Water Security 1 (2017) 36–45

Contents lists available at ScienceDirect

Water Security

journal homepage: www.elsevier.com/locate/wasec

Four dimensions of water security with a case of the indirect role of water in global food security

Olli Varis *, Marko Keskinen, Matti Kummu

Water & Development Research Group, Aalto University, Espoo, Finland

ARTICLE INFO

Article history:
Received 22 December 2016
Received in revised form 9 June 2017
Accepted 12 June 2017
Available online 11 July 2017

ABSTRACT

Water security is a concept with several aspects and dimensions. We identify four such dimensions, each consisting of two complementary aspects: direct-indirect, macro-micro, technical-political, and peace-conflict. We investigate this idea with a case study focusing on one aspect along each dimension. The case analyzes the indirect role of water for food security at global scale, using quantitative spatial approach. We find such a case particularly interesting, as food production is the planet's biggest anthropogenic water user and food security is thus in many ways interwoven to water security. We analyze where water scarcity hampers food production, and how food trade influences this interplay. We also consider how societal resilience relates to these themes, and identify regions that face particular challenges in this regard. With this we systematize the concept of water security and link it with to issues of vulnerability, resilience, and, ultimately, sustainability.

1. Introduction

Freshwater has been recognized as one of the fundamental elements of the sustainability of the planet's key life-supporting functions [52,58]: it is interwoven in almost all processes and constituents of natural ecosystems and human societies.

Water is a sector in its own right, but at the same time water is a part of almost any conceivable economic sector, as well as the lifeline of ecosystems and the planet's life-supporting system. Therefore, the task of managing and governing water has innumerable facets. This may lead to conflicts and tensions, as well as challenges even in conceptualizing what water management and water governance mean, include and exclude. This challenge is clearly demonstrated by the perennial debate on what common, related concepts such as Integrated Water Resources Management and Water-Food-Energy Nexus actually mean [1,5,10,20,30,38,51,56,63]).

Water security has emerged as one of these deliberated concepts. It is growingly used as a term that captures in various ways our capacity to ensure availability and access to water by responding to various risks, vulnerabilities, insecurities, inequities and policy challenges that societies and ecosystems face due to variations and levels of either quantity or quality of water as well as water-related disasters [61]. Thus the concept can be seen to bring together water-related vulnerability with societies' adaptive capacity i.e. resilience to such vulnerabilities. At the same time, the concept includes the term 'security', which has many meanings depending on the context. Some understand it as national or political security, while others consider it e.g. as technical security or human security. Recent years have seen an array of reviews and analyses summarizing various analytic approaches and definitions to water security [3,12,17,26,35,43,61,62,77].

Zeitoun et al. [77] provide an analysis of two contrasting research approaches to complex water security policy challenges. One approach is labeled 'reductionistic', and it is seen to include technical, quantitative and macroscale dominated approaches that consider security through certainty and seek to reduce complexity through quantified analyses. The other approach is labeled 'integrated' as it views security through plurality and focuses on social and/or governance directed approaches and definitions. Examples of the former ones include analyses on interrelations of water availability and macroeconomic development [23,39,44,71], whereas the latter ones emphasize diversity of societies, disadvantaged echelons of the society, governance capability and so forth [4,42,59].

An important aspect of water security is that in many situations, it is felt indirectly through its impacts on other sectors, or it is caused by other sectors. Zeitoun [76] presented a "web model" for water security, which has (national-level) water security at the center, and is attributed to social and physical vulnerability. This center is surrounded by a sphere of six factors: National Security, Human/Community Security, Climate Security, Water Resources Security, Energy Security and Food Security. Such a broad definition was taken as the point of departure to our present study.

* Corresponding author.
E-mail address: olli.varis@aalto.fi (O. Varis).

http://dx.doi.org/10.1016/j.wasec.2017.06.002
2468-3124/

We investigate how water security influences and is linked to food security. This is due to food production's key importance on water demand as agriculture accounts for over 70% of all global water withdrawals and up to 90% of water consumption [32]. We include here the food availability part of food security that is only one part of the total food security system [15]: yet, for the sake of clarity, we call it food security in what follows. Consistent to the definition of Zeitoun [76], we look water security as a macro-level concept through social and physical vulnerability. We focus on food and leave other security concerns such as energy, climate and communities for further studies.

Our methodological goal is to develop a quantitative analytic approach to water security studies, because we see an opportunity for harnessing the rapid progress in global-scale, earth-system approaches in the water security context. Some of the most prominent ones include the following. Sood and Smakhtin [57] provided a comprehensive overview of most commonly used global hydrological models. Most sophisticated analyses are available on the water availability per capita and water use in relation to water availability [32,34,37,69,72]. Often such studies – including our present study – are juxtapositioned with analyses on agricultural production [31,36,46,47], water demand and climate change [21,54,67,68,70,74], ecosystems [22], energy demand [24] and upstream-downstream relations [22,40]. We think that studies such as these are attractive entry points to investigations on the intersectoral aspects of water security.

One stream of macro-scale, quantitative freshwater studies are due to multidisciplinary vulnerability analyses, which incorporate an array of factors that are related to social, economic and environmental aspects influencing either water resources governance or ecological status. These studies often are based on the triple bottom-line approach to sustainable development in which economic, social and environmental development are looked together. Geographically, water resources vulnerability assessments have had either national [11], subnational [50,73] regional [2,25,28,45,64–66] or global [41] focus. These studies are also an attractive entry point to macro-scale water security studies, as vulnerability is a term which is quite often associated to the water security (e.g. Zeitoun [76]).

We fusion in this analysis the water vulnerability approach to food availability analysis, in the global scale. Such an analysis is crucial in two ways. First, it provides a global overview of vulnerability and resilience of water resources to food supply. Second, it offers a platform for targeting scholarly and policy-related activities on geographic areas that are most critical in terms of water and food security. Besides, the methodological progress is an important aspect since concurrent water security approaches do not, in our opinion, harness much of the potential that could be provided by earth systems science.

2. Materials and methods

2.1. Vulnerability approach including societal resilience

Our analysis on food-water security is based on the vulnerability approach, which has been developed from the River Basin Vulnerability Index (RVBI) methodology [64–66]. RBVI approach compiles six vulnerability factors that drive water security in an array of geographic areas in the Asian continent. Three of the factors are environmental in character (natural hazards, environmental footprint and water scarcity), while the other three are societal (economy, human development, governance).

In the present approach, we use the three societal factors of RBVI approach as a combined proxy for societal resilience. This is done in order to clarify their role as cornerstones of society's capacity to adapt and thrive under change. Resilience was selected as a concept, since it can be seen as flip side to vulnerability, with close linkages to both sustainable development and security [16,75]. As noted by Folke et al. [16], resilience is not merely about sustaining capacity and options for development, but also an issue of environmental, social as well as economic security. Resilience is often seen to take three different but interlinked forms, namely environmental and ecosystems related resilience, social resilience, and economic resilience (e.g. [75]). In this study we build on the ideas of two latter forms, combining them into societal resilience that is represented by three key factors related to governance, economy, and human development (cf. [65]).

