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Key Points:
- We quantify resilience of the world's river basins using geospatial social-ecological systems approach
- The approach uses composite indicators of both adaptive capacity and ecological vulnerability
- Africa and Asia show the lowest resilience, which is due to low adaptive capacity in Africa and high ecological vulnerability in Asia

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The Planet's Stressed River Basins: Too Much Pressure or Too Little Adaptive Capacity?

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Abstract Freshwater is one of the most critical elements for sustainable development of ecosystems and societies. River basins, concomitant with administrative zones, form a common unit for freshwater management. So far, no comprehensive, global analysis exists that would link the ecological challenges of the planet's river basins to the capacity of the societies to cope with them. We address this gap by performing a geospatial resilience analysis for a global set of 541 river basins. We use the social-ecological systems approach by relating three ecological vulnerability factors (human footprint, natural hazards, and water scarcity) with three adaptive capacity factors (governance, economy, and human development), based on temporal trajectories from 1990 to 2015. Additionally, we examine resilience by subtracting ecological vulnerability from adaptive capacity. The most striking result is the fundamentally different patterns of controlling factors of the resilience in different developing regions, particularly those of Africa and Asia. Their root causes are particularly low adaptive capacity in Africa and high ecological vulnerability in Asia. Alarmingly, the difference between those continents grew within the study period. Finally, this study highlights the rapid dynamics of adaptive capacity in comparison to ecological vulnerability, the latter having more inertia. Their fragile balance is of our interest; they can either support or counteract each other depending on the geographic location.

Plain language summary The ongoing global environmental change highlights the critical role of freshwater for sustainable development of ecosystems and human societies. Resilience is the capacity to absorb disturbance and reorganize while undergoing changes. In this study, we perform a spatial analysis for 541 watersheds to identify the drivers of this resilience. We define resilience of each basin by first examining their adaptive capacity, which is a combination of governance, economy, and human development. We then define ecological vulnerability by combining human footprint, natural hazards, and water scarcity into one index. To conclude, resilience indicates the strength of community's adaptive capacity in the presence of ecological vulnerability. Our results indicate the different patterns resilience across the globe, pointing out how the similarly low resilience in Africa and Asia is caused by low adaptive capacity and high ecological vulnerability, respectively. Our temporal analysis 1990–2015 shows how this difference has been increasing over time. Interestingly, adaptive capacity was more dynamic over time, compared to more constant ecological vulnerability. The examined balance between adaptability and vulnerability provides a useful tool for managing the resilience of freshwater resources.

1. Introduction

Shortage of freshwater and degradation of aquatic ecosystems constitutes one of the key challenges for the sustainability of the planet (Rockstrom et al., 2009; Sivapalan et al., 2012; Steffen et al., 2015). Since the world's river basins represent a broad spectrum of natural and human conditions, the freshwater challenges largely vary across river basins. The challenges typically constitute a mix of ecological, economic, and social features, and hence, the tripod conception of sustainable development is relevant.

1.1. River Basins as Hydrological and Policy-Making Units

A river basin is one of the elementary units for investigating freshwater systems. This holds true when studying water per se as a component of nature through the lenses of a hydrologist. This is equally true for diagnosing or finding solutions to the challenges facing these areas, caused either by humanity or natural conditions. The river basin approach provides a pragmatic and functional link between hydrology and water policies because river basins form a commonly used unit for policymaking in water sector, endorsed by organizations such as the United Nations through the concept of Integrated Water Resources Management (Jonch-Clausen & Fugl, 2001; Rahaman & Varis, 2005; Sivapalan et al., 2014). Indeed, uses and other changes upstream influence water quality and quantity downstream, having an impact on water uses and ecosystems (Munia et al., 2016). Most countries adopt the river basin approach in one way or another as the basis for their water resources management policy (Kazbekov et al., 2016; Kummu et al., 2018b). River basin management is typically linked to two other spatial governance patterns, namely, administrative divisions and economic zones and corridors, which quite often do not coincide with one another nor with river basin boundaries.

River basins are systems in which humans must be able to adjust and adapt their behavior to the limits of the basin ecosystems sustainably (Costanza et al., 2000; Folke, 2006). Accordingly, river basins can easily be viewed through the lenses of social-ecological systems (SESs; Berkes & Folke, 1998). This concept is widely used in Earth and sustainability sciences (Adger, 2006; Folke, 2006; Hinkel, 2011; Janssen & Ostrom, 2006; Shahadu, 2016) as well as by the climate change community (Smit et al., 2001; Smit & Wandel, 2006). In addition, the terms socioecological systems (Gallopín, 1991) and coupled human-environment systems (Turner et al., 2003) are also used in a largely synonymous manner. These terms emphasize the importance of studying the dynamics and interconnections between societal and ecological systems (Janssen & Ostrom, 2006).

1.2. Contemporary Approaches to Freshwater Assessments

The advent of high-resolution geospatial data together with perennially refining global hydrological models has led to an increasing number of assessments on various aspects of challenges concerning water management at both river basin and global scales (Liu et al., 2017). In this regard, Vorosmarty et al. (2000) and Vorosmarty (2002) have made important contributions by introducing global-scale spatial analyses into the field. As a result, sophisticated analyses are increasingly available on the water availability per capita and water use in relation to water availability (Kummu et al., 2016; Mekonnen & Hoekstra, 2016; Porkka et al., 2016; Wada & Bierkens, 2014). Often, such studies have a multidisciplinary approach combining analyses for various purposes, including agricultural production (Kummu et al., 2014; Mekonnen & Hoekstra, 2014; Pfister & Bayer, 2014), water demand and climate change (Gosling & Arnell, 2016; Schewe et al., 2014; Veldkamp, Eisner, et al., 2015; Veldkamp, Wada, et al., 2015; Vorosmarty et al., 2000; Wanders & Van Lanen, 2015), ecosystems and biodiversity (Green et al., 2015; Vorosmarty et al., 2010), energy demand (Holland et al., 2015), and upstream-downstream relations (Green et al., 2015; Munia et al., 2016, 2018). These studies have demonstrated a relationship between the supply of freshwater and selected demand factors, including population pressure.

In addition to linking water resources availability to water demand and/or the size of the population, several studies have linked water availability to nations' societal capacity to tackle water problems as well as future development scenarios. For example, Kulshreshtha (1993) and Raskin (1997) used the national Gross Domestic Product (GDP) for this purpose. The concept was refined by Seckler et al. (1999) to globally identify the areas subject to physical or economic water scarcity and areas free from water scarcity. They found an association between economic water scarcity and those countries which, according to their scenario analysis, have sufficient water resources to meet their demand by 2025, but would "*... need to embark on massive water development programmes to actually utilize these resources*" (see also IWMI, 2000).

