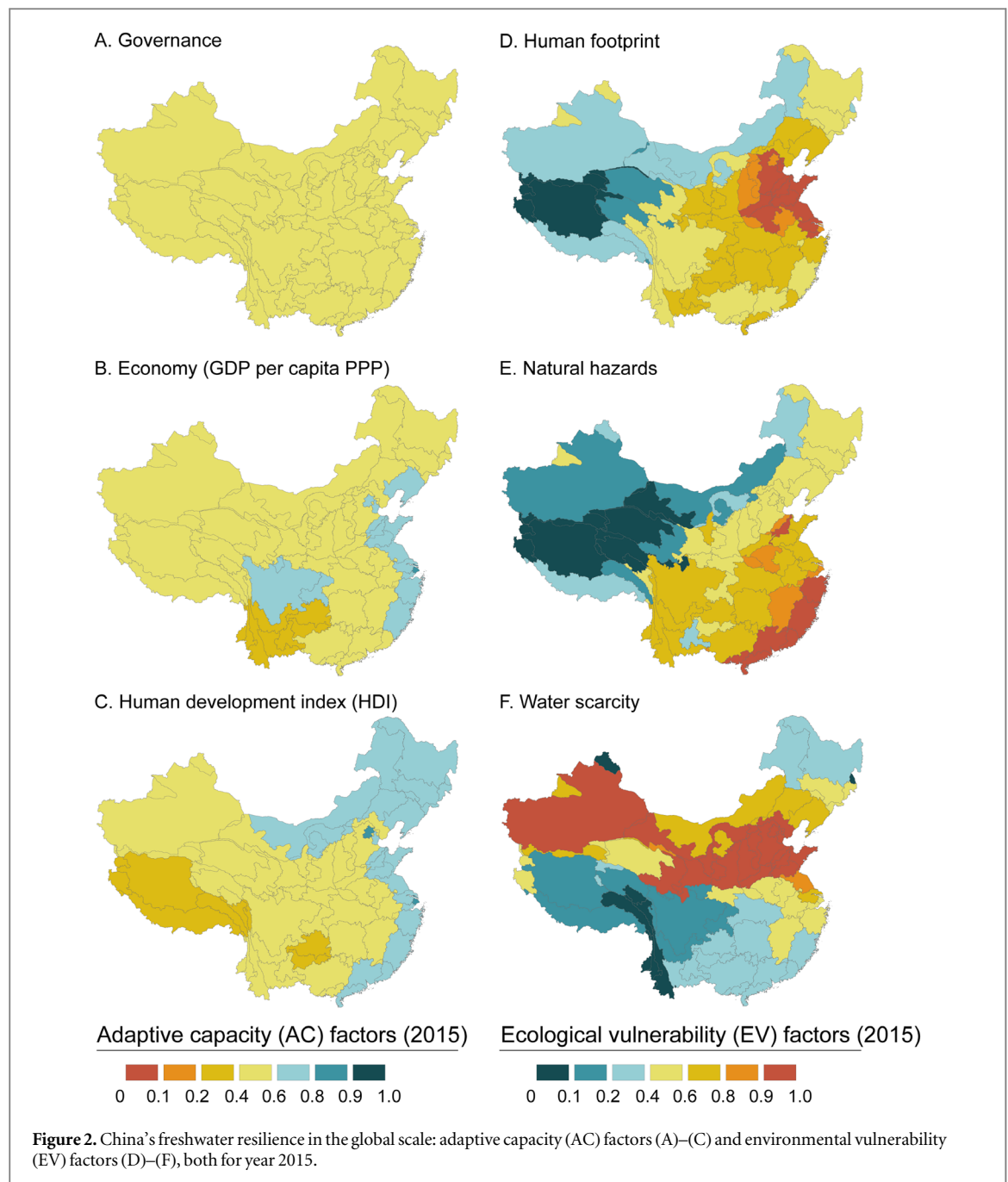
The analysis reveals an intricate and multidimensional pattern of China's freshwater-related EV, AC and resilience.