To describe the level of governance, we used Worldwide Governance Indicator national level data, derived from Kaufmann et al. [29]. For both GDP and Human Development Index HDI, we used a combination of national and sub-national data. Sub-national data for GDP was extracted from Gennaioli et al. [18], while national data from World Bank's World Development Indicator database [33]. In case of HDI, we used sub-national from UNDP's national reports, collected by OMICS International, while national data was derived from UNDP's Human Development Reports [33]. For countries to which no sub-national data existed, we used national data. For countries to which sub-national data was available but there was no data record for year 2010, we used national data to interpolate or extrapolate the needed value from the available sub-national data points (see more in [33]).

The geospatial datasets were used to derive the resilience index, all showing the status of the indicator in question for year 2010. Each of these indicators was scaled between 0 and 1 so that the world's most favorable geographic unit received the value 1 and the least favorable the value 0. To censor the outliers, 5% of the highest and lowest values got value 1 and 0, respectively. The overall resilience was calculated as the arithmetic mean of the three factors, and we thus consider the three factors to be equally important for resilience (with economy getting bit more emphasis as it also constitutes 1/3 of HDI).

To sum up, for the assessment of the global water-food security situation, we developed an approach, in which food-related water vulnerability situations relay on societal resilience when facing challenges due to such vulnerability as well as broader development-related changes.

2.2. Water-food vulnerability

The water-food vulnerability was calculated in the following way. We first included the water, both green and blue water, requirements for food production and related that to the availability of these resources, i.e. so called green-blue water (GBW) scarcity index [19,31,47]. After that, we included food net-imports to each given area [48]. The calculations were conducted at the level of Food Production Units i.e. FPUs [9,14]. FPUs divide the globe into 281 units, which are hybrids of river basins and economic regions. Kummu et al. [34] further divided some of the largest FPUs to smaller units, resulting in total 309 units.

We used LPJmL model [6,53] to assess GWB requirements of food production globally, as well as availability of those resources. The model simulates the water demand for each crop in a given location. We included 12 most common crops when investigating the water consumption needed to produce a reference daily diet of 2400 kcal (after losses and waste is subtracted from total food availability) per each individual. We followed the approach by Gerten et al. [19], who estimated than in in healthy diet the share of animal-based calories is 20% of total calorie intake, and the water consumed was estimated to be sixfold to plant-based diet components. Diet in each analysis unit consist of plant-based foodstuff cultivated in that unit and thus, the diet composition takes into account the cultural preferences. However, as the animal foodstuff is fixed in each unit to 20% of total calorie intake, the simulations do not take into account the differences between areas in that aspect.

For each FPU, the GBW scarcity index value was then calculated. It indicates whether an area in question is capable of producing enough food for its inhabitants, assuming the above-defined reference diet. The value 1 would imply that the area is at the limit of having enough GBW resources to meet the food requirements, whereas, for instance, a value 0.6 would indicate that it could meet only 60% of its own food demand due to the GBW constraints.

2.3. Food trade

Nearly all GBW scarce areas are using food imports in adapting to either chronic or occasional resource scarcity situations [48]. While water availability is critical to food production in these countries, it does not directly correspond with actual food availability, as countries use food imports as one important means to adapt to water scarcity [48]. In this way, food trade can be seen as one resilience strategy to respond to water and food related scarcities (while also noting that countries' possibilities to rely on food trade are partly dependent on our three resilience factors, particularly economy). We included food net-imports in this study by estimating the percentage of population that could be nourished by food imports (see more in Porkka et al. [48]). If for instance that was 50%, half of the population could be fed by imports, while negative values would mean that an area is net-exporter of food. Combining these, yields the total potential for food availability. In our example this would be 0.6 + 0.5 = 1.1, implying that the specific FPU would have the potential to have adequate food supply to its citizens, when both own production potential and food imports are considered. For countries with no reliable trade data available, we assumed only local food production. Finally, it should be noted that we did not consider from which country the food is imported and thus, in some cases the food exports might increase the unsustainable use of water resources [13].

To assess the importance of resilience in FPU's ability to adapt to scarce GBW resources, we tested with Pearson's linear correlation the relationship between resilience and changed water-food vulnerability due to food net-imports (i.e. how much imports improve the potential food availability given the available resources).

3. Results

3.1. GBW scarcity

The water demand to produce the reference diet varies widely across the globe. Whereas in many parts of Northern and Central Europe as well as in certain parts of the United States and Canada it remains below 650 m^3 per year per capita, it exceeds double of that volume in large parts of Asia, and goes even 3 to 4-fold in Africa (Fig 1A). The reasons to this high variability are partly due to farming practices and technologies in use, and partly due to climatic factors. The more advanced methods, fertilizers and varieties are being used, the less water is needed for producing a unit yield. Climate in turn influences evaporation; the warmer and drier the climate, the bigger volume of water evaporates in the production of food.

In most parts of the globe, the available water resources exceed the water demands to produce the reference diet (Fig. 1A and B). The most notable areas in where availability does not meet the requirements (and water scarcity occurs), are in several locations of Northern and Eastern Africa, Middle East and Southern Asia as well as in China (Fig. 1C). These areas are subject to high (GBW index 0.5–1) or extreme (<0.5) GBW scarcity (Fig. 1C). Around two billion people (or 30% of world total population) dwell in those areas, while another two billion people live in areas facing moderate (1–1.5) or approaching (1.5–2) GBW scarcity (see small table at Fig. 4A).

3.2. Food imports as an adaptation strategy to scarcity

The basic approach to compensate the insufficient food production capability due to factors such as water scarcity is the import of food. Fig 2 shows the food net imports to each of the FUPs as the percentage of all food demand, averaged over the years 2005–2009. Strikingly, not so many FPUs were food net exporters, whereas most FPUs were net importers (for a more detailed study with time trajectories, see [48,49]). African continent as well as much of Europe and large parts of Asia are particularly import-dependent on meeting their food demand.

The comparison of Fig. 1C and D gives an opportunity to explore how the food imports bring down the (theoretical) GBW water scarcity levels in the FPUs that are unable to meet their food demand, or approaching that situation, due to insufficient GBW availability. The very densely populated stripe from China across India to Middle East and Turkey remains quite GBW scarce even after taking imports into account. Most challenging areas can be found in Pakistan, the Ganges Basin and Oman (Fig. 1D). The same occurs in certain locations of Africa, most notably in Ethiopia, Eritrea, Malawi, Burkina Faso, Swaziland and Morocco. Egypt and Tanzania have also notable challenges. At the same time, various Middle East countries were able to lift their status to approaching scarcity.