One group of freshwater studies include multidisciplinary and transdisciplinary vulnerability analyses, which incorporate social, economic, and environmental factors influencing either water resources governance or ecological status. These studies typically rely on the triple bottomline approach to sustainable development, in which economic, social, and ecological factors are examined in conjunction. They, however, have not yet adopted the SES concept. Nevertheless, the societal component is often included in a manner that is broad enough and goes sufficiently beyond technicalities to allow a SES analysis. Geographically, water resources vulnerability assessments have had either national (Chang et al., 2007), subnational (Qian et al., 2016; Wan et al., 2015), or predominantly, a regional focus (Babel & Wahid, 2008; Cai et al., 2017; Huang et al., 2008; Kattelus et al., 2015; Pascual et al., 2015; Varis & Kummu, 2012). Globally, only one freshwater vulnerability analysis has been conducted thus far (Padowski et al., 2015). The developed vulnerability concept combines water demand with available infrastructure, institutions, endowment capacity, and exogenous factors, such as imports of water and virtual water. However, as it excludes economic and social aspects, it does not address the tripod of sustainable development. The Water Poverty Index approach

(Sullivan, 2002) includes social and economic aspects, as it combines indicators from five aspects of water poverty, which are Resources, Access, Capacity, Use, and Environment. Although it is targeted to measure water stress at the household and community levels, and not vulnerability nor resilience, it has plenty of relevance to our present study.

1.3. River Basins as Social-Ecological Systems (SESs)

Currently, no systematic, global-scale SES framework (as defined by Berkes & Folke, 1998; Gallopín, 1991; Turner et al., 2003) is available for river basins, which would be based on the tripod of sustainable development. Despite its widespread acceptance, the SES methodology remains largely nonoperational with many voices calling for further development (Ostrom et al., 2007). In fact, river basins, particularly the North American Great Lakes basin (i.e., the upper part of the Saint Lawrence River basin), have been among the pioneering geographical areas for the development of the SES concept as early as in the 1980s (Rapport et al., 1985; Steedman & Regier, 1987). Despite this, the approach has not yet been generalized for systematic analysis of river basins with global coverage.

In the past three decades freshwater studies have manifested a growing tendency for including social and human aspects into specific fields such as hydrology (Xu et al., 2018). Although the number of published scientific papers was at first low, the number increased exponentially thereafter. Over the last two decades, large-scale hydrological models have increasingly included components describing human influence on water resources, yet Wada et al. (2017) maintain that "*... the representation of human activities in hydrological models remain challenging*." Sociohydrology, a subfield of hydrology, has recently been launched to improve understanding of the processes linking human activities to hydrology (Sivapalan et al., 2012, 2014). This concept is highly welcome, yet the published studies are still centered at a local to regional scale (Xu et al., 2018), and as stated by Wada et al. (2017) "*... still requires more detailed parameterizations of human behavior and process-oriented modelling frameworks*." A bold shift to transdisciplinarity is pivotal (Melsen et al., 2018).

Accordingly, major challenges still exist in the detailed parameterization of SES for the field of human-water systems (Wada et al., 2017; Xu et al., 2018), and there is a need to move toward increasing transdisciplinarity when addressing such systems (Melsen et al., 2018). Therefore, we propose an indicator-based, gridded approach for analyzing the global interaction of humanity and freshwater as a SES. The indicators for this analysis were designed to be transdisciplinary and to represent the social, economic, and ecological systems as comprehensively, parsimoniously, and coherently as possible. For the sake of transparency, our approach allows repeatability and extendibility, based on the principle of parsimony, followed by keeping the number of assumptions (indicators) at the minimum. Moreover, our requirement for the indicators is that (1) they need to be the dominant ones in current use in the policy domain by global and regional governance actors as well as by the scientific community, (2) they need to be available globally with full coverage of the Earth's land surface area, and (3) to be continuously updated, historical trajectories being available for several past decades.

Due to the diversity in hazards, Dilley et al. (2005) consider them as an additive composite. We are consistent to their approach in our formulation of ecological vulnerability (EV), as it is composed of natural hazards (Dilley et al., 2005), human footprint (Venter et al., 2016), and water scarcity (Kummu et al., 2016). Those are of primary importance on the ecological state of the system. Data sets of governance effectiveness (WGI, 2018), economy, and human development are used for adaptive capacity (AC) assessment. The difference between of AC and EV is interpreted as resilience.

In a series of analyses from major Asian river basins, we have developed for this purpose a multidisciplinary approach (Kattelus et al., 2015; Varis et al., 2014, 2012), which is here extended to the global level and aligned with the SES concept. For climate change analysis, the University of Notre Dame, Illinois, has developed an approach with some similarities to our own (Chen et al., 2017). This Notre Dame Global Adaptation Index also shares a vulnerability-resilience approach but targets vulnerability solely to climate change and readiness to improve adaptation.

Our analysis is crucial in two ways. First, it provides a global overview of the magnitudes and relations of an array of key factors that have influenced the resilience of river basins through developments in AC and EV globally. Second, it offers a platform for targeting scholarly and policy-related activities, as well as studies on geographic areas that are the most critical ones in terms of freshwater-related challenges and their resilience to potentially increased future pressures. Third, we address the concern of Ostrom et al. (2007) on the lack of operationalization of the key SES concepts (resilience, AC, and vulnerability): "*The caveat is, ... that it is difficult to translate the concept in practice, causing resilience researchers to resist systematically measuring or characterizing adaptive capacity ... operationalization and generalization are discouraged.*" (Engle, 2011).

2. Materials and Methods

We analyze the recent temporal evolution of EV, AC, and the resilience of the SES by country and river basin for all of the 309 large river basins in the world (i.e., areal extent ≥50,000 km^2). The smaller basins are aggregated into 232 units based on the coastal area of discharge by modifying the method of Meybeck et al. (2006). Accordingly, the study encompasses 541 geographical entities, which are analyzed using annual data spanning the period between 1990 and 2015.

2.1. The Composite Index Approach for Social-Ecological System (SES)

Our approach to SES is based on the concepts of resilience, vulnerability, and adaptation, which have been widely adopted for use in climate change, Earth systems, and sustainability sciences (Adger, 2006; Gallopín, 2006; Janssen & Ostrom, 2006). We apply the concept of EV to indicate the status of the ecological system and AC to indicate the ability of the social system to aid in balancing the ecological system. Resilience indicates the strength of AC in the presence of EV. All these key concepts have a plurality of definitions in scientific literature. Below we specify how we approach them in our study.

We use the Equal Weight Composite method for constructing the numerical indices for AC and EV. This is a common method in fields such as finance, economy, environment, and society when constructing composite indices from elements that are in wide policy-related use as such (e.g., Ding et al., 2018). Ideally, a composite index should be based on a theoretical definition, which allows individual factors to be selected, combined, and weighted in a manner which reflects the dimensions or structure of the phenomena being measured. Such an index is decomposable to its elements directly and is maximally transparent and parsimonious. Examples of such indices include the Human Development Index (HDI; UNDP, 2018), which is widely used in the United Nations system, and the World Bank's Governance indicators (WDI, 2018). When developing our approach, we are challenged by the trinity of parsimony, representativeness, and pragmatism. We aim at covering as much of the sphere of AC and EV with as few indicators as possible, while ensuring the wide use of our indicators for policy support and even in public communication.