#### 3.1. Adaptive capacity (AC)

As for the components of AC, the governance indicator gives a uniform view of China's governance capacity (figure 2(A)) for the simple reason that a nationwide indicator was used, as no data with finer resolution was available. The level is close to the mean of the global range (interval of world's highest and lowest values; in statistical terms, the mid-range  $M$  of the sample minimum and sample maximum).

The economy also levels out close to  $M$  for most of China, except for being slightly lower in Yunnan and Guizhou and higher in most of the coastal areas from Liaoning to Zhejiang as well as in Sichuan and Chongqing (figure 2(B)). Shanghai stands out as the most prosperous area.

For human development, too, much of the country is close to the world's mid-range  $M$ . The level is lower in Tibet and Guizhou and higher in most of the coastal areas, Inner Mongolia and the northeast



(figure 2(C)). Beijing and Shanghai show the highest human development.

### 3.2. Ecological vulnerability (EV)

The components of EV (figures 2(D)–(F)) offer a far more diverse picture of China than those of the AC. The human footprint is at the highest 10% of the world's range in Tianjin, Hebei, Henan, Shandong and Jiangsu (i.e. the eastern parts of Huang (Yellow), Huai and Hai basins (3H basins)). Above-*M* (i.e. mid range) regions cover most of the densely populated parts of China—from Liaoning to eastern Yunnan, except Fujian, Guangxi and parts of Guangdong. Most of the west and Inner Mongolia fall below *M*. Western Tibet

and parts of Qinghai have a particularly low human footprint.

Exposure to natural hazards is very high in coastal areas south of the Yangtze Delta and at the mouth of the Yellow River. In contrast, exposure is low or very low in most arid parts of western China (from Inner Mongolia to Xinjiang and Tibet). A belt from Heilongjiang to Eastern Gansu and Chongqing is close to *M*.

In terms of water scarcity, China has a problematic belt from Xinjiang through the Hexi Corridor in Gansu to the coastal provinces of Hebei, Shandong and northern Jiangsu. There, water scarcity falls in the worst 10% of the world's range. In sharp contrast, large areas are exceptionally affluent with water (the



Amur (Heilongjiang) basin in the northeast, the Irtysh basin in Xinjiang, and the southern stripe from Tibet to Fujian fall above 90% of the world's range). The other water-affluent areas include the Yangtze basin, the basins south of it, and most of the transboundary basins that drain from China to the territory of its neighbours.

### 3.3. Combined AC, EV and resilience

The combined indicator for AC (figure 3(A)) recaps the fairly even geographic pattern of China's AC. The coastal provinces, Beijing, the northeast, Inner Mongolia, Sichuan and Chongqing stand out somewhat above the others.

The EV pattern (figure 3(B)) is far more uneven. A large area that includes the 3H basins, Liaoning, Hebei, Shanxi, Hubei, Anhui, Zhejiang and Jiangxi all fall in the worst-off 10% within the world's range. This is alarming since much of the area is affluent with water, with water scarcity touching only the northernmost part of the area. In contrast, China includes large, scarcely populated areas in Tibet, the Irtysh (Ertix) Basin and northern Inner Mongolia, with a lower EV than the world's mid-range  $M$ .

The resilience map (figure 3(C)) shows a highly fragile area (resilience below 10% of the world's range) in most parts of the Huai and Hai basins and the lower-mid Huang basin. China's highest resilience areas occur in most parts of Qinghai and Tibet and the northern part of Inner Mongolia.

### 3.4. Temporal trends

Whereas China's AC map for year 2015 (figure 3(A)) is fairly homogenous, the temporal trends in AC (as shown in figure 4(A)) reveal disparities in growth. Most of the areas with capacity above the mean  $M$  of the world's range (see figure 3(A)) have been on rapid increase. In contrast, Tibet, Yunnan and Guizhou are witnessing a much slower increasing trend, and the country has thus been polarizing.