3.3. Resilience

The maps on the three included resilience factors, namely Governance (Fig. 3A), Economy (Fig. 3B) and Human development (Fig. 3C), share many similarities. North America, parts of Europe, Japan, Republic of Korea, Australia and New Zealand, and parts of Latin America (Chile in particular) show high resilience in all these aspects. Africa and some FPUs in Asia (particularly Afghanistan), in turn, show particularly low resilience. Governance shows less areas in the highest resilience categories than the other factors.

The aggregated Resilience index (Fig. 3D) averages the maps described above. The challenging situation of large parts of Africa, Ukraine, Syria and Iraq, Mongolia, PDR Korea, much of the stripe of FPUs from Turkmenistan and Uzbekistan to the Sunda Islands, and certain FPUs in Latin America becomes quite clear on this map.

3.4. Importance of resilience in adaptation to GBW scarcity

One interesting question is how societal resilience link to green-blue water (GBW) scarcity in different areas. In order to understand this better, we tested whether a statistical relationship exists between resilience and the GWP scarcity (including net imports) among the FPUs (cf. Fig. 4). We first calculated how much the imported food changes the scarcity index, and then correlated this to resilience using Pearson's correlation analysis. We divided the FPUs to three categories: i) those under high or extreme scarcity (without net imports, GBW scarcity < 1), ii) those under moderate or approaching scarcity (GBW scarcity 1–2), and iii) those with no scarcity (GBW scarcity > 2), and performed the correlation analysis separately to each category.

In all groups, the dependent variable was not normally distributed and no commonly used transformations were able to change that. The distribution was, however, not badly skewed when examined visually and with Shapiro-Wilk test. Thus, we were rather confident that Pearson's correlation would give us

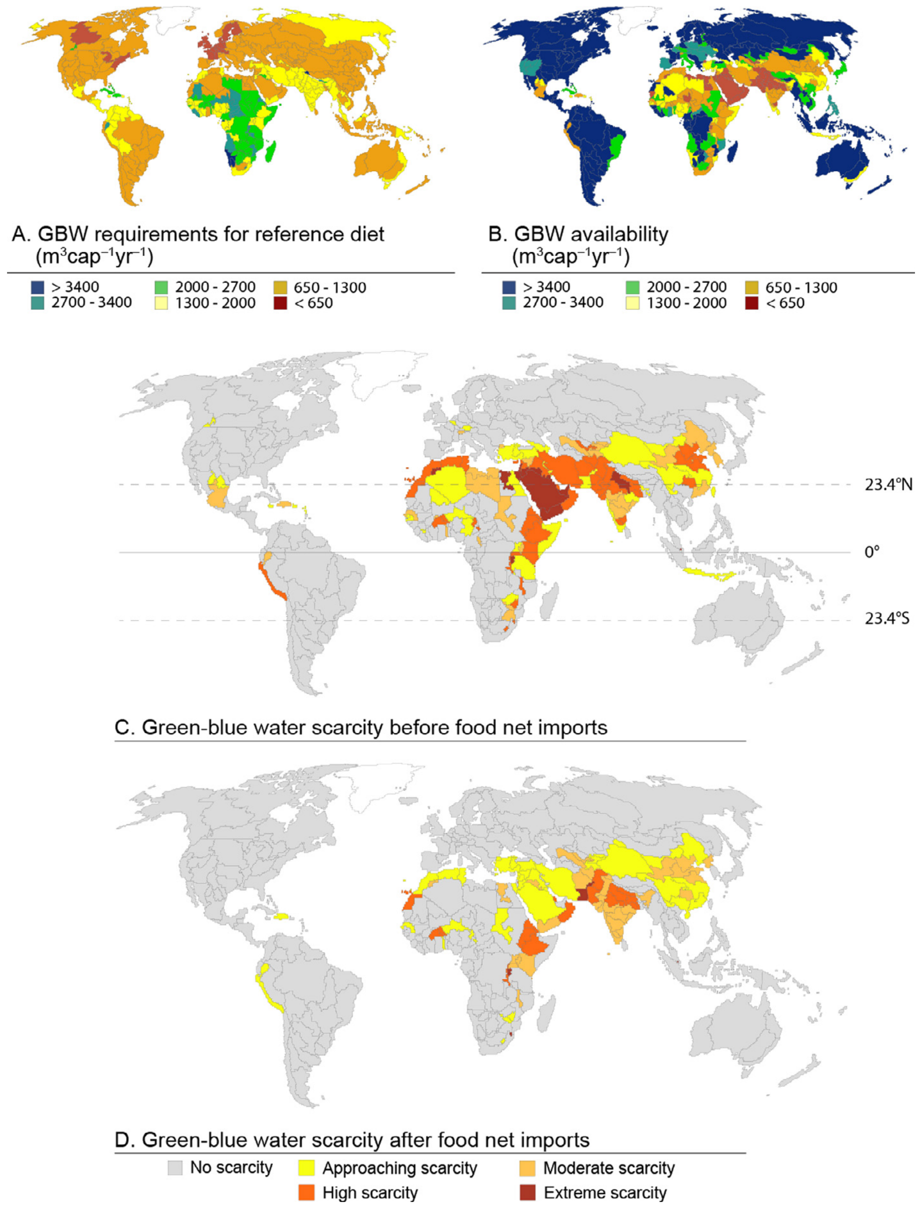

Fig. 1. Food production requirements vs. available freshwater per Food Production Unit (FPU). A. Green-blue water (GBW) requirements for producing the reference diet. B. GWB availability per FPU. C. GBW scarcity without food net imports, and D. GBW scarcity including net imports. GBW index for extreme scarcity: <0.5; high scarcity: 0.5–1; moderate scarcity: 1–1.5; and approaching scarcity is 1.5–2.

defendable results, although not all the assumptions were met. For independent variable, we used power-to-3 link function for two first groups, giving the best correlation of tested commonly used functions. For third group, no link function was used due to no improvement in correlation. It is worth to mention, that while link function resulted higher R and p values, status of statistical significance at level $p < 0.05$ did not change. Finally, we omitted the FPUs with no data for net imports (Fig. 2) and those extreme FPUs with more than 500% net exports in relation to food demand.

When assessing the FPUs under high or extreme scarcity and without net imports, we found strong relationship between resilience and their ability to improve scarcity with food imports ($R = 0.657$, $p < 0.0001$; $n = 50$). The relationship was still statistically significant for the FPUs with moderate or approaching scarcity, but considerably weaker ($R = 0.338$, $p < 0.01$; $n = 58$), whereas no statistical significant relationship was found in the group of FPUs without scarcity ($R = -0.103$, $p = 0.177$; $n = 173$). This indicates that FPUs with high resilience were able to better adapt to GBW scarcity than those with low resilience. In areas without scarcity, the relationship was not statistically significant and opposite to FPUs under scarcity, i.e. the higher the resilience the higher the exports.