As indices derived from several fields are not expressed in commensurable units, a rescaling is needed in order to make the indices scale independent. We eliminate the potential outliers from the data by using the observations between the 95th and 5th percentiles and thereafter use the min-max normalization method (e.g., Theodoridis & Koutroumbas, 2008) for rescaling all indices and their components globally into the range [0, 1]. Using that rescaling, the value 0.5 in AC and EV indicates that the entity under concern is at the midrange of the sample minimum and maximum. Resilience is min-max normalized to the range [−1, 1], the value 0 indicating the global mean range value, for reasons described below. Before the normalization, we create a harmonized gridded data set with 5 arc min-resolution (~9 km at the equator) with a unified land mask. The composite indices for AC and EV are calculated as the arithmetic mean value of their three factors, and we thus consider the three factors to be equally important for resilience (with the economy getting slightly more emphasis as it also constitutes one third of HDI). All of our input indicator data are published and available in openly available data repositories (Table 1). Output data derived from our analysis is availabe at https://doi.org/10.5061/dryad.h2v2398.

We also cluster the world basins spatially into seven groups, characterized by the trend patterns in AC, EV, and resilience from the Mann-Kendall trend test and the sign of the resilience (negative/positive) for the years 1990–2015. Hence, we use five parameters for the clustering.

2.2. Adaptive Capacity (AC)

For AC, we use the following definition (Adger et al., 2011): "*Adaptive capacity refers to the preconditions necessary to enable adaptation and the ability to mobilize these elements. It is represented by the set of available resources and the ability of the system to respond to disturbances and includes the capacity to design and implement effective adaptation strategies to cope with current or future events. Resources include physical capital, technology and infrastructure, information, knowledge, institutions, the capacity to learn, and social capital.*"

Table 1
Introduced Indicators and Their Input Data Sets With Their Spatial Resolution and Key Statistics

Overall indicator	Indicator	Input indicator	Source	Spatial resolution
Resilience (AC – EV)	Adaptive capacity (AC)	Government Effectiveness	WGI (2018)	National
		Gross Domestic Production per capita PPP (USD)	Kummu et al., 2018a, 2018b)	5 arc min
		Human Development Index	Kummu et al., 2018a; Kummu et al., 2018b)	5 arc min
	Ecological vulnerability (EV)	Human footprint	Venter et al. (2016)	1 km^2
		Natural hazards	Dilley et al. (2005)	2.5 arc min
		Water scarcity	Kummu et al. (2016) and Wada et al. (2016)	30 arc min

Note. PPP = purchasing power parity.

AC, in our terminology, thus encompasses the social part of the SESs; both the reactive and proactive facets as articulated by many scholars (e.g., Engle, 2011; Tompkins & Adger, 2005) and quoting Lutz and Muttarak (2017): "*... includes societies' important aspects of societal change that affects adaptive capacity*."

Our Equal Weight Composite Index for AC is derived from the classical 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 the human individual as well as institutions, law, and their implementation (Rössner, 2018). The global indicators used for the operationalization of the concept are governance, economy, and human development (Figure 1). These three indicators—alike those that we use to indicate EV—are those used dominantly by both governance and scholarly communities globally; they are openly available, continuously updated, and historical time series are available for several decades.

To describe the quality of governance, we use the World Bank's national level data set of "Government Effectiveness" (WGI, 2018) for 1996–2015 (Table 1). This index indicates "*... the quality of public and civil services and the degree of their independence from political pressures, together with the quality of policy formulation, implementation, and the credibility of the government's commitment to them*" (WGI, 2018). For the years 1990–1995, the value for 1996 is used. Due to its definition, the index is country specific and not gridded. To represent economy and human development, we use subnational data of GDP per capita purchasing power parity (purchasing power parity in USD) and HDI, respectively, from Kummu et al. (2018a). The missing years in the subnational data were filled by temporal interpolation using national data. The GDP values were log transformed to allow scale independence of the indicator: It is common in econometrics to consider GNP as an outcome of an exponential process (Gelman & Hill, 2007; UNDP, 2018). For instance, a scale-invariant measure is typically used when referring to economic changes, progress or volatility, or many basic economic policy instruments such as the interest rate. Using a logarithmic scale for GDP allows compatibility of our approach with mainstream econometric analyses.

Figure 1. A schematic of the factors included in our analytical approach to river basin resilience analysis.

2.3. Environmental Vulnerability (EV)

Whereas our definition of AC encompasses the active component of a SES, our take for vulnerability then is understood as the latent, passive part of it. This is why we call it EV. Adger (2006) reviewed the various research traditions of vulnerability to environmental change and noted that there are too many different formulations and research needs to allow universally acceptable formulations for the concepts of vulnerability and resilience (see also Berkes & Folke, 1998). It is also worth understanding, as several studies (Adger, 2006; Cutter, 1996, 2003; Engle, 2011; Janssen & Ostrom, 2006) point out, that different research traditions draw demarcation lines in very different ways between the concepts of resilience, vulnerability, and AC, and therefore, case-specific specifications are needed.

Among the many traditions of defining the concept of vulnerability, Adger (2006) sees two principal research directions relevant to SES, namely, those stemming from the social and those from the ecological side. He sees the classical pressure-release model (Blaikie et al., 1994) as one of the bridging approaches between those traditions. The pressure side is in alignment with our "latent" definition of vulnerability, whereas the release side falls to our AC, since it encompasses an actor-centric part of a SES. With this division, we follow the interpretation of "vulnerability as exposure," as classified by Cutter (1996), who also sees two traditions in vulnerability research: the one being "vulnerability as exposure" and the "vulnerabilty as a social condition" being the other. This division is close to the division of Adger (2006), mentioned above.

The reason to demarcate between the latent and actor-centric parts of a SES along the dividing line of the ecological and social parts of a SES is the following. We want to have a clear demarcation between the social and ecological systems, which tends to be subject to confusion and inconsistency in the literature (Engle, 2011; Janssen & Ostrom, 2006; Lang et al., 2017). Moreover, in a long-term macroscale study, it is appropriate in our view to consider the society as a whole as an active part of a SES and the ecological system as the latent one. Nevertheless, since the interpretation of the concept of vulnerability is highly context and scale-dependent (Adger, 2006; Berkes & Folke, 1998), we do not want to undermine the concept of social vulnerability in general. In contrast, in many conditions this term is of high worth, such as when addressing societal disparities within a society and groupings of people who are not empowered or otherwise capable of improving their conditions and building their capacity.

Our composite index for EV is derived from the disciplines of natural capital and ecosystem health. That literature is highly diverse, but one typical approach is to analyze natural capital stock together with the degradation of ecosystems, given a certain management context (see, e.g., Costanza & Daly, 1992). As we use river basin as the basic geographic unit for our analysis, we use water scarcity as an indicator for natural capital. Degradation of ecosystems is indicated by human footprint, and the management context is included as the variability of the resource. 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.