The EV trend map (figure 4(B)), likewise, shows growing spatial disparities. The Huang basin and Liaoning have witnessed the strongest negative (i.e. vulnerability is increasing) development. The vulnerability in Hebei, Inner Mongolia, Western Gansu, Qinghai, mid and low Yangtze Basin, as well as in the Mekong (Lancang) and Red River (Hong) Basins has also increased but more modestly. Fujian, Guangdong and Guangxi have been improving (EV decreased) in terms of EV. Here we observe also a polarizing development as most of the low-EV areas have been degrading further, whereas the situation in a few highly humid areas in the southeast has improved.

The resilience trend map (figure 4(C)) recapitulates China's polarising development. Resilience in the coastal areas up to Jiangsu, the northeast, the capital area, Xinjiang, Chongqing and Sichuan has increased rapidly (as scaled to the world's range of 2015), while

Tibet, Yunnan and the Huang basin are among the areas with the weakest, but still clearly positive, resilience development.

### 3.5. Spatial resilience clusters

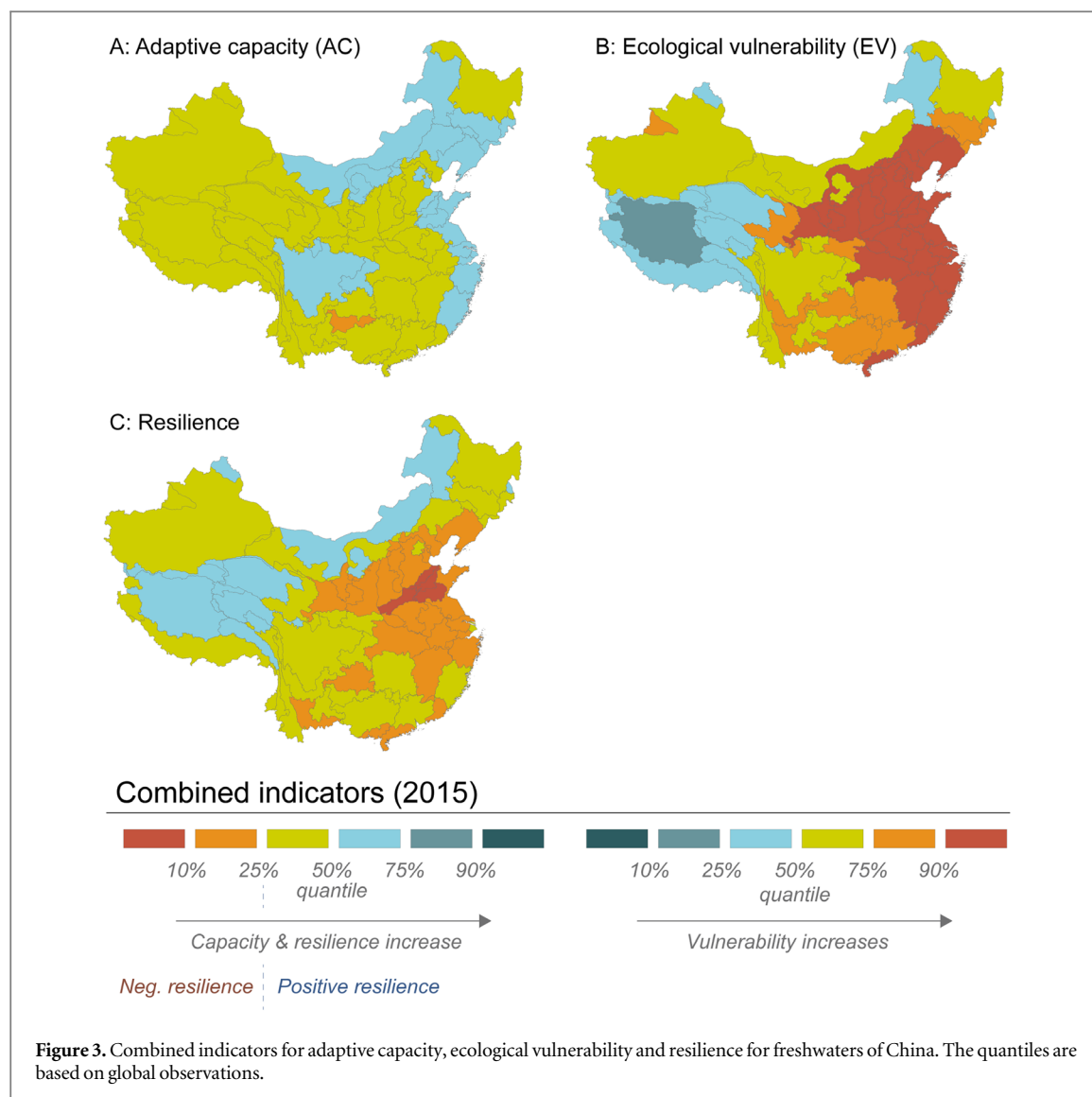
*K-means* clustering was made to the temporal trends of figures 4(A)–(C). Five clusters are identified, as shown in figure 4(D):