The relationship in the first two groups was further validated when plotting the resilience against GBW scarcity of each FPU (Fig. 4) separately without net imports and with them. That analysis shows that nearly all FPUs with higher resilience than the global average were able to move away from the extreme and high scarcity zone, resulting that population within that part of the matrix decreased from 605 million to 17 million. At the same time, the population in FPUs with GBW scarcity < 1 and resilience below the global median decreased only from 1396 to 867 million when food net imports were taken into account (Fig. 4).

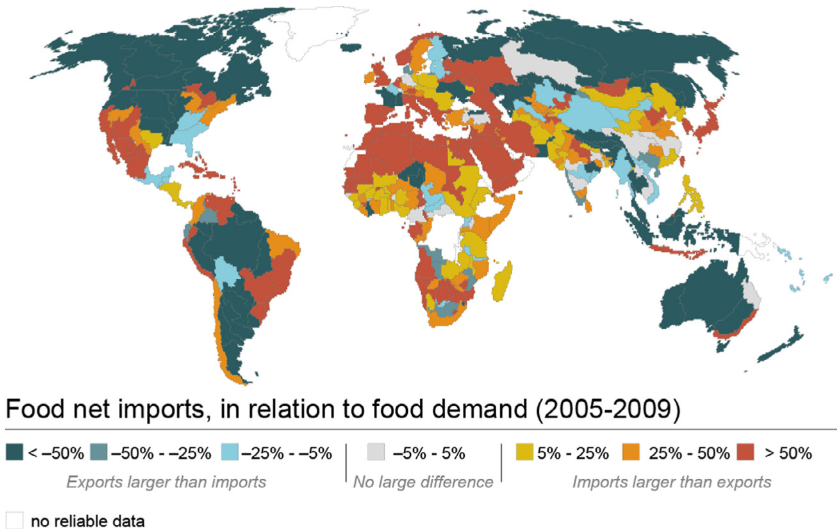

Fig. 2. The percentage of food net imports of total food demand by FPUs, averaged over 2005–2009.

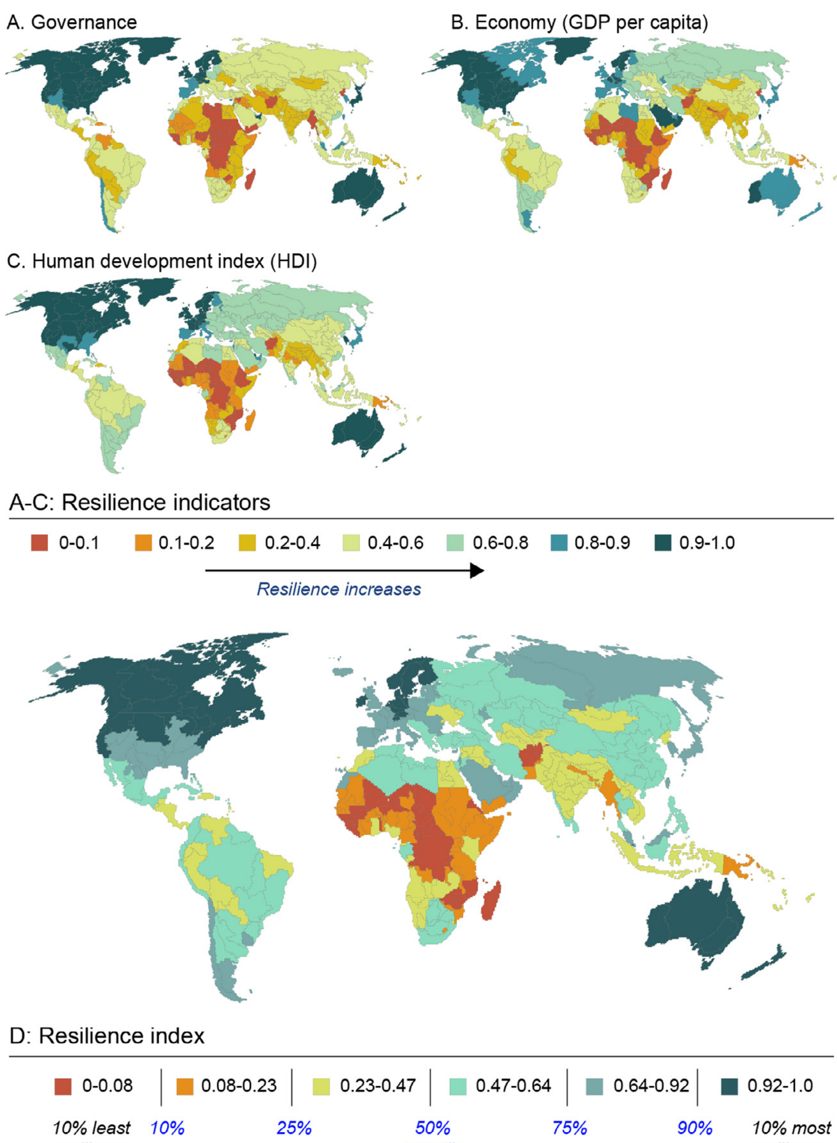

Fig. 3. Resilience: the three resilience factors Governance (A), Economy (B) and Human development (C) and the aggregated Resilience index (D). The Resilience index is calculated as the average value of the three resilience factors.

Fig. 4. Resilience of each food production unit (FPU) plotted against its green-blue water scarcity index. A: situation without net imports; and B: situation after net imports are included. Bubble size represents the population of a given FPU. The small tables indicate the total population in each parts of the matrix, with percentage of global population indicated in brackets. Note: many FPU's moved from moderate scarcity and approaching scarcity categories to 'no scarcity' when food net imports were considered and thus, are not visible in tile B.

4. Discussion

We developed a generic approach for the conceptualization and analysis of water security. It consists of four dimensions: direct-indirect, macro-micro, technical-political, and peace-conflict. We investigated this concept with a case study on the global relations of water security and food security. We developed a methodology that allows quantitative, multidisciplinary assessment of relationships between water security and food security at macroscale, making use of increasing availability of spatially explicit global datasets.

4.1. Global water-food security analysis

The novelty of the results of this paper is due to the joint consideration of water scarcity and food supply with societal adaptive capacity i.e. resilience in quantitative manner at global scale, allowing comparison between regions. We were able to show that resilience, in the way we determined it, seems to play an important role in the ability of an FPU to adapt to food-water insecurity.

Most previous analyses have not addressed these two facets jointly. Instead, the global quantitative analyses on water have dominantly relied on water availability and use aspects only. This is the case in water scarcity studies [32,34,37,69,72] and those which include also agricultural production [31,36,46,47], water demand and climate change [21,54,67,68,70,74], ecosystems [22], energy demand [24] and upstream-downstream relations [22,40].

The existing, multidisciplinary vulnerability analyses of water resources, which incorporate an array of factors influencing either water resources governance or ecological status, are in many ways closer to our present approach than the pure water availability – water use based analyses mentioned in the previous paragraph. Such vulnerability approaches [2,11,25,28,41,45,50,64,73] embrace often economic, social and environmental factors jointly.