For water, several concepts exist for sustainability. For example, water security has very specific definitions reflecting the user's own agendas and perspectives (Cook & Bakker, 2012; Grey & Sadoff, 2007; UNU/INWEH, 2013; van Beek & Arriens, 2014; Zeitoun et al., 2016). To ensure a reliable index of sustainability of water resources, we included water scarcity into EV to reflect available freshwater resources (for both nature and humans) and anthropogenic water use, representing the hydrological complexity of a given area (Wada et al., 2016). Water scarcity is calculated as a combination of water stress (ratio of water use to availability) and water shortage (per capita water availability), as shown in equation (1). This formula is based on Falkenmark matrix (Falkenmark, 2013, among her other articles), in which both of these indicators are present. Water stress and water shortage represent different kinds of pressures on water resources (see more details in Kummu et al., 2016, and Falkenmark, 2013) and this way we are able to take both of them into account. The original data (Kummu et al., 2016; Wada et al., 2016) include both surface waters and groundwater aquifers. They were modified to take into account spatially explicit environmental flow requirements, based on "variable monthly flow" method by Pastor et al. (2014). Before calculating water scarcity, both water stress and shortage were scaled so that the extreme water stress and shortage get a value of 1. Annual values were interpolated from decadal values over the study period.

$$W_{\text{scarcity}} = \sqrt{{W_{\text{stress}}}^2 + {W_{\text{shortage}}}^2} \tag{1}$$

where W_{scarcity} is water scarcity index, W_{stress} is water stress, and W_{shortage} is water shortage.

Human footprint—aggregating the extent of built environments, crop land, pasture land, human population density, nighttime lights, railways, roads, and navigable waterways—is included in EV as it indicates the cumulative impact of anthropogenic pressures to nature (Venter et al., 2016). The data exist for years 1993 and 2009, which we use for linear interpolation and extrapolation to get continuous time series for our study period. It is complemented by natural hazards because the human footprint does not include extreme events, which are important factors in the interplay of a SES. The used natural hazards indicator (Dilley et al., 2005) measures a combination of multiple hazards for a given area, combining the following data: cyclones, drought, floods, earthquakes, volcanoes, and landslides. As no reliable time series exists at grid scale, we use a long-term average.

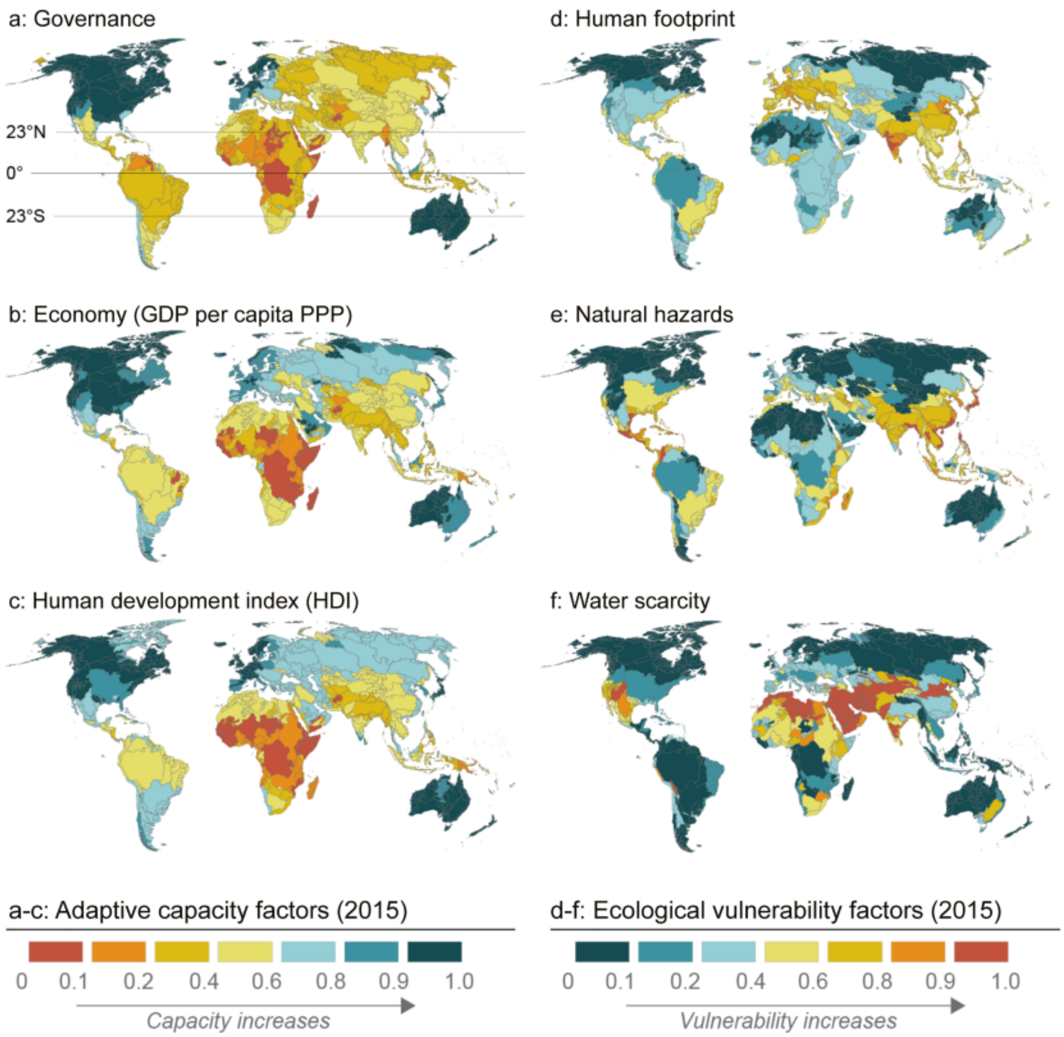

Figure 2. (a–f) Geographic distribution of adaptive capacity and ecological vulnerability indicators in 2015. All indicators are scaled globally; the value 0 represents the lowest value and a value of 1 the highest value in the data set after censoring 5% of the lowest and highest values as outliers. The scale is arithmetic, showing equal spacing of the units. GDP = Gross Domestic Product; PPP = purchasing power parity. Data availabe at https://doi.org/10.5061/dryad.h2v2398.

2.4. Resilience

For resilience, we use the definition from the same source as for AC (Adger et al., 2011): "*the capacity of a system to absorb disturbance and reorganize while undergoing change so as to retain essentially the same function, structure, identity, and feedbacks*." Accordingly, EV is related to AC; the higher the EV, the more AC is needed to yield a certain level of resilience. The numerical range of the resilience is from −1 to 1. The value 0 indicates that the resilience value is at the global midrange, and it does not imply that AC is in "balance" with EV. This normalization approach permits us not to fix any commensurable scale between EV and AC; we merely express how they fall in the frequency distribution of global data of 2015.

To sum up, the formula for resilience introduced in this study can be seen as a parsimonious approach to relate AC to EV and to analyze their spatial and temporal characteristics on a basin-scale resolution.

3. Results

3.1. Factors of Adaptive Capacity (AC)

The results of the governance analysis for 2015 are shown in Figure 2a. The figure shows that the lowest values (<0.1) are apparent mainly in several basins within Africa and the Arabian peninsula between the tropics. In contrast, Western Europe, North America, Japan, and Australia show the highest values. In terms of economy, Sub-Saharan Africa is even more clearly the weakest area with the lowest AC (Figure 2b). In Asia, a belt extending from central Asia to Indonesia is well below the midrange (<0.4), and the same applies to South America's eastern parts. Areas with the strongest economy are found in North America, Western Europe, parts of the Arabian Peninsula, the southernmost parts of South America, and parts of Arctic Russia. On a global scale, the HDI is clearly the lowest in Sub-Saharan African basins and in southern parts of the Arabian Peninsula (Figure 2c). Challenges in human development were mostly found in the same areas as in the case of the economy (Figure 2b).