1. Areas with resilience clearly improved from low to high, and where EV has increased slightly, include the coast from Guangxi to Shanghai, the northeast, Xinjiang, Sichuan and Chongqing.
2. Areas with rapidly growing AC, not much changes in EV but still resilience remaining below  $M$  in the last time step (2015), include large parts of the coast from Beijing and Tianjin to Guangzhou, as well as mid-reaches of the Huang River basin.
3. Areas with growing EV and/or where AC has not improved fast enough to bring resilience to a decent level. Large areas from Liaoning to Jiangxi and to the 3H basins, as well as some areas in the south (including the Red River basin and parts of Guizhou) belong to this cluster.
4. Areas in which resilience has remained high over the whole period include northern Tibet and Qinghai, except for the Yellow (Huang) river basin.
5. Areas with improved resilience from below to above  $M$ . Despite the proliferation of some components of EV, AC improvements have outpaced the improvements in EV. Much of Inner Mongolia, Gansu, Brahmaputra (Yarlung Zangbo) basin, Salween (Nu) basin and Mekong (Lancang) basin, and mid-reaches of the Yangtze and Pearl (Zhu) River basin's upper-western parts belong to this cluster.

## 4. Discussion

### 4.1. China's resilience challenge

In terms of resilience, and its temporal trajectories, China has been facing a very rapid growth of AC providing increased opportunities for sustainable development actions and policies, but at the same time the environmental challenges have been in growth as indicated with increasing EV. The use of global observations in normalising the indicators (see methods), allows us to put the development in China on a global context. Thus, our results indicate that China's resilience (in relation to global range) has been improving (figure 4(C)). The big question is whether China will decide to make use of this increased capacity to the benefit of the environment or for activities that further deteriorate the ecosystems. There are ambitious policies in place (Su *et al* 2013,



Jiang 2015, Cai *et al* 2017b, He *et al* 2018, Xu *et al* 2018), but the success of their implementation remains to be seen. The success will in part depend on the ability of linking sectorial policies together. This will not be self-evident, since the scientific research, as well as policy-making, is strongly sectorial in China (Cai *et al* 2017a, He *et al* 2018).