We argue that considering also resilience in water scarcity and food supply studies can take them to a new level, and make them better aligned with the water security debate. The societal capacity to face and adapt to water scarcity and related vulnerabilities is, after all, a very basic factor in addressing waters security concerns.

4.2. Water security

Water security is a concept that is currently at an emerging phase. But instead of converging towards a commonly-accepted definition, it keeps still diverging and new definitions keep evolving [12,17,26,35,43,62,77]. We see this as a natural situation since water is used by societies in myriad of ways, and at the same time water is fundamental to ecosystem and has many basic functions in them. Moreover, the security-related aspects of water and other natural resources are under continuous debate.

Our analysis may obviously blur the existing definitions, as our key message is that water security debate should better acknowledge that water is an intrinsic component of several other sectors. Water security is thus deeply intertwined in the security-related questions of those other sectors, and not only on water sector *per se*. We demonstrated one such connection by a global analysis of interlinkages of water and food sectors; this is obviously among the most important cross-sectoral linkages since food production accounts roughly for 70% of all water use by humans on this planet and 40% of the land is used for food production.

Methodologically, one of the key questions arising from our study relates to its use for ‘integrated’, policy- and politics-orientated water security analyses. In line with Zeitoun et al. [77], our study has a clearly ‘reductionist’ approach with its focus on macro-scale and quantitative data analysis at global scale. Yet, similarly to the conclusions by Zeitoun et al. [77], we see that novel quantitative analyses are very important to expand the research agenda and, to advance water security field in general. As such, studies using both research approaches are needed to understand the complex dynamics and varying contexts related to water security.

One way to advance the water security discussion and to overcome the possible challenges of conflicting research approaches is to visualize into one diagram the key aspects related to water security. We propose a four-dimensional model (visualized in the graphical abstract) to help organizing many of the various aspects proposed under the term water security. The model has axes that run between two complementary yet often largely opposing aspects:

– *macro-micro, both spatially and temporarily*: some water security studies are focused on large-scale issues such as geopolitics, transboundary waters and international relations, while others concentrate on localized issues. We see that both are needed, just like we need macro and microeconomy and neither of them is generically superior or subset to the another. A temporal parallel to the macro-micro axis is the acute-chronic consideration. Many water security issues are short-term or acute in character, while other ones are chronic. Reasons may be either societal or natural.
– *peace-conflict*: societies tend to operate in different modes in normal, peaceful conditions and in emergency and conflict situations. Security doctrines and policies often have close linkages to water-related issues such as critical infrastructure, evacuation plans, food delivery, exceptional emissions and so forth. This conflict-related aspect is so far largely absent in mainstream water security literature.
– *direct-indirect*: large part of the water security literature concentrate on water sector itself, forming thus a direct aspect of water security. Yet, water links to other sectors such as agriculture, health, environment, climate, and navigation, indicating the need to consider also indirect aspects of water security. One example of the importance of such indirect aspects are due to United Nations Sustainable Development Goals [60]. They include one goal (6) that is directly related to freshwater; yet all the other 16 goals are in various ways interdependent on water and thus have an indirect water security aspect.
– *technical-political*: there are many ways to consider risk, vulnerability, resilience, and security. Technically orientated approach focuses on quantifying and then targeting the issue by e.g. infrastructure or other technical and physical ways, while politically and sociologically orientated approach considers primarily governance, equity, power relations and politics related to resource use and security. These two directions are sometimes contrasted, but we think that they need and even depend on each other. Thus they are two sides of the same coin like hardware and software.

The idea of this model is to show that the water security incorporates various and often contrasting aspects: as result they can often be attributed in axes connecting these aspects. While this may feel evident, we believe that such a simplified illustration may actually provide a way to look at various interpretations of water security (or for that matter e.g. food security and energy security), and to illustrate in visually powerful manner their fundamental differences. In this way, our illustration may help to understand why water sector manifests itself so differently in varying contexts.

Ideally, water security study or policy would cover all these aspects and axes; however, specific studies and policies are bound to select a combination of viewpoints in order to keep the study feasible and outcomes meaningful. Our combination in this study is Indirect – Peace – Technical – Macro, which also helps to understand why we did not include certain aspects in our analysis. Recognizing in this way into which category i.e. combination of different aspects a certain study belongs helps to understand its focus – and related strengths and weaknesses.

We want to point out that we exclude all value judgment from this debate, and intend not to say that our combination is in any way better (or worse) to any other combination. The plausible combination, instead, depends on the problem at hand, and on the viewpoint taken. As a result, we would select a different combination for a different water security problem setting: we also feel that many contexts would benefit from a set of water security studies having different combinations as their starting point.

4.3. Ways forward

Open data and data mining allow the fast development of assessments such as the present one. We anticipate a speedy progress particularly in the expansion of data availability, both in terms of available datasets and indicators as well as their resolution – both in time and space. Evidently elaborate indicators that are potentially useful in water security studies are being developed and released at an accelerating pace. We may expect that most if not all aspects that we have been studying will be available in high spatial-resolution format in very few years. The speedy development underlines the importance of developing approaches and methodologies that use up-to-date datasets, since they pave the road for further developments of the comprehension of and conceptualizations to water security.

We embrace the importance of multidisciplinarity and the principles of sustainable development. Linking water resources related stresses to economic, social and governance capabilities as well as key water-using activities, such as food production, has been underweighted at global and regional scales in current water security literature. Our aim was to provide one take to fill this critical gap. There are many possible development pathways, depending on the aspect of water security to be investigated. One is to focus more stringently on water, aquatic ecosystems and water related services. We proceed to this direction with a pilot on China [8] and move on further along the paths initiated most importantly by Vorosmarty et al. [71] on harnessing data-based approaches and investigating their usefulness in water security studies.

One way to benefit from vulnerability studies is to use the vulnerability mappings as a base of studies that assess the risks, vulnerabilities, feasibility etc. of an array of developments, which are not directly water sector activities but are linked to and possibly constrained by water. A pilot case is the recent study of Zheng et al. [78] in which all China's planned thermal power plants were plotted on the vulnerability maps of China by Varis et al. [65], or to urban development [7], and food production (as done here). Such an approach allows a useful and relatively fast way to produce policy advice on matters, which entail highly complex interrelations of intersectoral impacts of strategic policy decisions.

For many policy-related purposes, either a national, river basin or FPU scale are quite useful. Yet, more localized, quantitative analyses are often needed, as they help to portray more precisely the actual complexities and dimensions related to water security. The present approach is extendable by including temporal variability, spatial resolution and social variety if needed, within the limits of data availability.

As our goals were on one hand in the scrutiny of the concept of water security and on the other hand in the development of quantitative analyses for water security studies, we focused on providing results on one reference year only. While being fully aware of the dynamism and temporal evolution of all of the aspects that our approach includes, we deliberately decided to provide only one temporal snapshot to this entity. We envisage further studies to analyze temporal patterns and dynamism of water security, vulnerability and resilience.