When calculating the composite index of the three AC factors (governance, economy, and HDI) for 2015 (Figure 3a), most of Sub-Saharan Africa appears to be the world's weakest area in terms of AC, accompanied by Afghanistan and parts of Yemen. The highest AC is found in basins in North America, Australia, Europe, parts of Russia, and coastal basins of East Asia. AC is currently the lowest in the zone between the tropics, and it increases toward polar areas (Figure 4).

3.2. Factors of Environmental Vulnerability (EV)

The highest human footprint values are located in very few basins, namely, in densely populated basins in central-western India and in China close to Beijing. Areas with increased values are concentrated on a coastal belt from Japan to Pakistan, as well as in continental Europe. Certain areas in other continents also show high human footprint, mainly in coastal regions (Figure 2d).

Natural hazards are particularly high in coastal areas of Central America and eastern Asia. These regions, together with many eastern parts of other continents, portray high hazard risk related to tornados, winter storms, and wildfires (Figure 2e). In terms of water stress, a distinct belt of significant scarcity stretches from Morocco to Arabian Peninsula and central Asia to North China Plain (Figure 2f). Most water-stressed areas are mainly located on both sides of the tropic of cancer (from 15° to 45°N). There is an asymmetry since the Southern Hemisphere does not show such a water-scarce band. This is due to the essentially higher concentration of population to the Northern Hemisphere (7/8) in comparison to the Southern Hemisphere (1/8; Kummu & Varis, 2011).

The composite index for EV for the year 2015 (Figure 3b) points out that there is a particularly challenging zone around and north of the tropic of cancer. This zone includes most areas between Japan, Vietnam, and the Mediterranean coast. North of this zone, the EV is much less pronounced. In the Southern Hemisphere, no such concentration of areas with increased EV can be detected. The latitudinal variation in EV is modest, with the highest EV between 25 and 50°N (Figure 4).

3.3. Resilience

Globally, Asia (excluding Russia and Japan), Arabian Peninsula, and Africa include large areas in which the resilience falls below the world's midrange. Interestingly, there is a concentration of low-resilience areas around the Indian Ocean, both on the Asian and African sides (Figure 3c). In addition, the North China Plain is partly in this category, and parts of Morocco and parts of Peru belong to the world's least resilient areas. Globally, the areas with the highest resilience are somewhat similar with those on the AC maps. The only difference occurs in the belt of higher EV, but otherwise, resilience increases toward poles.

Those areas may not be the most surprising ones to fall in that category but perhaps more astonishing is to realize that the drivers to that are fundamentally different in Africa and Asia. In Africa (except for Morocco), the weak resilience is due to low AC (Figure 3a), whereas in Asia it derives from high EV (Figure 3b). In Asia, EV is mostly very high, but at the same time, AC is essentially higher than in Africa.

3.4. Temporal Development

The world has seen plenty of changes with regard to the different components of EV within the relatively short period from 1990 to 2015. We summarize those changes in the maps of the temporal evolution of combined indicators for AC (Figure 3d), EV (Figure 3e), and resilience (Figure 3f). AC has been in the increase in most parts of the world (Figure 3d). Most notable growth has taken place in China and in certain parts of northern Russia (Yamalo-Nenets autonomous area, which produces 90% of Russia's natural gas). Other fast growers include the areas from Turkey, Southern Caucasus, and Iran to the central Asian shores of the

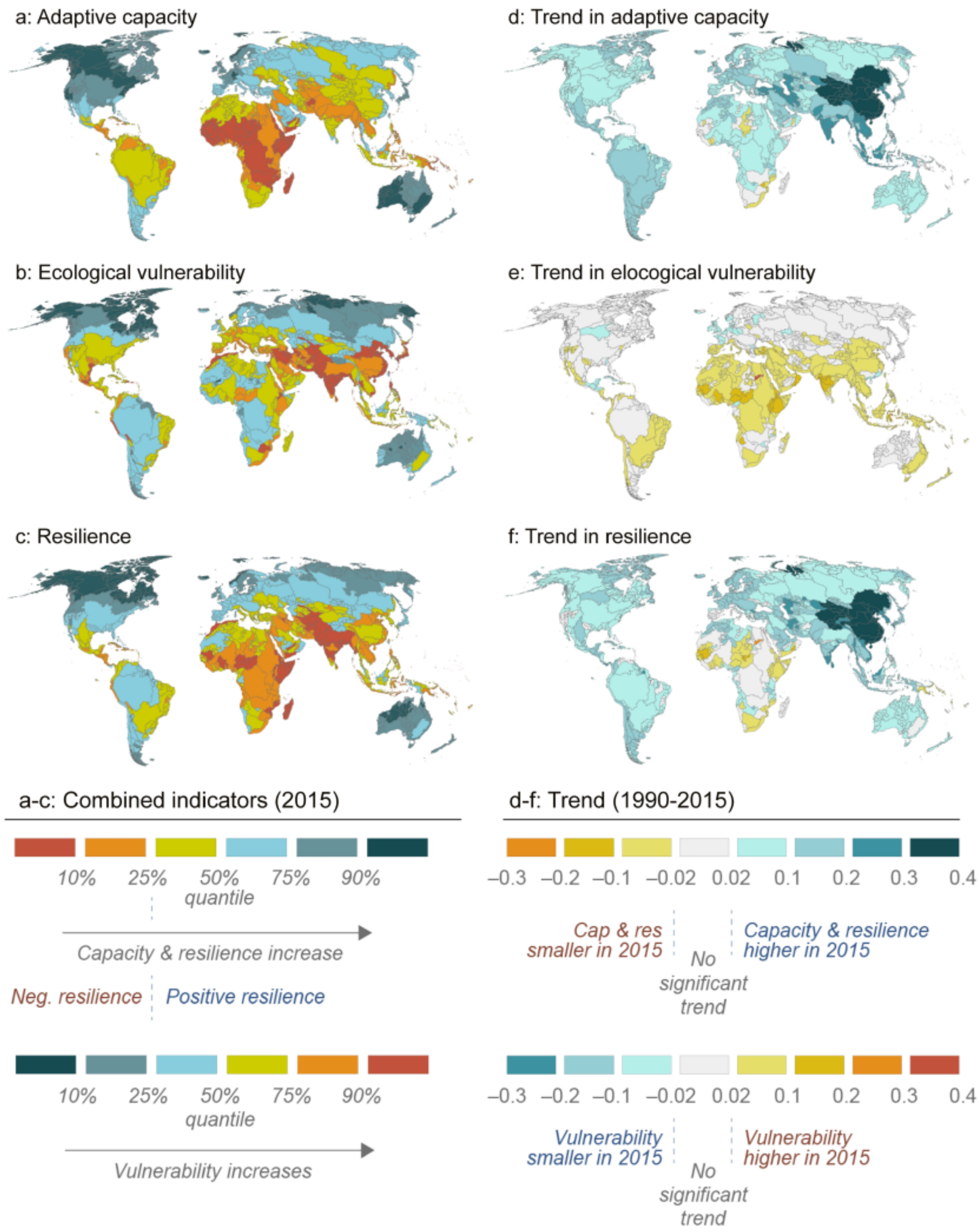

Figure 3. Results for the world's river basins: composite indices. (a) Composite index for adaptive capacity (AC; governance, economy, and human development index), (b) ecological vulnerability (EV; water scarcity, human footprint, and natural hazards), and (c) resilience (difference between AC and EV, negative resilience meaning that EV is higher than AC) index maps for 2015, and their trends, significance of the trend evaluated with Mann-Kendall trend test, between 1990 and 2015 (d–f). Data availabe at https://doi.org/10.5061/dryad.h2v2398.