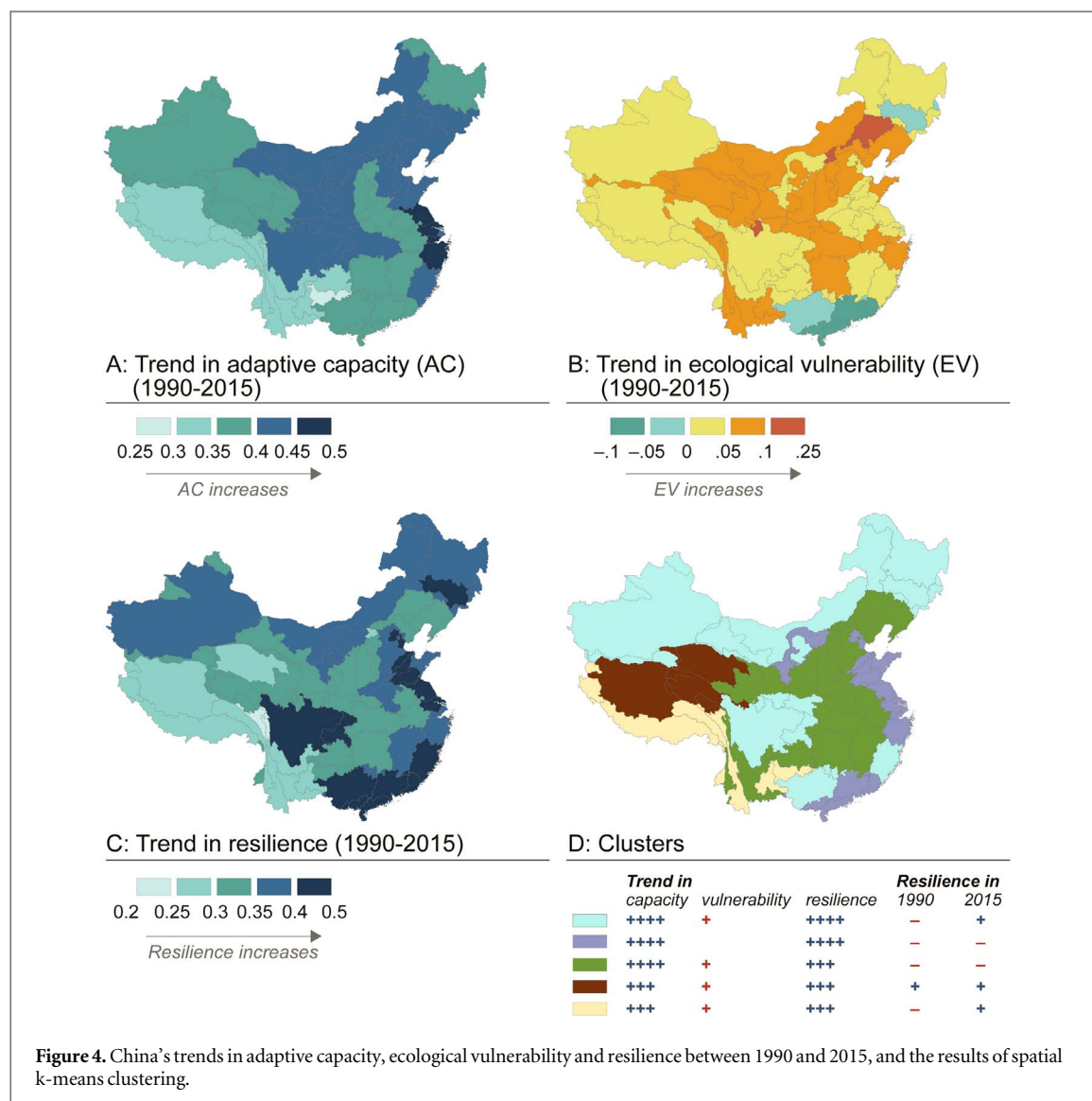
Areas with highest environmental vulnerability (EV) (see figure 3(B)) deserve elevated concern, with particular attention to the sub-area in which the resilience is at the lowest level. The highest EV occurs in a large and crowded area in Central-Eastern part of China, with a worrying, rapidly growing trend in EV since 1990. A positive sign is that much of that area has showed a very fast improvement in AC. In fact, it includes most of China's areas that classify above the 60% of the world's range in both economy and human development (figures 2(B) and (C)). Interestingly, it does not include any of China's less advanced regions with regard to those two factors. This suggests that, at least on a macroeconomic scale, environmental degradation and social-economic progress have occurred