Finally, we call for modesty in the expectations to such positivistic approaches in how they can capture the essence of water security problems locally. In our case, each FPU contains an array of different livelihoods, societal strata, agricultural and economic conditions to name a few. However, as microeconomics may not replace macroeconomics but they rather complement one another, also positivistic studies may be quite useful in complementing localized analyses, particularly when designing policies.

5. Conclusions

The discussion about water security centers, for obvious reasons, on water. Yet, as water security challenges intertwine typically with several other sectors, it is meaningful to integrate such sectors into the concept of water security. One way to differentiate between these two aspects is to talk about direct water security (dealing solely with water) and indirect water security (which includes selected water-related sectors and their security aspects).

This analysis focuses on the importance of such indirect aspects of water security by looking at the connections between water and food production, which is by far the largest water consuming sector globally. We combine freshwater availability and water requirements for food production with general societal adaptive capacity, i.e. resilience. This analysis presents for the first time a global analysis of water-food security, which incorporates systematically societal resilience to water and food security issues.

We argue that vulnerability and resilience are relevant themes for water security, and suggest that water security studies should make better use of the concept of resilience. The emergence of resilience as a relevant approach for socio-ecological contexts [16] and, increasingly, general security and even military security settings [27,55] suggest that resilience can provide useful framings also for water security discussion. For the same reason, resilience may offer a way to tie the two key terms of water security, namely water and security, more firmly together. Vulnerability and resilience can also be seen as building blocks for sustainability, and they may thus be used as one way to enhance the linkages between water security and sustainable development. For we see that this is also what water security is essentially about: ensuring sustainable use and development of freshwater and related resources in our planet.

Methodologically, we document a quantitative approach for the analysis of water and food security interlinkages, which harnesses spatial, macroscale analysis experience from earth sciences tradition and makes use of rapidly increasing availability of spatially explicit global datasets. We acknowledge that this analysis provides only one of the myriad viewpoints to water security, which as a concept has many facets and can be approached in numerous ways, from various angles [77].

It is obvious and fully acceptable that water security may also globally be viewed through different approaches and lenses than what we have done here – not to speak about smaller spatial scales – simply because water has so many roles within the society and the environment [62]. Thereby, we invite other authors to investigate global water security issues and their relations – both quantitative and qualitative – to other sectors and actors. To help visualize the diversity that such studies are likely to take, we propose a 4-dimensional conceptualization for different aspects of water security, hoping that it will be useful in conceptualizing and studying water security further.

Acknowledgements

This study was done under the Academy of Finland coordinated From Failand to Winland Project, which is funded by the Strategic Research Council of the Government of Finland. The study was also supported by Maa- ja vesitekniikan tuki r.y. MKu was also supported by Emil Aaltonen foundation funded project 'eat-less-water'. We are thankful for the splendid support and ideas from our collaborators, particularly Stefan Siebert, Miina Porkka, MikaJalava, Joseph Guillaume and Suvi Sojamo as well as our Winland colleagues and new WDRG team members Maija Taka, Lauri Ahopelto, AmyFallon, Matias Heino, Marko Kallio, Pekka Kinnunen and Venla Niva.

References

[1] M. Al-Saidi, N.A. Elagib, Towards understanding the integrative approach of the water, energy and food nexus, Sci. Total Environ. 574 (2017) 1131–1139.
[2] M.S. Babel, S.M. Wahid, Freshwater Under Threat: South Asia, United Nations Environment Programme, Nairobi, 2008.
[3] K. Bakker, Water security: Research challenges and opportunities, Science 337 (2012) 914–915.
[4] K. Bakker, C. Morinville, The governance dimensions of water security a review, Philos. Trans. R. Soc. A Math. Phys. Eng. Sci. 371 (2013).
[5] A.K. Biswas, Integrated water resources management: A reassessment, Water Int. 29 (2004) 248–256.
[6] A. Bondeau, P.C. Smith, S. Zaehle, S. Schaphoff, W. Lucht, W. Cramer, D. Gerten, H. Lotze-Campen, C. Muller, M. Reichstein, B. Smith, Modelling the role of agriculture for the 20th century global terrestrial carbon balance, Glob. Change Biol. 13 (2007) 679–706.
[7] J. Cai, V. Niva, J. Guillaume, O. Varis, M. Kummu, Vulnerability and resilience of China's cities to floods and droughts: a double-edged sword, Int. J. Water Resour. Dev. (2017), http://dx.doi.org/10.1080/07900627.2017.1353411.
[8] J. Cai, O. Varis, H. Yin, China's water resources vulnerability: A spatio-temporal analysis during 2003–2013, J. Cleaner Prod. 142 (Part 4) (2017) 2901–2910.
[9] X. Cai, M.W. Rosegrant, Global water demand and supply projections, Water Int. 27 (2002) 159–169.
[10] R. Cairns, A. Krzywoszynska, Anatomy of a buzzword: The emergence of 'the water-energy-food nexus' in UK natural resource debates, Environ. Sci. Policy 64 (2016) 164–170.
[11] H. Chang, J. Franczyk, E.S. Im, W.T. Kwon, D.H. Bae, I.W. Jung, Vulnerability of Korean water resources to climate change and population growth, Water Sci. Technol. 56 (2007) 57–62.
[12] C. Cook, K. Bakker, Water security: Debating an emerging paradigm, Global Environ. Change 22 (2012) 94–102.
[13] C. Dalin, Y. Wada, T. Kastner, M.J. Puma, Groundwater depletion embedded in international food trade, Nature 543 (2017) 700–704.
[14] C. de Fraiture, D. Wichelns, Satisfying future water demands for agriculture, Agric. Water Manage. 97 (2010) 502–511.