Caspian Sea and some parts of South and Southeast Asia. AC has decreased in only a few individual basins in Africa and East Timor.

EV, in turn, has been growing, too, although in majority of the basins the changes have been modest (Figure 3e). North China Plain, parts of India and Turkey, coastal areas of Morocco, Algeria, and Tunisia, as well as parts of the Nile Basin have shown the most drastic increase. The stripe from China through India, Iran, and West Asia to the Mediterranean region and all the way to central Africa has been growing

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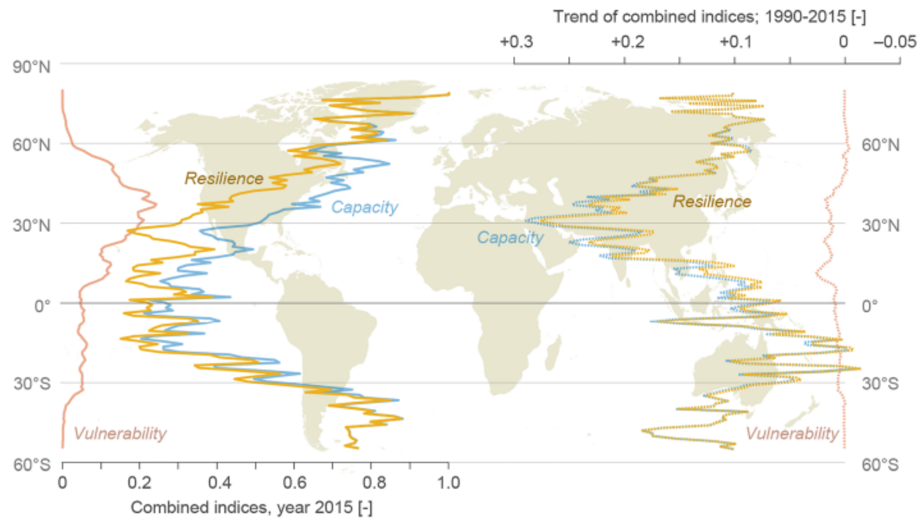

Figure 4. Latitudinal view on the composite indices (left) and their trend (right) over 1990–2015. Capacity refers to adaptive capacity and vulnerability to ecological vulnerability.

in EV but more modestly. So have done the crowded coastal parts of South America and Mexico. Some smaller areas in Europe, North and Central America, Asia, and Africa have experienced decreasing EV.

As the EV has stayed relatively stable over time, the trend in resilience (Figure 3f) is globally strongly controlled by the temporal trend of AC (Figure 3d). Yet certain positive development in AC has been outset by increasing EV in areas such as China, Southeast Asia, India, Iran, and Turkey. Africa, Yemen, and East Timor include areas where resilience has been decreasing. Globally, EV has experienced modest changes compared to AC and resilience. The latter ones have increased especially in the belt from 25°N and 50°N (Figure 4), indicating that the index values in these regions have recently undergone improvements. Additionally, this belt is inhabited by the majority of the global population (see also Kummu & Varis, 2011). To conclude, we demonstrated the latitudinal sensitivity of the indices and their trend in time, which derives from the continental differences of the examined indices.

3.5. Spatial Clustering

We performed a K-Means clustering in order to identify and classify the main development trends in AC, EV, and resilience, over the period from 1990 to 2015. The following seven clusters were identified (Figure 5):

- A Areas with a very fast increase in AC and growth in EV, leading to improved resilience. Nevertheless, the base level of resilience remains low. North China Plain and the Yangtze Delta and surroundings, plus some smaller areas in China and South India, are included in this category.
- B Areas where both AC and EV have increased but less rapidly than in the Cluster A. The AC development has been faster, and the resilience has improved. These areas include large parts of China, some basins in the Philippines and Indonesia, and a few basins in every continent except in Australia.
- C Areas with a moderate increase in AC without changes in EV belong to this category. Resilience has remained above the world's midrange over the study period. Basins from all regions, particularly Europe, central Asia, and South America, are included.
- D Similar past and present resilience as in Cluster A but less progress in AC. The basins of Syr Darya, Yalu, Mekong, and Irrawaddy are examples of this cluster and so are a major part of basins in South Asia, Iran, Indonesia, and the Philippines; coastal areas of the western Maghreb; and a few smaller basins in Africa and Latin America.
- E A modest increase in AC combined with no significant changes in EV, which lead to a modest improvement in resilience. The base level of resilience is high. Approximately 40% of the basins belong to this group, covering most parts of North and South America, Europe, Australia, Russia, and Mongolia, together with some parts of Africa, the Arab Peninsula, and Southeast Asia.
- F Slow improvement in AC, combined with increased EV. Resilience is on the decrease. Most of Sub-Saharan Africa belongs to this category, together with small parts of West Asia and Latin America.

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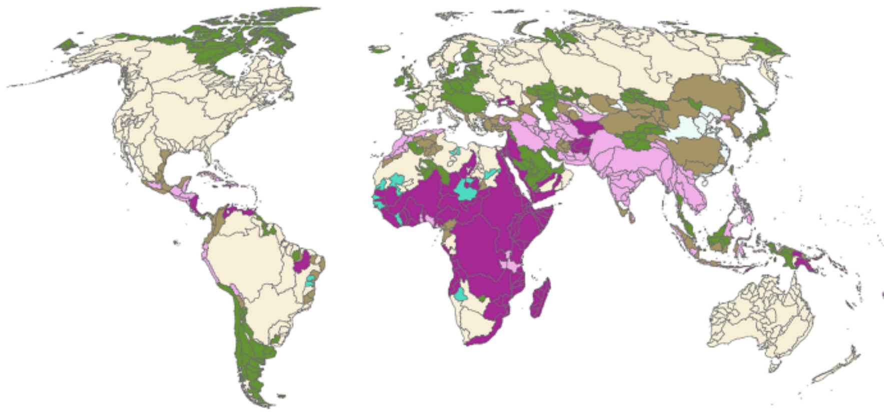

Basin clusters based on their trend over 1990-2015

		Trend in capacity	vulnerability	resilience	***Resilience in*** 1990	2015
A. (*n* = 11)		++++	+	++++	–	–
B. (*n* = 60)		+++	+	++	–	+
C. (*n* = 107)		++		++	+	+
D. (*n* = 70)		++	+	+	–	–
E. (*n* = 215)		+		+	+	+
F. (*n* = 69)		+	++	–	–	–
G. (*n* = 9)			++	–	+	–

Figure 5. Spatial clustering of the world's river basins on their trend between 1990 and 2015. Capacity refers to adaptive capacity, while vulnerability to ecological vulnerability.

G This cluster shows a decrease of resilience, with an alarming combination of increasing EV and stagnant AC. A few African basins belong to this cluster.