largely on same areas, thus polarizing the country in terms of both AC and EV. Many analyses have drawn attention to the large cost that China's environment has been exposed to due to the economic boom of past decades (Economy 2004, Liu and Diamond 2005, Fu *et al* 2007, Liang *et al* 2014, Lü *et al* 2015, Zuo *et al* 2016). We share this attention by pointing out that the increasing capacity should be more deployed towards environmental protection and sustainable development than done during our study period 1990–2015.

#### 4.2. Methodological remarks

The developed methodology offers new perspectives on the multidimensional understanding of contemporary freshwater challenges by allowing the combination of resilience, AC and EV spatially with a global coverage. The use of the SES approach (Gallopín 1991, Berkes and Folke 1998, Adger 2006, Janssen and Ostrom 2006, Engle 2011) (which is in the mainstream of climate change and earth systems research and policy support) is important in bridging freshwater





studies and policy making with climate change and earth systems research and policies. The need for such bridges is obvious (Lang *et al* 2017), especially given the fundamental role of the water sector in climate change adaptation and mitigation.

When relating AC to EV in our calculations, one needs to bear in mind that these two factors are not commensurable, and both are normalised globally. For instance, if an area unit has a value of 0.5 for both AC and EV (and hence a resilience value of 0), this merely indicates that all these indicators are at the mean of the global range. It does not necessarily mean that AC is sufficient to tackle EV.

## 5. Conclusions

China's freshwater challenge continues to be momentous, and the way to harmony between humanity and nature is still very long. However, the rapidly improving AC of society offers enhanced opportunities for accelerating progress towards a more resilient freshwater situation in the world's most populous country

than what we see today. The big question in the giant country is whether this increasing AV is used to turn the low EV towards improvements. A considerable portion of China's most populated parts fall within the lowest 10% of the world's range for EV, while the same areas have among the highest AC in China.

Notable is the great heterogeneity in geographic terms in all the analysed components of EV. In them all, China includes regions that are among the top and bottom levels of the entire world (figure 2). In contrast, AC is shown to be relatively homogeneous throughout China, levelling out close to the mean between the lowest and highest values in the world.

The resilience maps show a large spatial disparity. We clustered China in five zones with regard to the evolution of AC, EV and resilience from 1990–2015. China's regional differences (i.e. polarization of the country) have been in growth. One of the zones shows particular woes, which includes large areas from Liaoning to Jiangxi and to the 3H basins, as well as some areas in the south including the Red (Hong) River basin and parts of Guizhou. This cluster is

drifting further apart from the quested harmony between humanity and nature. Opposing development, i.e. certain success in evolving in the direction of harmony, appears in the cluster that covers the coast from Guangxi to Shanghai, the northeast provinces, Xinjiang, Sichuan and Chongqing. In the other two clusters, such a distinctive development direction is not visible.

It is remarkable that much of the water-affluent area is located in transboundary basins from which waters flow out of China to its neighbouring countries (see, Varis *et al* 2014, Kattelus *et al* 2015, Lei and Jia 2018). It is also interesting to observe that besides the water-scarce areas, large water-affluent areas of China also appear highly vulnerable in ecological terms.

We highlight the importance of macro-level contextualization of freshwater challenges and the related EV and AC, both inside nations (such as China) and worldwide. Framing policies and coping strategies for the freshwater sector benefits largely from such spatial, analytic information. Likewise, we emphasise the importance of developing bridging methodologies and concepts between freshwater management, hydrology, climate change and earth sciences in the way we did in this study.

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## Authors' contribution and competing interests

The study was designed together by OV and MK. MK was responsible for computational analyses. OV was responsible for the writing. The authors declare that they have no conflicts of interest.

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