[15] FAO, IFAD, WFP, (2015) The State of Food Insecurity in the World 2015. Meeting the 2015 international hunger targets: taking stock of uneven progress. Food and Agricultural Organization of the United Nations, Rome.
[16] C. Folke, S. Carpenter, T. Elmqvist, L. Gunderson, C.S. Holling, B. Walker, J. Bengtsson, F. Berkes, J. Colding, K. Danell, M. Falkenmark, L. Gordon, R. Kasperson, N. Kautsky, A. Kinzig, S. Levin, K.-G. Mäler, F. Moberg, L. Ohlsson, P. Olsson, E. Ostrom, W. Reid, J. Rockström, H.S. Savenije, U., Resilience and sustainable development: building adaptive capacity in a world of transformations. Scientific background paper on resilience for the process of The World Summit on Sustainable Development on behalf of the Environmental Advisory Council to the Swedish Government. Edita Norstedts Tryckeri AB, Stockholm, 2002.
[17] G.M. Garfin, C.A. Scott, M. Wilder, R.G. Varady, R. Merideth, Metrics for assessing adaptive capacity and water security: common challenges, diverging contexts, emerging consensus, Curr. Opin. Environ. Sustainability 21 (2016) 86–89.
[18] N. Gennaioli, R. La Porta, F. Lopez-de-Silanes, A. Shleifer, Human capital and regional development, Quart. J. Econ. 128 (2013) 105–164.
[19] D. Gerten, J. Heinke, H. Hoff, H. Biemans, M. Fader, K. Waha, Global Water Availability and Requirements for Future Food Production, J. Hydrometeorol. 12 (2011) 885–899.
[20] M. Giordano, T. Shah, From IWRM back to integrated water resources management, Int. J. Water Resour. Dev. 30 (2014) 364–376.
[21] S.N. Gosling, N.W. Arnell, A global assessment of the impact of climate change on water scarcity, Clim. Change 134 (2016) 371–385.
[22] P.A. Green, C.J. Vorosmarty, I. Harrison, T. Farrell, L. Saenz, B.M. Fekete, Freshwater ecosystem services supporting humans: Pivoting from water crisis to water solutions, Global Environ. Change 34 (2015) 108–118.
[23] D. Grey, C.W. Sadoff, Sink or Swim? Water security for growth and development, Water Policy 9 (2007) 545–571.
[24] R.A. Holland, K.A. Scott, M. Florke, G. Brown, R.M. Ewers, E. Farmer, V. Kapos, A. Muggeridge, J.P.W. Scharlemann, G. Taylor, J. Barrett, F. Eigenbrod, Global impacts of energy demand on the freshwater resources of nations, Proc. Natl. Acad. Sci. U.S.A. 112 (2015) E6707–E6716.
[25] Huang, Y., Cai, M., Zhang, D., Cai, J., (2008) Freshwater under threat: Northeast Asia. In Vulnerability assessment of freshwater resources to environmental change. United Nations Environmental Programme, Nairobi.
[26] A. Jägerskog, A. Swain, J. Öjendaj, Water Security, Sage, London, 2014, p. 1150.
[27] A.E. Juncos, Resilience as the new EU foreign policy paradigm: a pragmatist turn?, Eur Secur. 26 (2017) 1–18.
[28] M. Kattelus, M. Kummu, M. Keskinen, A. Salmivaara, O. Varis, China's southbound transboundary river basins: a case of asymmetry, Water Int. 40 (2015) 113–138.
[29] D. Kaufmann, A. Kraay, M. Mastruzzi, The Worldwide Governance Indicators: A Summary of Methodology, Data and Analytical Issues, Policy Research Working Paper. World Bank, New York, 2010.
[30] M. Keskinen, J.H.A. Guillaume, M. Kattelus, M. Porkka, T.A. Rasanen, O. Varis, The water-energy-food nexus and the transboundary context: insights from large Asian rivers, Water 8 (2016) 25.
[31] M. Kummu, D. Gerten, J. Heinke, M. Konzmann, O. Varis, Climate-driven interannual variability of water scarcity in food production potential: a global analysis, Hydrol. Earth Syst. Sci. 18 (2014) 447–461.
[32] M. Kummu, J.H.A. Guillaume, H. de Moel, S. Eisner, M. Flörke, M. Porkka, S. Siebert, T.I.E. Veldkamp, P.J. Ward, The world's road to water scarcity: shortage and stress in the 20th century and pathways towards sustainability, Sci. Rep. 6 (2016) 38495.
[33] M. Kummu, M. Taka, J.H.A. Guillaume, Gridded global datasets for Gross Domestic Product (GDP) and Human Development Index (HDI) over 1990–2015. Scientific Data, 2017.
[34] M. Kummu, P.J. Ward, H. de Moel, O. Varis, Is physical water scarcity a new phenomenon? Global assessment of water shortage over the last two millennia, Environ. Res. Lett. 5 (2010), http://dx.doi.org/10.1088/1748-9326/5/3/034006.
[35] B. Lankford, K. Bakker, M. Zeitoun, D. Conway, Water Security: Principles, Perspectives and Practices, Earthscan, London, 2013.
[36] M.M. Mekonnen, A.Y. Hoekstra, Water footprint benchmarks for crop production: A first global assessment, Ecol. Ind. 46 (2014) 214–223.
[37] M.M. Mekonnen, A.Y. Hoekstra, Four billion people facing severe water scarcity, Sci. Adv. 2 (2016) e1500323.
[38] F. Molle, Nirvana concepts, narratives and policy models: Insights from the water sector, Water Altern. 1 (2008) 131–156.
[39] M. Muller, A. Biswas, R. Martin-Hurtado, C. Tortajada, Built infrastructure is essential, Science 349 (2015) 585–586.
[40] H. Munia, J.H.A. Guillaume, N. Mirumachi, M. Porkka, Y. Wada, M. Kummu, Water stress in global transboundary river basins: significance of upstream water use on downstream stress, Environ. Res. Lett. 11 (2016) 13.
[41] J.C. Padowski, S.M. Gorelick, B.H. Thompson, S. Rozelle, S. Fendorf, Assessment of human-natural system characteristics influencing global freshwater supply vulnerability, Environ. Res. Lett. 10 (2015) 11.
[42] C. Pahl-Wostl, Water security, systemic risks and adaptive water governance and management, in: C. Pahl-Wostl, A. Bhaduri, J. Gupta (Eds.), Handbook on Water Security, Edward Elgar Publishing Limited, Cheltenham, 2016.
[43] C. Pahl-Wostl, A. Bhaduri, J. Gupta, Water Security Handbook, Edward Elgar Publishing, Cheltenham, 2016.
[44] M.A. Palmer, J.G. Liu, J.H. Matthews, M. Mumba, P. D'Odorico, Water security: Gray or green?, Science 349 (2015) 584–585
[45] D. Pascual, E. Pla, J.A. Lopez-Bustins, J. Retana, J. Terradas, Impacts of climate change on water resources in the Mediterranean Basin: a case study in Catalonia, Spain, Hydrol. Sci. J. 60 (2015) 2132–2147.
[46] S. Pfister, P. Bayer, Monthly water stress: spatially and temporally explicit consumptive water footprint of global crop production, J. Cleaner Prod. 73 (2014) 52–62.