4. Discussions

4.1. Social-Ecological System (SES) Approach

We provide the first global analysis of vulnerability, AC, and resilience of the world's river basins, using the SES approach (as defined by Adger, 2006; Berkes & Folke, 1998; Gallopín, 1991; Janssen & Ostrom, 2006). The SES concept proved to be appropriate to the analysis of river basins in which the human population needs to harness the ecological and natural resources base in a sustainable way. In other words, river basin provides a plausible platform for the analysis of a symbiosis of ecological and social systems. We include the social factors under the concept of AC and the ecological factors under the concept of EV. The reason for this approach is the following: we consider social systems as principally active systems, which are (or should at least be) driven to a considerable degree by conscious actors. This is examined with the temporal analysis over a few decades. Within the process of societal development and progress, there is a fundamental, active component of building capacity for mitigation and coping better with changes, not solely for adapting to those (cf. Lutz & Muttarak, 2017). The term of adaptation, which is behind the idea of AC, has its roots in biology, where it refers to the Darwinian response of an organism to its surrounding environment (Engle, 2011). In social sciences, particularly in anthropology, adaptation is a reaction of changing conditions, usually in a long term (Smit & Wandel, 2006). However, in contemporary societies, this overly passive ecological view is too one sided. Societies are, or at least should be, capable to build actively their capacity in terms of human development, governance, economy, and in other relevant aspects (Lutz & Muttarak, 2017).

We show that even in the time frame of a quarter of a century (1990–2015), the world has undergone remarkable development in all the regards that we include in AC, and those changes have not been distributed evenly (Figure 3d). Certain parts of the planet, particularly in East and South Asia, have been very committed, conscious, and successful in improving their economy and development processes at the national level. In contrast, large areas, particularly in Africa and West Asia, have not been able to build their AC in a similar way. On the other hand, EV appears to be more stable in time, due to the input factors that are not sensitive to sudden year-to-year changes, such as climate, infrastructure, and land use pattern.

Resilience is an ancient word used for many meanings (Alexander, 2013). Within SES literature, its conventional, ecologically rooted interpretation remains quite frequent, although the social part of a SES follows different principles than the ecological one (Berkes, 2007). The groundbreaking work by Holling (1973) on adaptive management was based on the ecological resilience concept, in which the system has an equilibrium state, to which it bounces back after a perturbation. A voluminous conversation took place whether a system may have more than one equilibrium state (Connell & Sousa, 1983; Folke, 2006). As defined, a tipping point was reached if a system did not bounce back to its original equilibrium but instead was driven to a different equilibrium state. Engle (2011) continued on the same theme: "*perhaps it is the human nature to resist change and to maintain status quo, because decision makers often use the concept of resilience to evoke a sturdy, robust or stalwart state of affairs; one that can quickly bounce back to its initial conditions*." This view may hold best for operational and tactical, short-term, responsive policymaking, if it holds at all to social systems in situations other than single accident type of incidents. Yet for societal settings that encompass longer time perspectives such as decades, this interpretation is fundamentally misleading.

The present analysis is a good example. Population growth, urban development, and educational improvements together with changing human footprints have modified the world's river basins tremendously over the study period. It would be naïve to think that most of the river basins of the planet could somehow "bounce back" to the state in which they were in the year 1990. Ecologically, this might be desirable in many cases but not by far universally. Socially, this way of thinking does not hold. Human demographics have undergone changes in terms of population size, age distribution, life expectancy, education level, and spatial distribution, and the economic and industrial systems have evolved vastly. There may be several cases in which the policy makers and/or scholars have been prone to "*resist change and maintain status quo*," requoting Engle (2011). Yet those countries may be among those that have collapsed, become sources of international refugee problems, or been driven to conflicts due to excessive stagnation within the social and economic scene (Varis, 2010, 2014).

Our recommendation, particularly to countries that show low AC (see Figure 3a), would be the full opposite. Those countries, in most cases, may suffer from conditions of societal stagnation in which the resilience shortcomings accumulate fast due to population growth (which is partly due to underdeveloped social and economic conditions, following often from stagnation) and inadequate governance capacity. The higher the EV, the more stringent investment into AC is needed to people and to the social system as a whole.

4.2. Global Resilience Analysis

Our purely data-based global analysis is able to identify many of the areas with largest challenges in sustainable development and peace (Figures 3a–3c). Such areas include Syria, Iraq, Afghanistan, Pakistan, the Horn of Africa, and Mozambique (cf., e.g., UCDP, 2018). Large areas of India, Bangladesh, and Myanmar, as well as Eastern part of the North China Plain show also particularly low in resilience. In terms of AC alone, majority of African basins fall into the lowest 10th percentile (Figure 3a), while only the analysis of resilience (Figure 3c) highlights the most critical areas, namely, Somalia and parts of Nigeria as well as Yemen in Middle East, that suffered from severe food insecurity in 2017 according to the United Nations Office for the Coordination of Humanitarian Affairs (OCHA).

Whereas the temporal resilience development across the planet is toward positive direction, the development in Africa is in many parts alarmingly reverse to this. This underlines the concerns related to the low resilience areas of that continent. Our analysis includes no predictive features, and it is purely diagnostic in nature, being based on globally observed conditions of the years 1990–2015.

When looking at the AC and EV jointly, it is crucial to understand that these two factors are not commensurable, and both are globally scaled. If, for instance, a particular area has a value of 0.5 for both, it does not indicate that AC is necessarily sufficient to the tackle the EV. It means simply that this area is at the world's statistical midrange in terms of AC, EV, and resilience.

Perhaps the most striking result globally is the profoundly different vulnerability-capacity profile of Africa and Asia (excluding the northern part of Asia). They both have low resilience but due to different root causes. Africa is dominantly subjected to low AC, while Asia is particularly troubled by high EV due to water stress, natural hazards, and human footprint, with areas suffering from weak AC (Figure 2). This is alarming especially in densely populated basins in India and central Asia.

Most of the global-regional freshwater assessments have not detected this pattern. However, the water supply and demand scenarios by the International Water Management Institute (IWMI, 2000; Seckler et al., 1999) indeed made a distinction between physical and economic water scarcity. Their scenarios share certain features with our observations. Yet they put most of Australia, Southern part of China, Southeast Asia, Indian coastal areas, Latin America, and Sub-Saharan Africa to a single category—dominated by economic water scarcity—whereas our results give very different and far more diverse results for those areas (Figure 3). For instance, our analysis suggests that Australia is in an essentially more favorable position in terms of resilience than Africa. These areas have similarities in EV, but the AC of Australia is remarkably higher than Africa's which in our methodology yields higher resilience for Australia.

The identification of the different root causes for water problems in Africa and Asia is visible also in the maps of the analysis of The Notre Dame Global Adaptation Initiative (Chen et al., 2017), although the authors do not particularly mention it. In the analysis of Vorosmarty et al. (2010), we can see this phenomenon, too, but neither there is explicitly noticed by the authors. The results show how Africa is mostly a low-threat area within a global analysis of "human water security and biodiversity," but it stands more out after "accounting for water technology benefits." Although the study of Vorosmarty et al. (2010) only addresses water sector technologies, it gives results that have some aligned features in the Africa-Asia comparison with ours.

Instead, Padowski et al. (2015) analyzed vulnerability of selected countries across the globe with regard to endogenous and exogenous factors that affect the water sector. They propose that Yemen, Jordan, and Djibouti are the most vulnerable nations. Our resilience results (Figure 3c) are more comparable to theirs than our EV results (Figure 3b). We identify larger areas in the least resilient category (Figure 3c). They also identify countries such as Chile and Argentina among the top 25 vulnerable nations—in the same category with Chad and Tunisia. Our results propose the two latter ones as weak in resilience but not the two first ones—they are above the world's midrange in resilience. Compared to our novel approach, which is able to identify the differences between Asia and Africa, Padowski et al. (2015) do not propose any clear systematic difference between these continents.

The Water Poverty Index (Sullivan, 2002; Sullivan et al., 2003) has been used extensively in locally targeted studies, yet some global results are available. Those results tend to dominantly rank economically and socially disadvantaged ("poor") countries and/or areas lowest and the "rich" countries highest (Cho et al., 2010; Lawrence et al., 2002).

Gain et al. (2016) addressed water security globally, in relation to United Nations Sustainable Development Goals. They have an aggregated variable called accessibility of water services. With regard to Africa and Asia, most of Sub-Saharan Africa, Afghanistan, East Timor, Korean Peninsula, and some other areas show particularly low accessibility. This map has certain similarities to our AC map (Figure 3a) but does not incorporate the EV feature of freshwater systems. Accordingly, like the other studies referred to above, it does not include the pairing of social and ecological systems. This is a major shortcoming of those analyses.

The apparent difference between Africa and Asia is a topic, which would deserve further research and policy alert. This observation shows clearly how much more potential—and urgent need—there is for capacity building in Africa than in any other continent and how the gap between Africa and other continents has been widening rapidly (Figures 3d and 3f). Africa is subjected to an evident danger of stagnation in terms of social progress, which may lead to an increasing gap between AC of the societies to tackle the challenges that they are facing.

4.3. Ways Forward

River basins are systems that are deeply intertwined with their surroundings, having a variety of societal and ecological links from local to global systems. Whereas a river basin is a natural unit of freshwater, in practice, freshwater is governed in a mix of river basins, administrative units, and economic areas such as economic corridors and food production units. Technical solutions typically create impact on a basin level, whereas policies are often done by administrative regions. The present analysis is easily extendable to include also the latter (Varis et al., 2014). Further extensions of the analysis would include combinations of ecological-climatic zones, ecological hot spot areas, climate change, urban areas, and/or economic reference units with river basins. These would provide marked extensions to the understanding of the vulnerability, AC, and resilience of freshwater in the global and regional perspectives.

In terms of used indicators, we see several avenues to develop our approach further. In particular, AC factors should be developed side by side with the analyses of water scarcity and those that combine agricultural production, ecosystems, climate change, and other aspects, as was described in the introduction. We see that the combination of AC and EV forms a crucial component in relating such analyses to sustainable development. In addition, natural hazards could be easily looked in more details. We used the multihazard index (Dilley et al., 2005), and it is readily decomposable to six categories (cyclones, drought, earthquakes, floods, landslides, and volcanoes), which all are interesting components of vulnerability per se. Similarly, the approach could be extended to more elaborate social analyses including factors such as Gini Index for income distribution and inequality-related extensions of the HDI (UNDP, 2018). Transboundary water questions would suit particularly well to the method. One further idea for future studies would be to investigate whether some of the indicators used by Padowski et al. (2015) and Gain et al. (2016) were useful to be incorporated in our approach.

Regional analyses of critical areas such as Sub-Saharan Africa, Middle East, and North Africa would be thrilling. The contrasting drivers of resilience in Africa and Asia indicate that they need to be studied individually. We performed already a geographically focused analysis for China (Varis & Kummu, 2019) and revealed the spatial heterogeneity of China's resilience map as well as the ongoing polarization of the country with regard to AC, EV, and resilience. With the earlier development versions of the same methodology, we have addressed some targeted areas including central Asia (Varis & Kummu, 2012), the Asia-Pacific Rim (Varis et al., 2012), and China (Kattelus et al., 2015; Varis et al., 2014).

The availability and spatial resolution of global databases on all the aspects that we include in this analysis is in rapid growth. Therefore, the approaches to the geospatial analyses of the character that we present are timely. The analysis of gridded, high-resolution data which represent several disciplines calls for operational, numeric approaches such as the one that we present. Transparent, policy-relevant indicators provide one promising approach to investigate such complex SESs.

5. Conclusions

We present for the first time a global analysis of AC, EV, and resilience of world's river basins, which is based systematically on the SES approach and the three pillars of sustainable development: economic, social, and ecological factors. We do this by using spatial mapping and analysis and analyzing the development trajectories during the period 1990–2015.

The approach allows new insight into resilience of the planet's river basins to present and future ecological stresses that they are facing and relates those to the AC of societies. Our analyses can be concluded on a continent-scale into the following findings:

1. Globally, the areas with the lowest resilience can be found in the Asian and African continents. In Asia, the most challenging areas are in the South, Central, and western Asia. In Africa, most of the continent has notable resilience shortcomings and particularly challenging are the Horn of Africa and some other coastal areas of east Africa as well as in Morocco. Our findings underline that the root causes of the resilience challenges differ profoundly between those continents.
2. Most of Africa is not significantly water scarce nor has a very high human footprint. However, the swift accumulation of many parallel social factors brings down its resilience. Consequently, Africa suffers largely from low AC, which does not improve intact with the relatively low but increasing EV. This makes the continent's river basin management increasingly challenging.
3. Asia includes a zone from China and Vietnam to the Mediterranean which is among the world's most troublesome areas in terms of EV. This belt also covers most of the other Mediterranean coastal areas as well as parts of Mexico. The AC of that zone varies largely, being the lowest in South and central Asia, particularly Afghanistan. However, it is mostly much higher than in Africa, and it has seen remarkable improvement during the study period. EV is very high, but AC is catching up gradually.
4. Asia (excluding northern Asia) and Africa differ thus fundamentally from each other as Africa has dominantly a low AC, while Asia has principally far higher EV yet includes also areas with deficiencies in AC.

5. Since 1990 large areas of the world have become more resilient vis-à-vis freshwater and river basin management challenges. This is mainly due to the growth of AC. Such areas can be found in all continents but most remarkably in eastern parts of Asia, China in particular. This is largely due to quite fast and country-/region-specific societal changes in the study period. We claim that this is too often overlooked in common discussions and also in scholarly work on natural resources.

The basic question is whether this increasing capacity will be used to mitigate the further degradation of the ecological systems or for turning the tide toward ecologically more sustainable development. Our recommendation is to pay increased attention to reversing globally the increasing EV, particularly in areas which show already high vulnerability and those which show deficient in AC. Equally, we recommend dramatic increase in the attention on shortages and too slow growth of AC in the African continent as well as other areas that manifest obvious deficiencies on that side.

Investigating the planet's freshwater challenges and river basins through the SES framework provides plenty of new insight and opportunities both for scholarly and for policy-related analyses. Freshwater management is an interplay of human and ecological systems, and looking systematically at them both, their interplay provides crucial, policy-relevant insight in the rapidly advancing global-scale freshwater resources studies which in our view are today still far stronger in physical-ecological aspects than in the societal side.

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