[47] M. Porkka, D. Gerten, S. Schaphoff, S. Siebert, M. Kummu, Causes and trends of water scarcity in food production, Environ. Res. Lett. 11 (2016).
[48] M. Porkka, J.H.A. Guillaume, S. Siebert, S. Schaphoff, M. Kummu, The global use of food imports to overcome limits to growth, Earth's Future 5 (2017) 393–407, http://dx.doi.org/10.1002/2016EF000477.
[49] M. Porkka, M. Kummu, S. Siebert, O. Varis, From food insufficiency towards trade dependency: a historical analysis of global food availability, PLoS One 8 (2013).
[50] L.X. Qian, R. Zhang, M. Hong, H.R. Wang, L.Z. Yang, A new multiple integral model for water shortage risk assessment and its application in Beijing, China, Nat. Hazards 80 (2016) 43–67.
[51] M.M. Rahaman, O. Varis, Integrated water resources management: evolution, prospects and future challenges, Sustainability: Sci. Pract. Policy 1 (2005) 15–21.
[52] J. Rockstrom, W. Steffen, K. Noone, A. Persson, F.S. Chapin, E. Lambin, T.M. Lenton, M. Scheffer, C. Folke, H.J. Schellnhuber, B. Nykvist, C.A. de Wit, T. Hughes, S. van der Leeuw, H. Rodhe, S. Sorlin, P.K. Snyder, R. Costanza, U. Svedin, M. Falkenmark, L. Karlberg, R.W. Corell, V.J. Fabry, J. Hansen, B. Walker, D. Liverman, K. Richardson, P. Crutzen, J. Foley, Planetary boundaries exploring the safe operating space for humanity, Ecol. Soc. 14 (2009).
[53] S. Schaphoff, U. Heyder, S. Ostberg, D. Gerten, J. Heinke, W. Lucht, Contribution of permafrost soils to the global carbon budget, Environ. Res. Lett. 8 (2013) 10.
[54] J. Schewe, J. Heinke, D. Gerten, I. Haddeland, N.W. Arnell, D.B. Clark, R. Dankers, S. Eisner, B.M. Fekete, F.J. Colon-Gonzalez, S.N. Gosling, H. Kim, X.C. Liu, Y. Masaki, F.T. Portmann, Y. Satoh, T. Stacke, Q.H. Tang, Y. Wada, D. Wisser, T. Albrecht, K. Frieler, F. Piontek, L. Warszawski, P. Kabat, Multimodel assessment of water scarcity under climate change, Proc. Natl. Acad. Sci. U.S.A. 111 (2014) 3245–3250.
[55] J. Shea, Resilience: A Core Element of Collective Defence, NATO North Atlantic Treaty Organization, Brussels, 2016.
[56] A. Smajgl, J. Ward, L. Pluschke, The water-food-energy Nexus - Realising a new paradigm, J. Hydrol. 533 (2016) 533–540.
[57] A. Sood, V. Smakhtin, Global hydrological models: a review, Hydrol. Sci. J. 60 (2015) 549–565.
[58] W. Steffen, K. Richardson, J. Rockstrom, S.E. Cornell, I. Fetzer, E.M. Bennett, R. Biggs, S.R. Carpenter, W. de Vries, C.A. de Wit, C. Folke, D. Gerten, J. Heinke, G. M. Mace, L.M. Persson, V. Ramanathan, B. Reyers, S. Sorlin, Planetary boundaries: Guiding human development on a changing planet, Science 347 (2015) 736.
[59] D. Tarlock, P. Wouters, Reframing the water security dialogue, J. Water Law 20 (2010) 53–60.
[60] UN, United Nations Department of Economic and Social Affairs, New York, 2016.
[61] UNU-INWEH, Water Security & the Global Water Agenda, A UN-Water Analytical Brief, UNU-INWEH, Hamilton, Ontario, 2013.
[62] E. van Beek, V.L. Arriens, Water Security: Putting the Concept Into Practice, Global Water Partnership, Stockholm, 2014, p. 52.
[63] O. Varis, K. Enckell, M. Keskinen, Integrated water resources management: horizontal and vertical explorations and the 'water in all policies' approach, Int. J. Water Resour. Dev. 30 (2014) 433–444.
[64] O. Varis, M. Kummu, The Major Central Asian River Basins: An Assessment of Vulnerability, Int. J. Water Resour. Dev. 28 (2012) 433–452.
[65] O. Varis, M. Kummu, C. Lehr, D. Shen, China's stressed waters: Societal and environmental vulnerability in China's internal and transboundary river systems, Appl. Geogr. 53 (2014) 105–116.
[66] O. Varis, M. Kummu, A. Salmivaara, Ten major rivers in monsoon Asia-Pacific: An assessment of vulnerability, Appl. Geogr. 32 (2012) 441–454.
[67] T.I.E. Veldkamp, S. Eisner, Y. Wada, J. Aerts, P.J. Ward, Sensitivity of water scarcity events to ENSO-driven climate variability at the global scale, Hydrol. Earth Syst. Sci. 19 (2015) 4081–4098.
[68] T.I.E. Veldkamp, Y. Wada, H. de Moel, M. Kummu, S. Eisner, J. Aerts, P.J. Ward, Changing mechanism of global water scarcity events: Impacts of socioeconomic changes and inter-annual hydro-climatic variability, Global Environ. Change 32 (2015) 18–29.
[69] C.J. Vorosmarty, Global water assessment and potential contributions from Earth Systems Science, Aquat. Sci. 64 (2002) 328–351.
[70] C.J. Vorosmarty, P. Green, J. Salisbury, R.B. Lammers, Global water resources: Vulnerability from climate change and population growth, Science 289 (2000) 284–288.
[71] C.J. Vorosmarty, P.B. McIntyre, M.O. Gessner, D. Dudgeon, A. Prusevich, P. Green, S. Glidden, S.E. Bunn, C.A. Sullivan, C.R. Liermann, P.M. Davies, Global threats to human water security and river biodiversity, Nature 467 (2010) 555–561.
[72] Y. Wada, M.F.P. Bierkens, Sustainability of global water use: past reconstruction and future projections, Environ. Res. Lett. 9 (2014) 17.
[73] L. Wan, J. Xia, S. Hong, H.M. Bu, L.K. Ning, J.X. Chen, Decadal climate variability and vulnerability of water resources in arid regions of Northwest China, Environ. Earth Sci. 73 (2015) 6539–6552.

[74] N. Wanders, H.A.J. Van Lanen, Future discharge drought across climate regions around the world modelled with a synthetic hydrological modelling approach forced by three general circulation models, Nat. Hazards Earth Syst. Sci. 15 (2015) 487–504.
[75] WRI, (2008) Roots of resilience—growing the wealth of the poor, Washington D.C.
[76] M. Zeitoun, The global web of national water security, Global Policy 2 (2011) 286–296.
[77] M. Zeitoun, B. Lankford, T. Kruege, T. Forsyth, R. Carter, A.Y. Hoekstra, R. Taylor, O. Varis, F. Cleaver, R. Boelens, L. Swatuk, D. Tickner, C.A. Scott, N. Mirumachi, N. Matthews, Reductionist and integrative research approaches to complex water security policy challenges, Global Environ. Change 39 (2016) 143–154.
[78] X.Z. Zheng, C. Wang, W.J. Cai, M. Kummu, O. Varis, The vulnerability of thermoelectric power generation to water scarcity in China: Current status and future scenarios for power planning and climate change, Appl. Energy 171 (2016) 444–455.